The energetic implications of storing wind and solar generated electricity

Royd Moor, UK

Musonoi Mine, DRC

Virginia, USA

Charles Barnhart

Global Climate and Energy Project, Stanford University

MIT LEAP Webinar, June 7th 2013

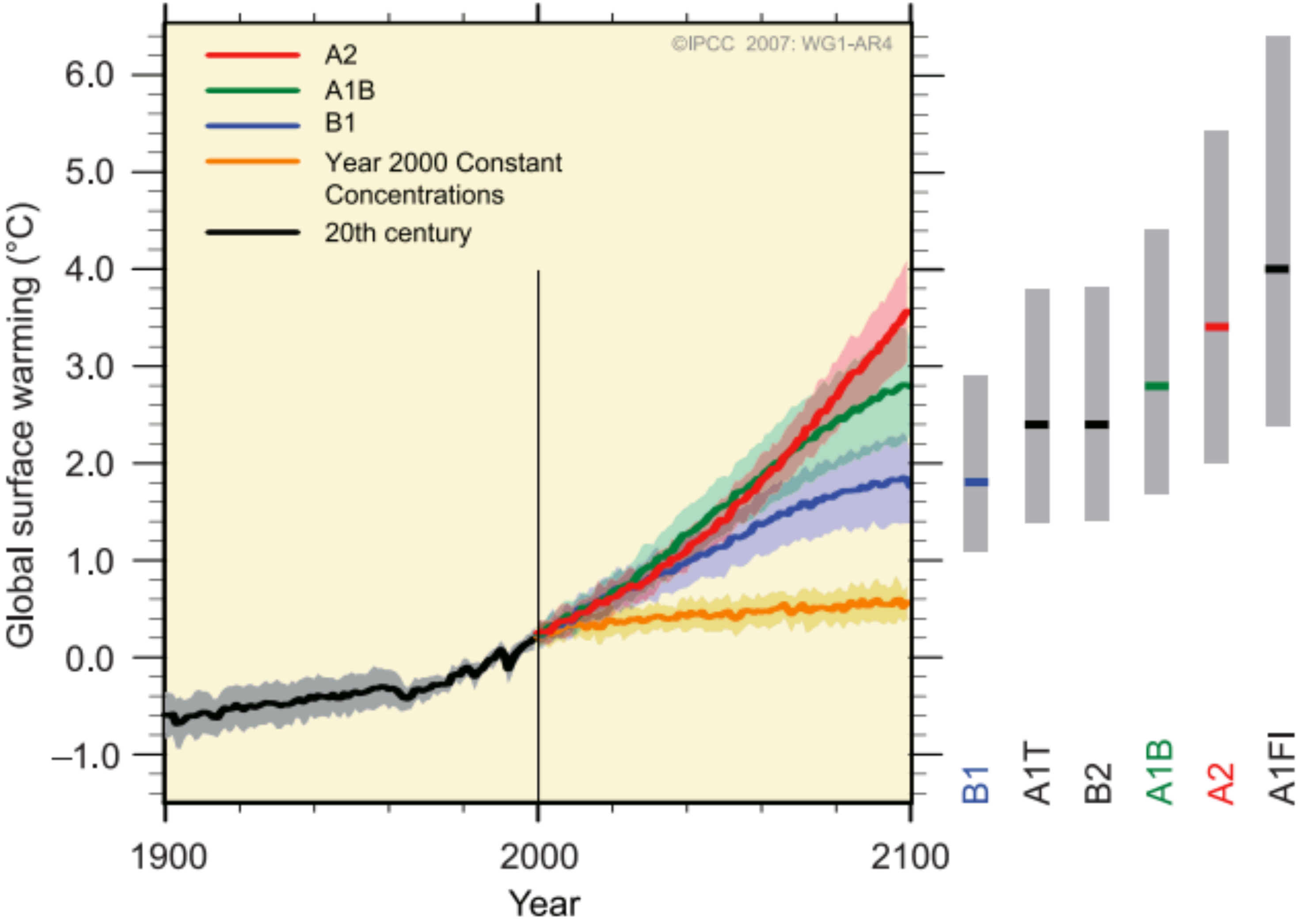
Outline

- Energy Systems Analysis
- Motivation for Renewable Energy Generation Paired with Energy Storage
- Energy Storage Options Appropriate for Grid Scale
- ~~Material Requirements for Energy Storage~~
- Energetic Requirements for Energy Storage
- Pairing Energy Storage with Renewable Resources

Energy Systems Analysis

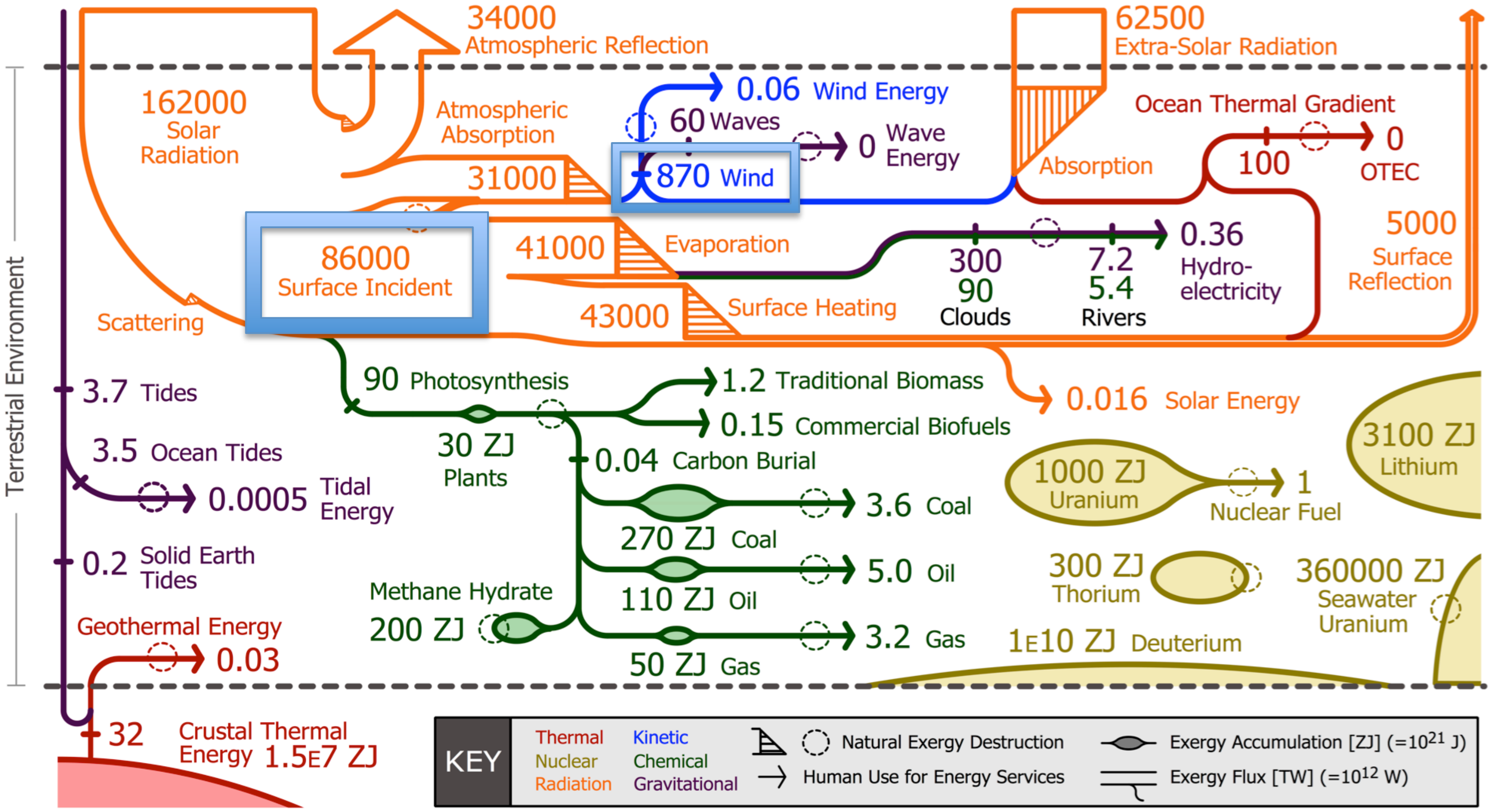
- We measure the material and energetic requirements of energy technologies to inform research, capital investment and policy.

Climate Change and Energy Transitions



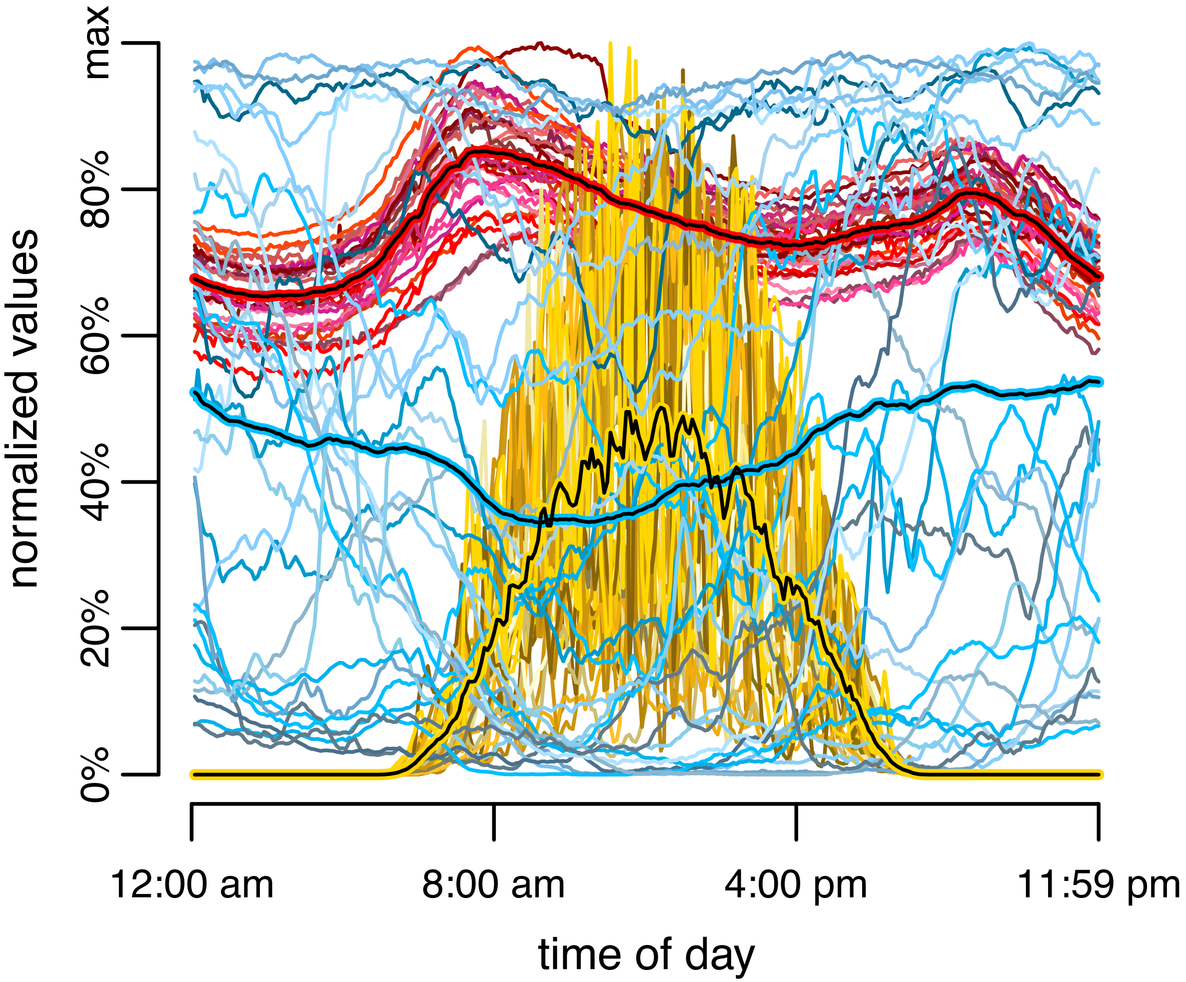
Meehl et al., 2007

Global Exergy Resources



Wes Hermann and A. J. Simon (2006) Energy

Wind and Solar Resources are Variable



timeseries data obtained from Bonneville Power Administration

plot concept motivated by Hawkins, 2005

Stable Operation of the Electrical Grid

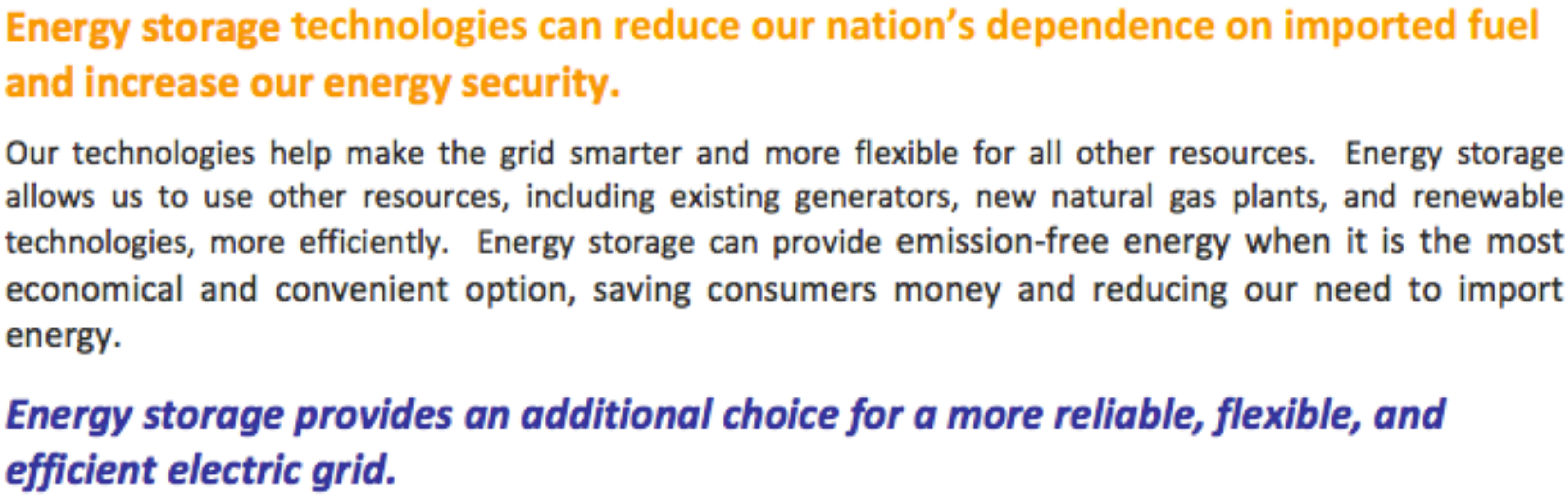
California ISO control room
©The New York Times, Max Whittaker, October 28, 2011

Grid Flexibility

- What is it?
  - “The ability of a system to deploy its resources to respond to changes in net load, where net load is defined as the remaining system load not served by variable generation.” -- Lannoye et al., 2012
- Options
  - Excess capacity and transmission
  - Natural gas combustion turbines (‘peaker plants’)
  - Demand-side management (smart grid)
  - Electrical Energy Storage

Why Storage

- Policy
  - 6 bills in U.S. Congress,
  - AB 2514 here in CA, first state to mandate storage
- Funding (ARPA-E, GCEP, VC)
- Electricity Storage Association (international trade assoc.)



Energy storage technologies can reduce our nation's dependence on imported fuel and increase our energy security.

Our technologies help make the grid smarter and more flexible for all other resources. Energy storage allows us to use other resources, including existing generators, new natural gas plants, and renewable technologies, more efficiently. Energy storage can provide emission-free energy when it is the most economical and convenient option, saving consumers money and reducing our need to import energy.

Energy storage provides an additional choice for a more reliable, flexible, and efficient electric grid.

Storage Technologies for Renewable Integration

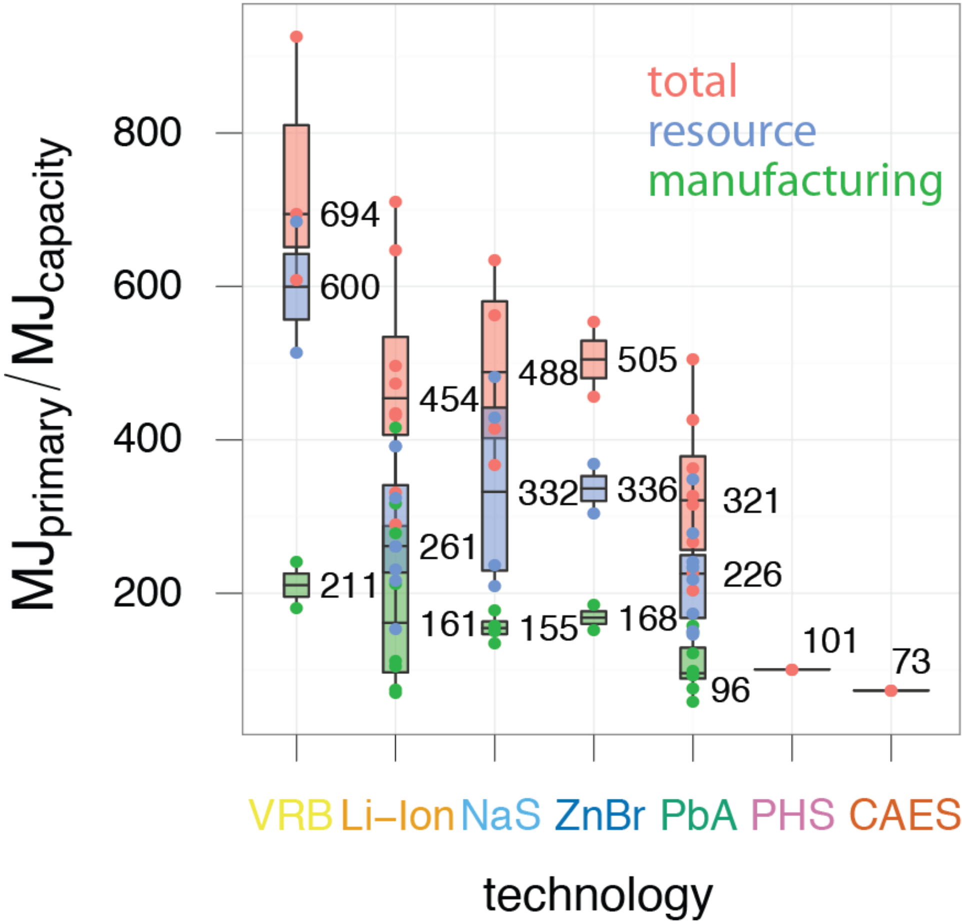
- Electrochemical
  - Lithium-Ion (Li-Ion)
  - Sodium Sulfur (NaS)
  - Lead-Acid (PbA)
- Flow Battery
  - Vandium Redox (VRB)
  - Zinc Bromine (ZnBr)
- Geological
  - Pumped Hydro (PHS)
  - Compressed Air (CAES)

Physical requirements

1. Spatial
2. Material
3. Energetic

Energy Demands of Electrical Energy Storage

Embodied Energy



roducing materials

ne, DRC

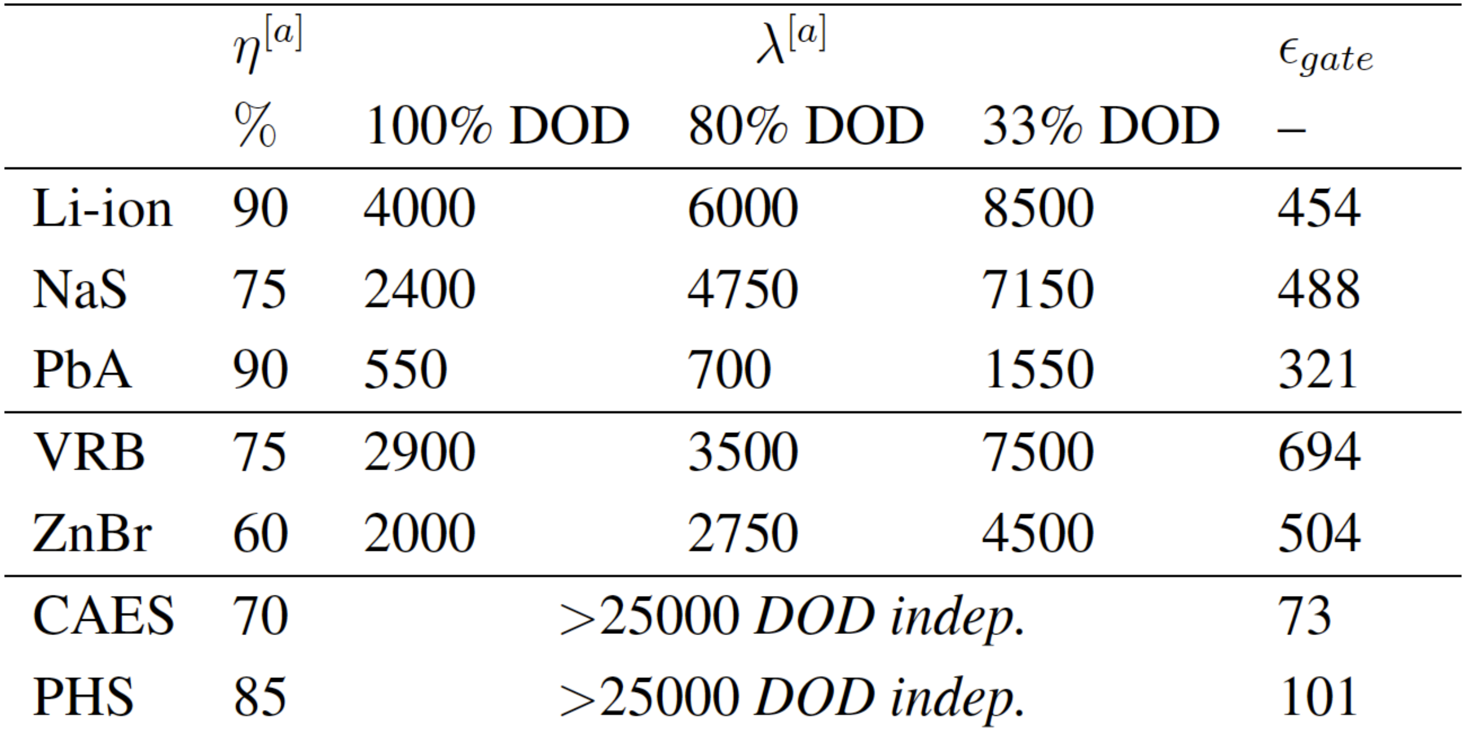
n manufacturing

etroit

Data assimilated from: Rydh et al., 1999, 2005; Denholm 2004, Argonne, 2010

Embodied Energy—Dynamic Effects

efficiency cycle life embodied energy



	$\eta^{[a]}$	$\lambda^{[a]}$			ϵ_{gate}
	%	100% DOD	80% DOD	33% DOD	–
Li-ion	90	4000	6000	8500	454
NaS	75	2400	4750	7150	488
PbA	90	550	700	1550	321
VRB	75	2900	3500	7500	694
ZnBr	60	2000	2750	4500	504
CAES	70	>25000 *DOD indep.*			73
PHS	85	>25000 *DOD indep.*			101

Depth of Discharge

Data obtained from Rydh et al., 1999, 2005; Denholm et al., 2004; ANL, 2011

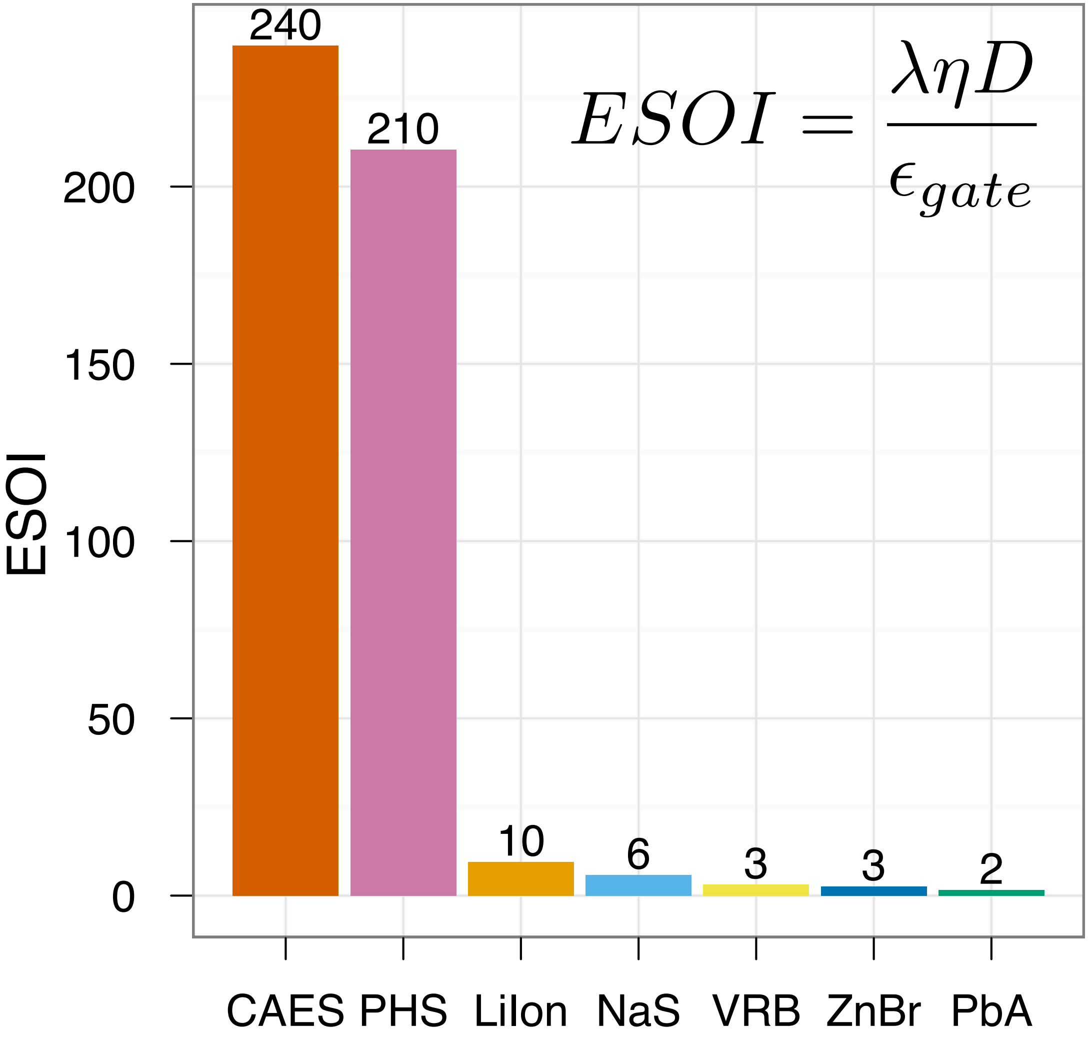
ESOI—Energy Stored on Energy Invested

$$ESOI = \frac{\text{energy stored over device lifetime}}{\text{embodied energy}}$$

$$\boxed{ESOI = \frac{\lambda \eta D}{\epsilon_{gate}}}$$

λ : cycle life
η : efficiency
D : depth of discharge
ϵ_{gate} : embodied energy

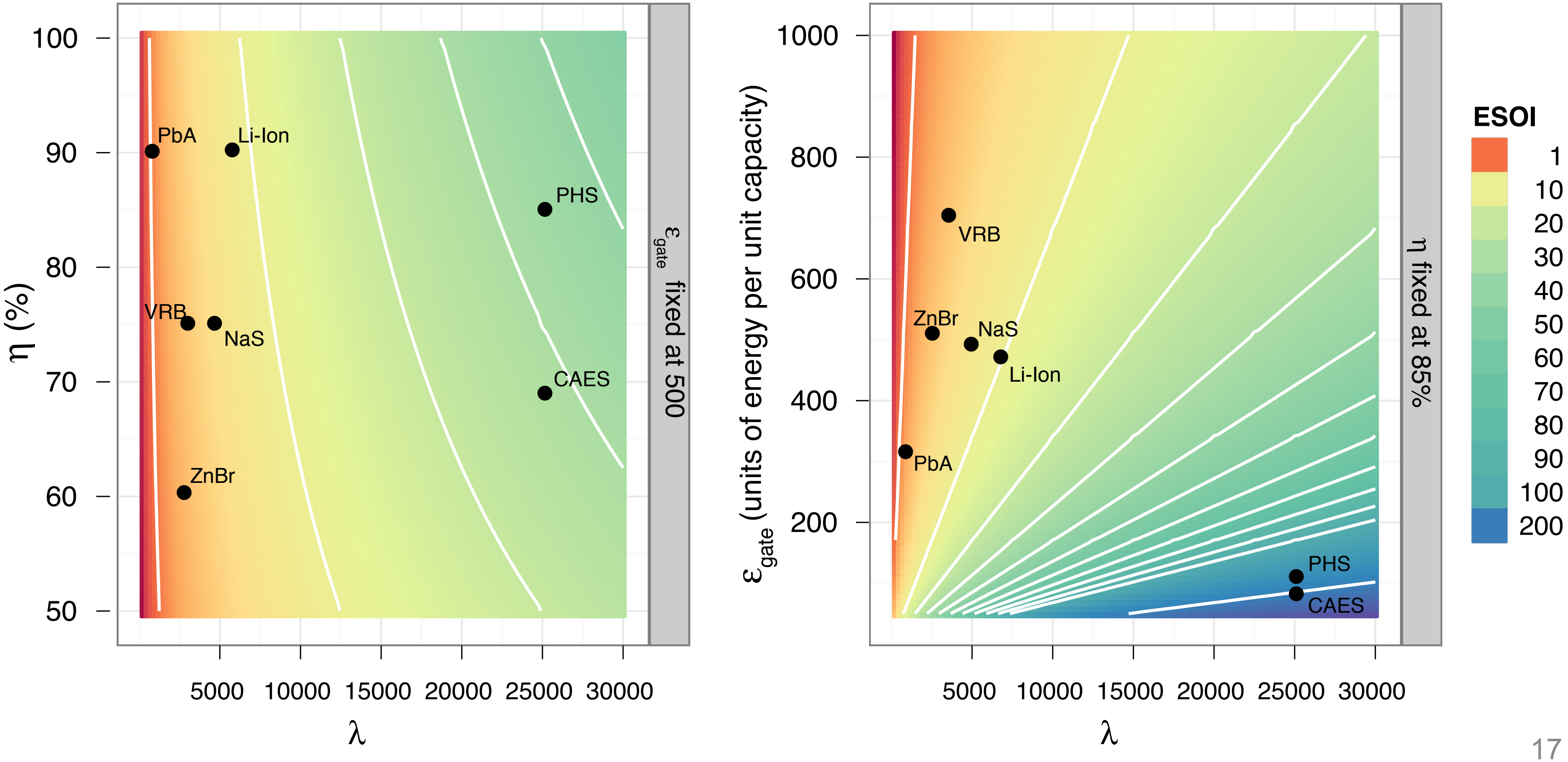
ESOI—Energy Stored on Energy Invested



$$ESOI = \frac{\lambda \eta D}{\epsilon_{gate}}$$

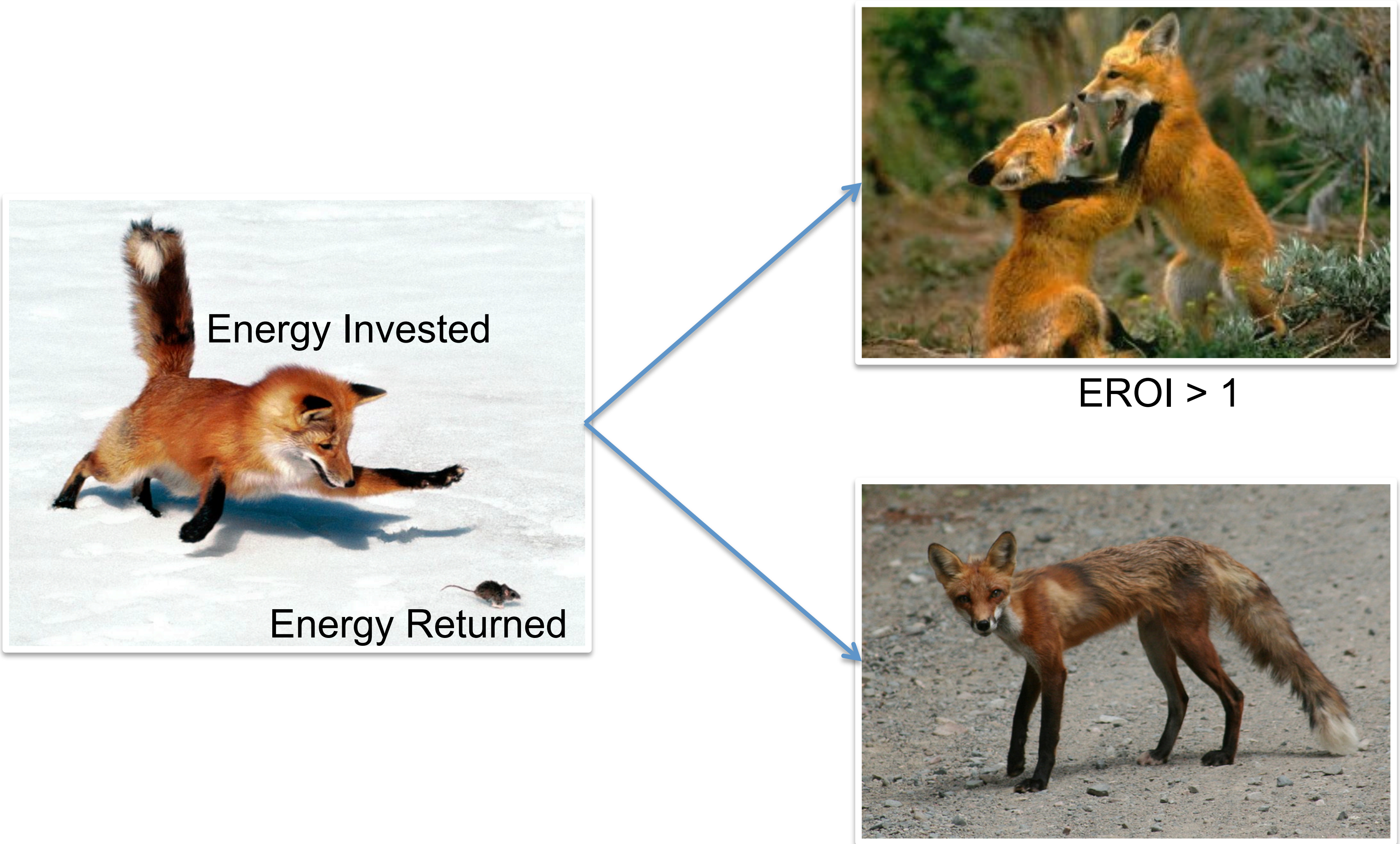
R&D strategy

$$ESOI = \frac{\lambda\eta D}{\epsilon_{gate}}$$



Which energy resource and storage pairings are optimum from a net-energy perspective?

Energy Return on Investment (EROI)



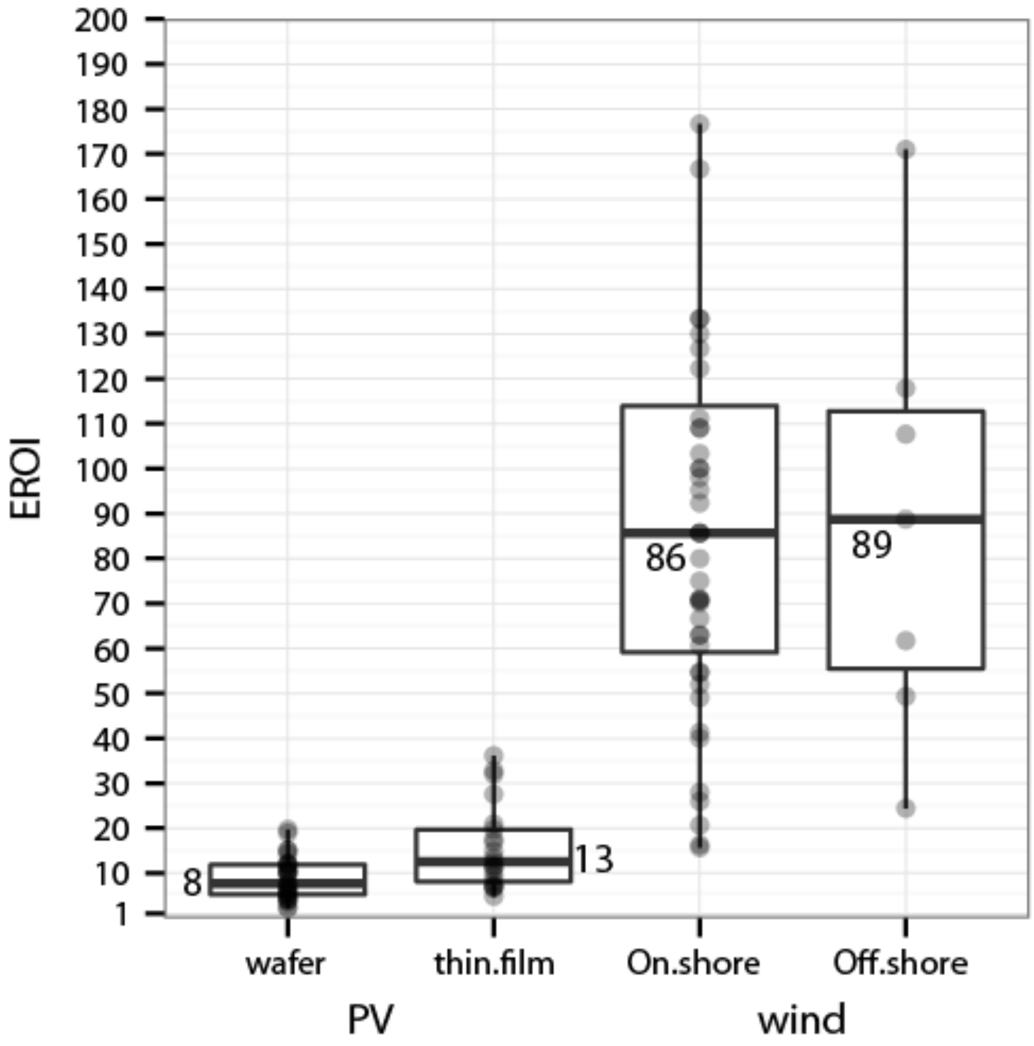
Energy Invested

Energy Returned

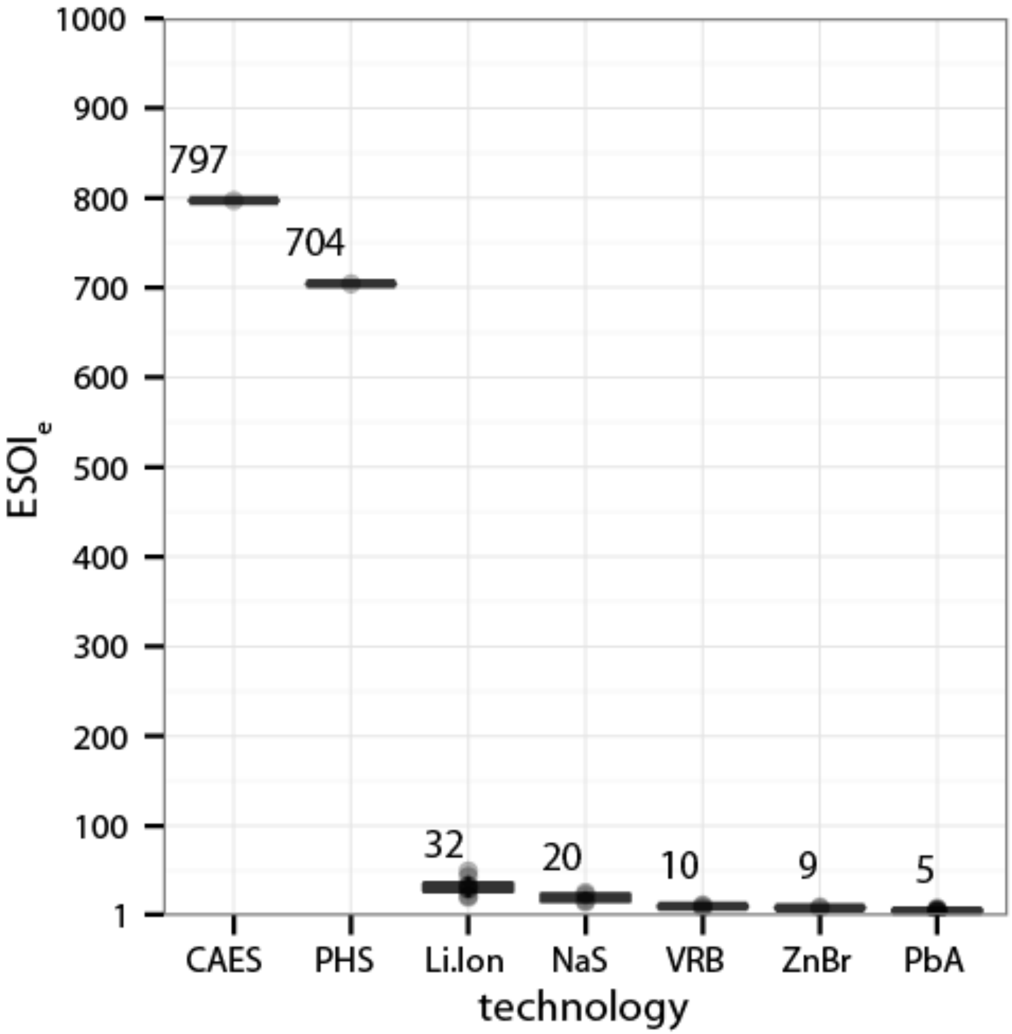
EROI > 1

EROI < 1

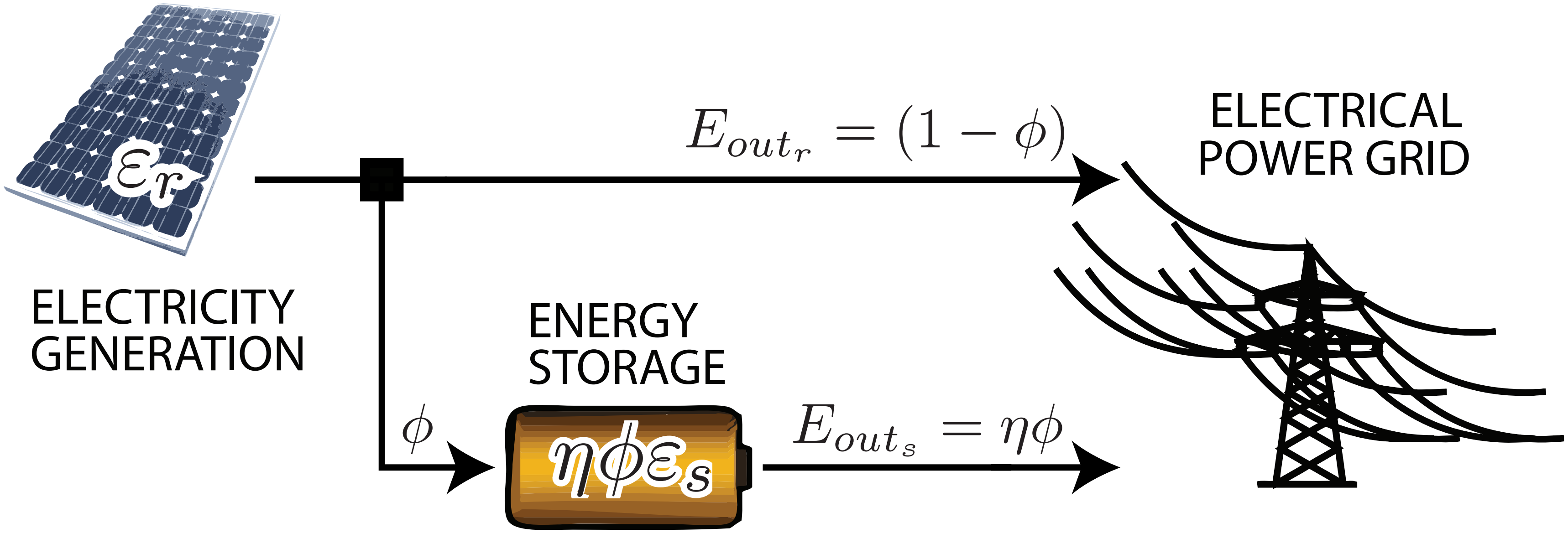
Solar PV and Wind Turbine EROI values



ESOI—Energy Stored on *Electrical* Energy Invested



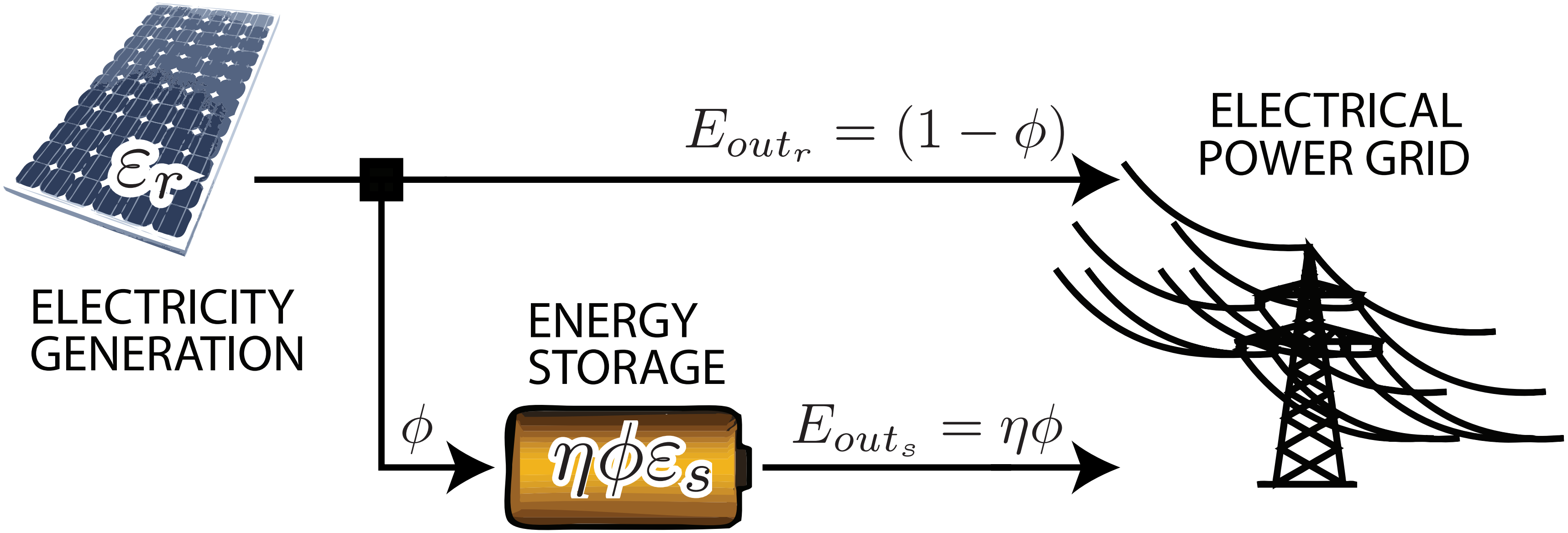
How does storage affect the grid-wide EROI?



$$EROI_c = EROI(1-\phi)$$

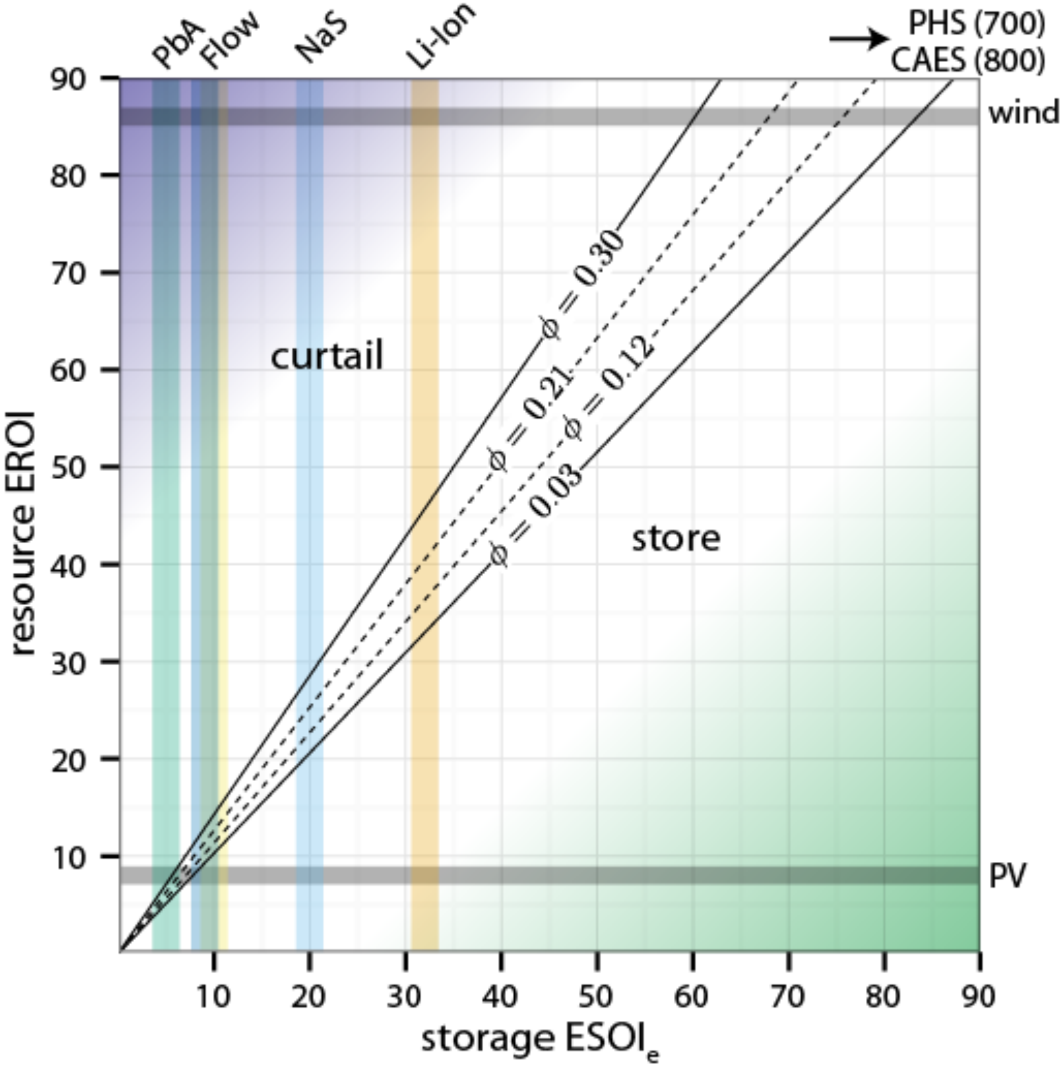
$$EROI_g = \frac{1-\phi+\eta\phi}{\frac{1}{EROI}+\frac{\eta\phi}{ESOI_e}} \quad \left[\frac{kWh_e \text{ generated}}{kWh_e \text{ embodied}}\right]$$

How does storage affect the grid-wide EROI?

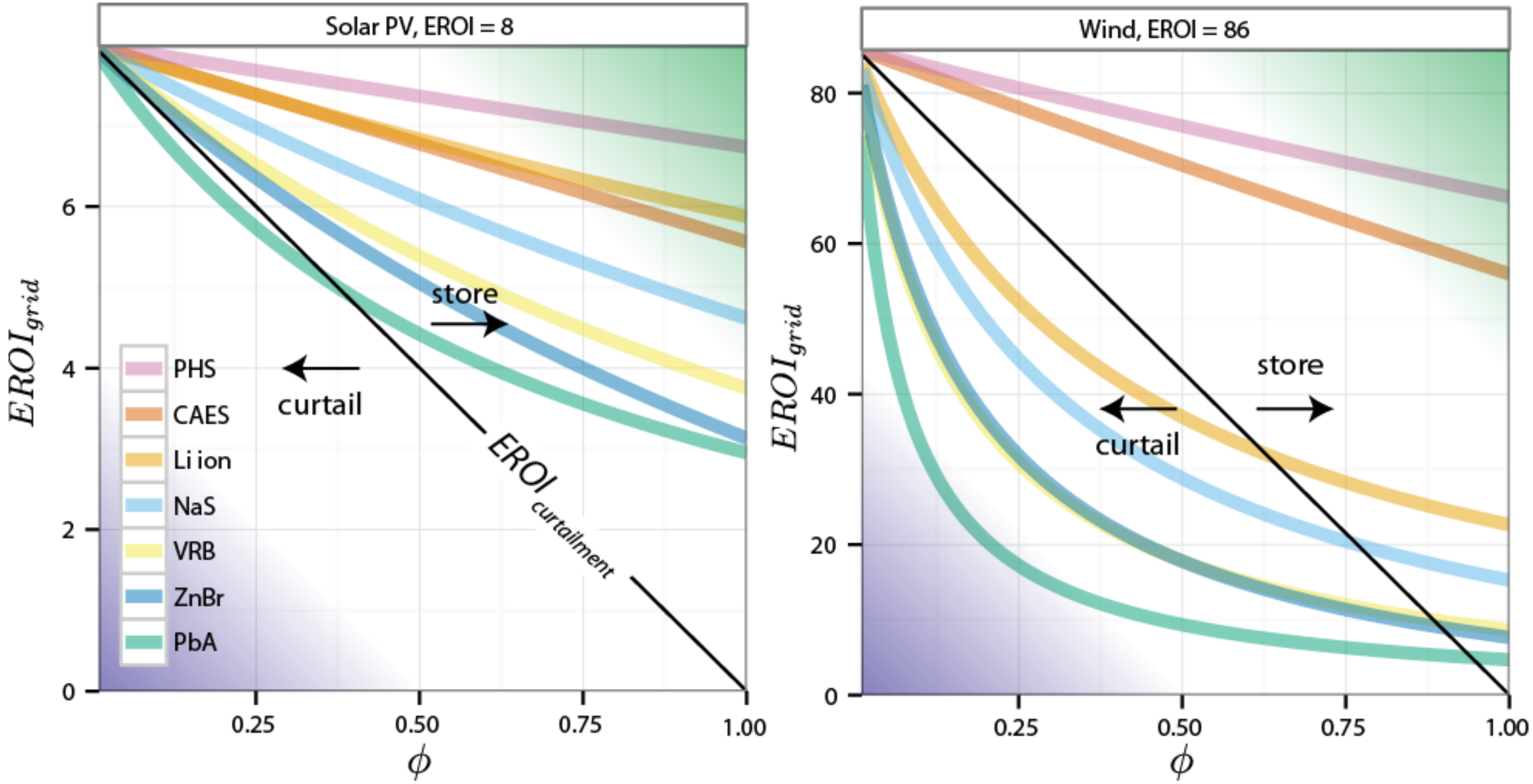


$$\boxed{\frac{ESOI_e}{EROI} \Rightarrow \begin{cases} \text{store if } > 1-\phi \\ \text{curtail if } < 1-\phi. \end{cases}}$$

$$\frac{ESOI_e}{EROI} \Rightarrow \begin{cases} \text{store if } > 1-\phi \\ \text{curtail if } < 1-\phi. \end{cases}$$



Resource—Storage System EROI



$$EROI_c = EROI(1-\phi)$$

$$EROI_g = \frac{1-\phi+\eta\phi}{\frac{1}{EROI}+\frac{\eta\phi}{ESOI_e}} \quad \left[\frac{kWh_e \text{ generated}}{kWh_e \text{ embodied}}\right]$$

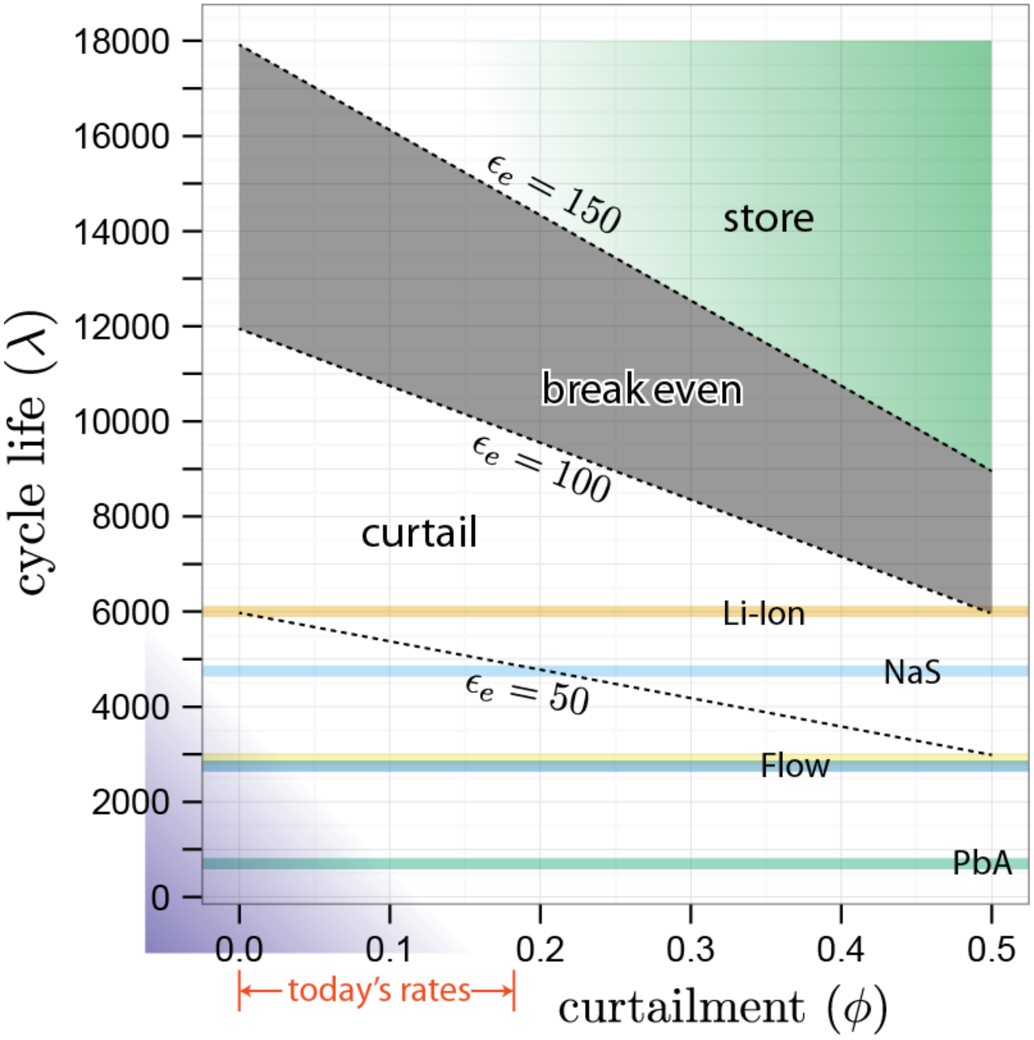
Technological improvements for batteries

$$\boxed{\frac{ESOI_e}{EROI} \Rightarrow \begin{cases} \text{store if } > 1-\phi \\ \text{curtail if } < 1-\phi. \end{cases}}$$

$$ESOI_e > \frac{1-\phi}{EROI}$$

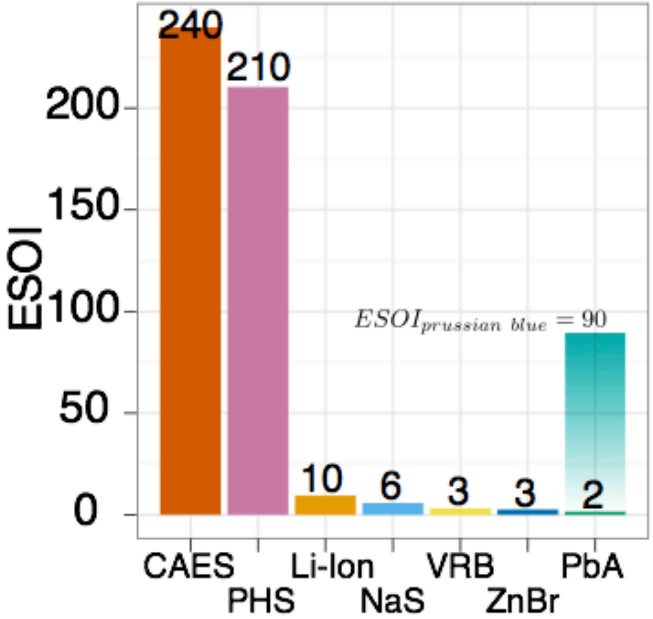
$$ESOI_e = \frac{\lambda \eta D}{\epsilon_e}$$

$$\boxed{\lambda > \frac{\epsilon_e(1-\phi)}{(\eta D)EROI}.}$$



Durable High-Cycle Life Battery Research

- Open framework of prussian blue analogues can enable:
  - ➢ fast ion transport
  - ➢ minimum strain
  - ➢ high cycle life



- Demonstrated 40,000 charging cycles using copper hexacyanoferrate

C. Wessels, R. Huggins, Y. Cui, *Nature Communication*, 2:550 (2011)
M. Pasta, R. Huggins, Y. Cui *Nat. Comm. (2012), In Press.*

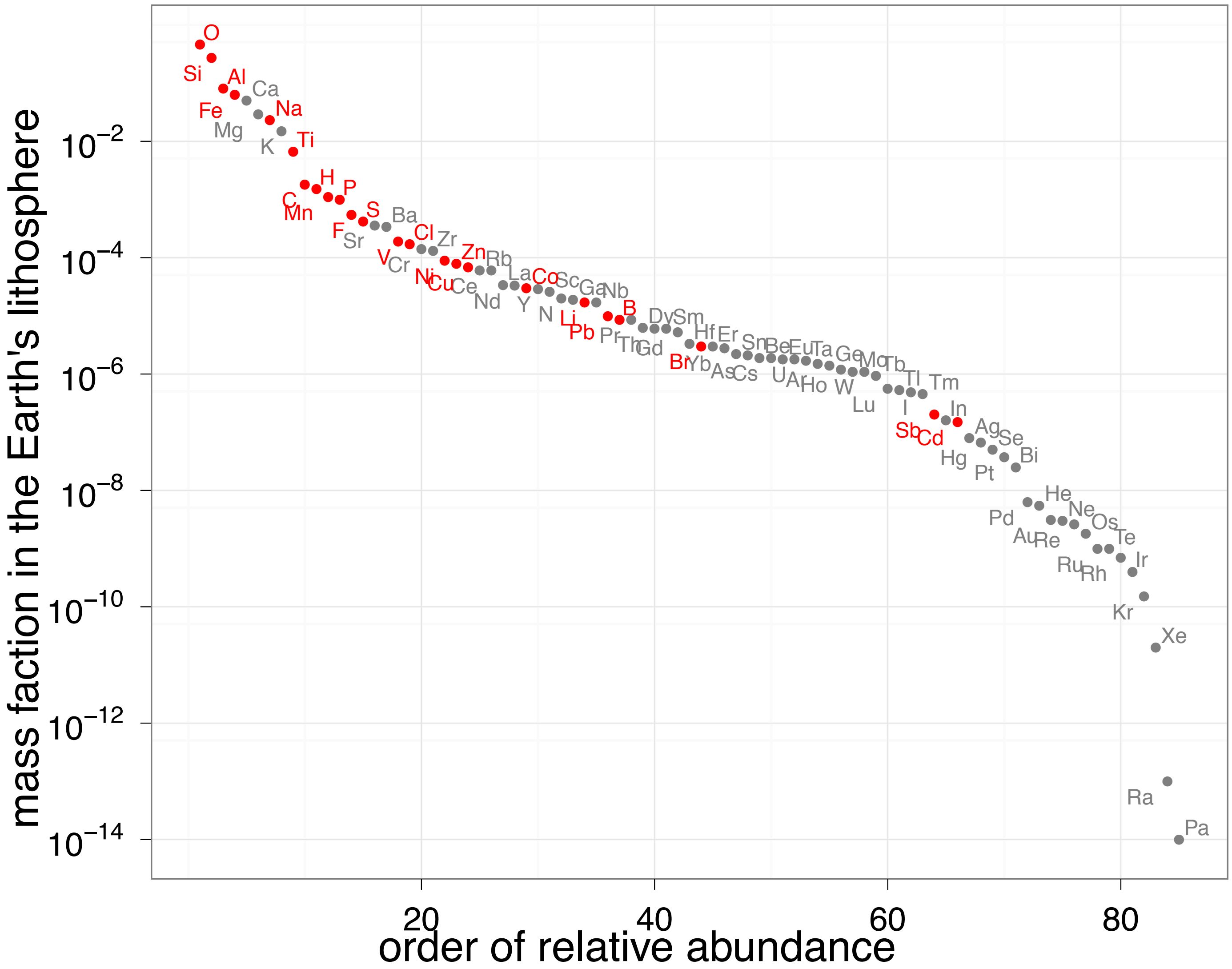
Summary and Conclusions

- Curtailing reduces system wide EROI
- So does storage
- Wind requires high ESOI storage (PHS and CAES)
- Batteries can store solar PV generated electricity and still yield EROI ratios that are greater than curtailment ratios
- Battery cycle life can and should be improved (need an ESOI of 86 and 10,000 to 18,000 cycles)
- Other options for otherwise curtailed electricity should be considered
- To be clear, storage holds great value, we only looked at it from one perspective: system energy efficiency…

Acknowledgements

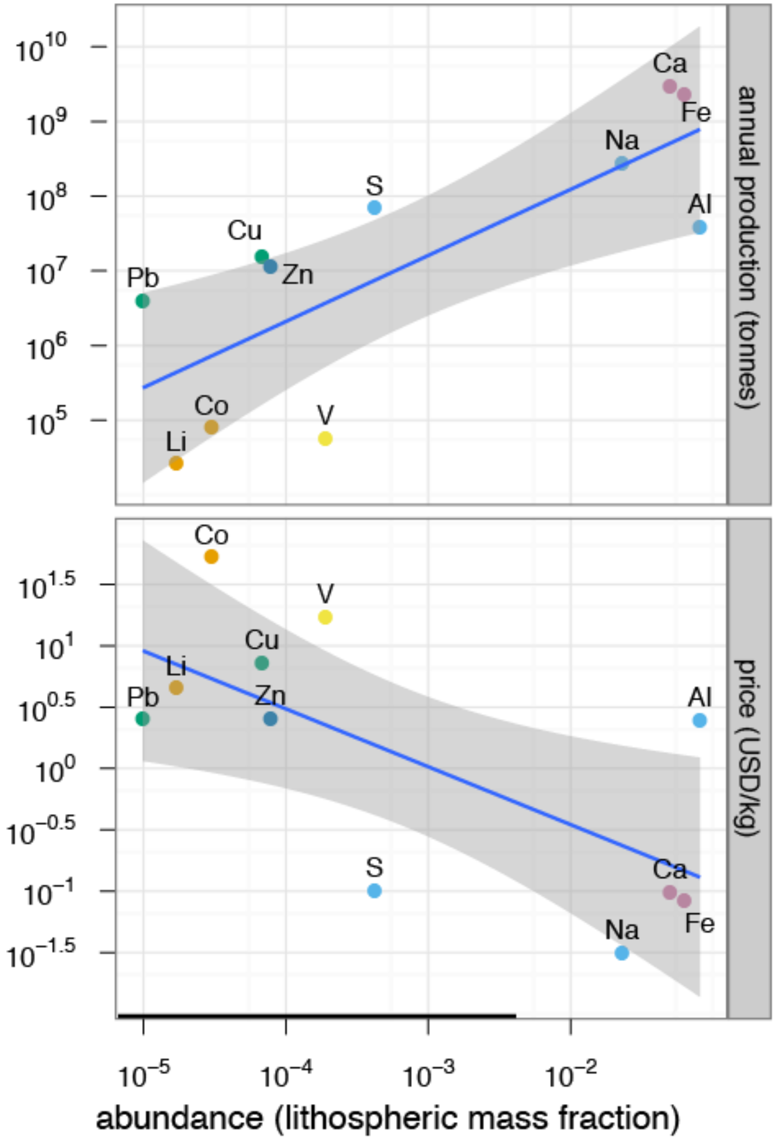
- Advisor: Prof. Sally Benson (ERE)
- Co-Authors: Mik Dale, PhD.; Prof. Adam Brandt (ERE)
- Stanford University's Global Climate and Energy Project
  - Richard Sassoon, Jenny Milne, Emilie Hung
  - Sponsors: GE, Exxon, Schlumberger, DuPont, Toyota
- Conversations with Prof. Bob Huggins, Prof. Yi Cui and Paul Denholm, PhD

Abundance of elements in lithosphere



Material Availability

"Civilization exists by geological consent, subject to change without notice."
– Will Durant



Barnhart and Benson, 2013

Data obtained from USGS Mineral Commodity Summary Reports (2006-2011)

Energy Storage Potential

$$ESP = \frac{\rho P}{m_f}$$

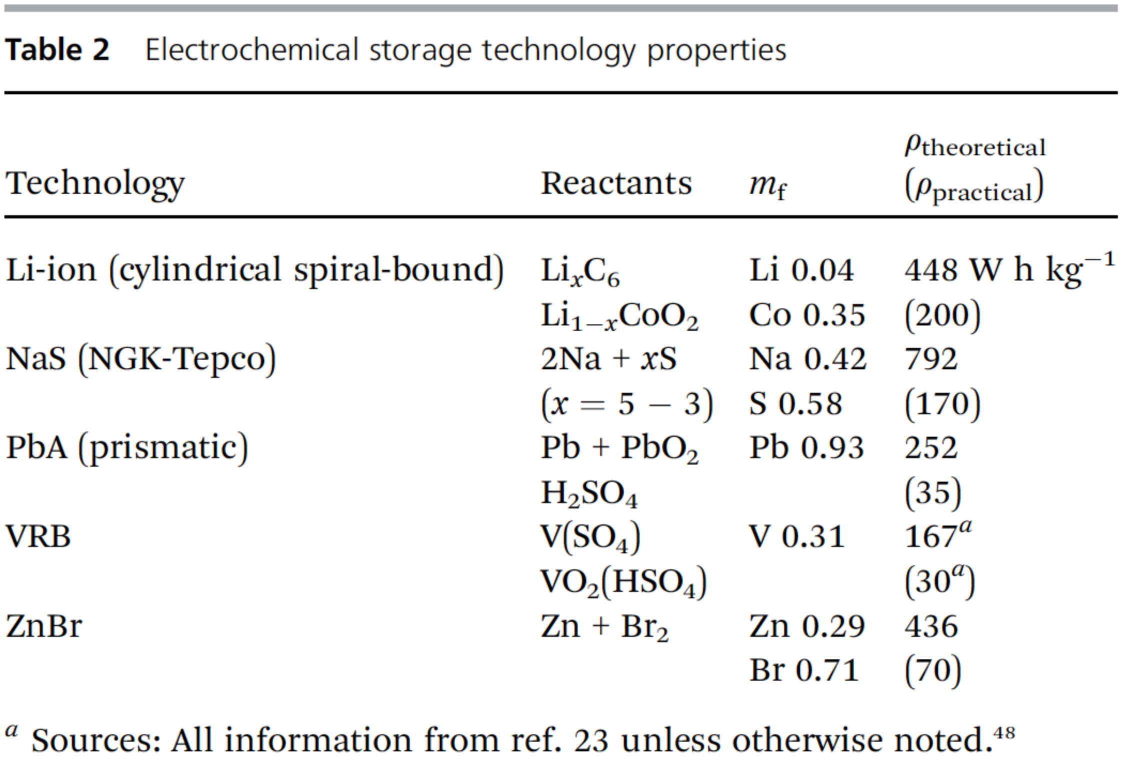
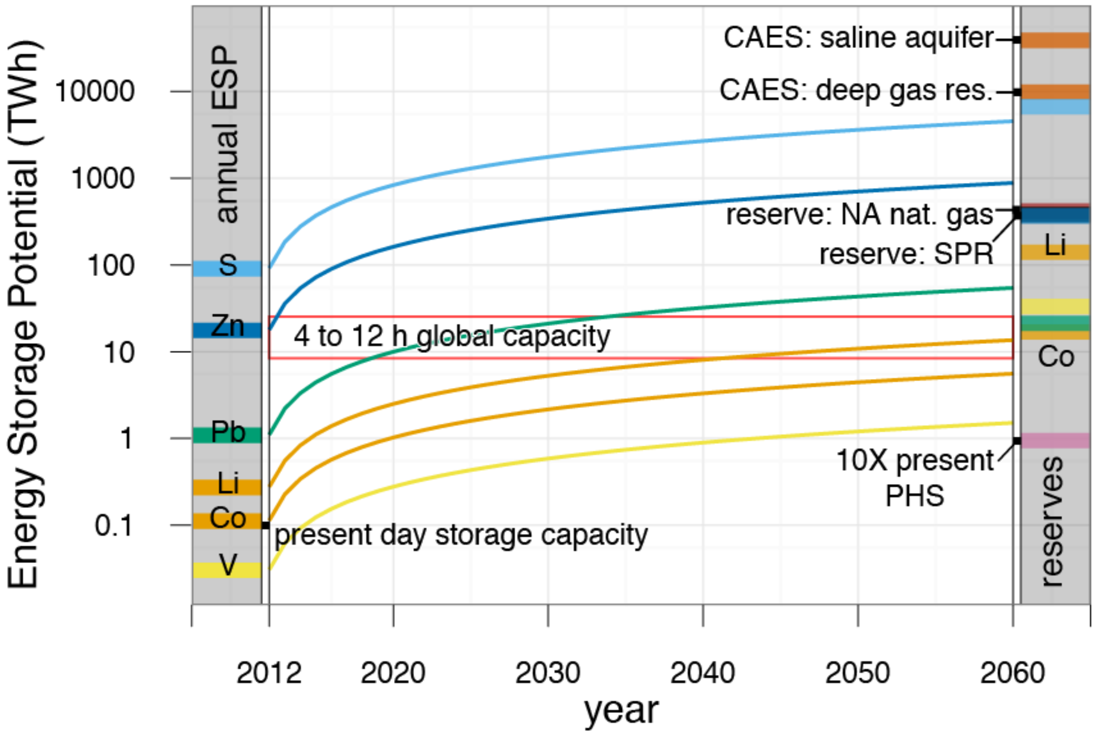


Table 2 Electrochemical storage technology properties

Technology	Reactants	m_f	$\rho_{\text{theoretical}}$ ($\rho_{\text{practical}}$)
Li-ion (cylindrical spiral-bound)	Li_xC_6	Li 0.04	448 W h kg^{-1}
	$Li_{1-x}CoO_2$	Co 0.35	(200)
NaS (NGK-Tepco)	2Na + xS	Na 0.42	792
	($x = 5 - 3$)	S 0.58	(170)
PbA (prismatic)	Pb + PbO_2	Pb 0.93	252
	H_2SO_4		(35)
VRB	$V(SO_4)$	V 0.31	167[a]
	$VO_2(HSO_4)$		(30[a])
ZnBr	Zn + Br_2	Zn 0.29	436
		Br 0.71	(70)

[a] Sources: All information from ref. 23 unless otherwise noted.[48]

Energy Storage Potential of Materials



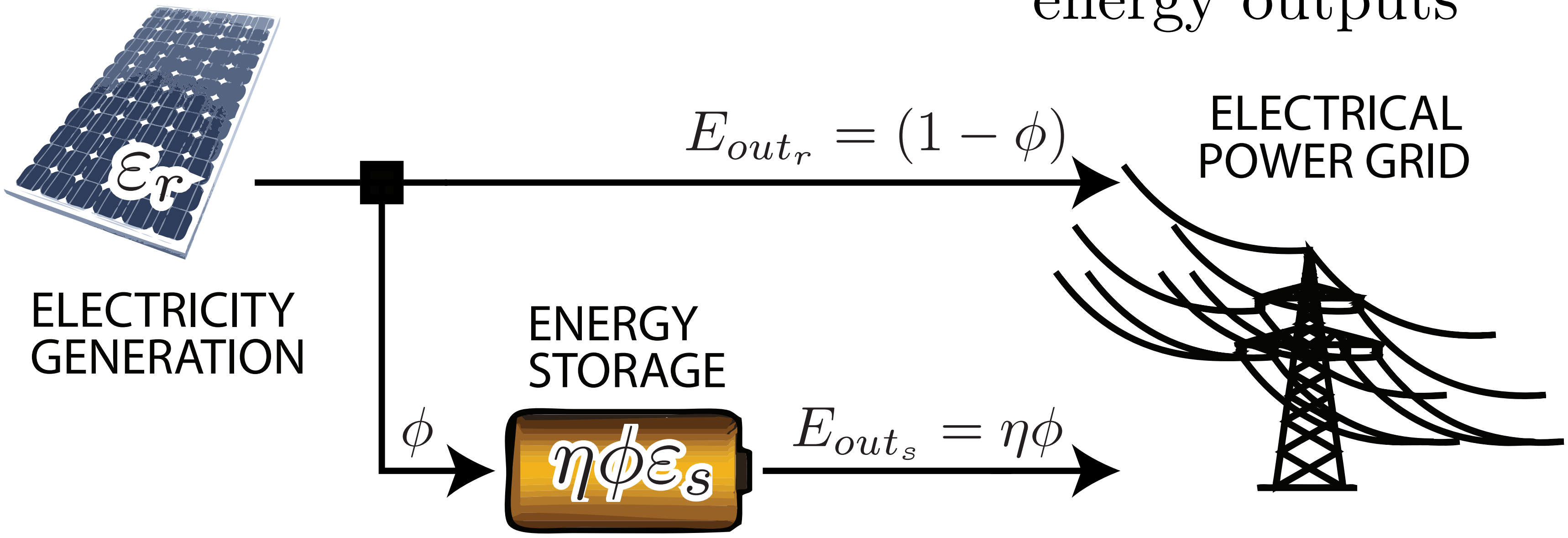
Promising Technologies: CAES, NaS, ZnBr

Barnhart and Benson, 2013
Data from USGS Mineral Commodity Summary Reports (2006-2011)
ESP Calculations motivated by Rydh et al., 1999; Wadia et al., 2011

$$ESP = \frac{\rho P}{m_f}$$

Theoretical Framework

$$\varepsilon = \frac{\text{energy inputs}}{\text{energy outputs}}$$



ε_r

ELECTRICITY GENERATION

$E_{out_r} = (1 - \phi)$

ELECTRICAL POWER GRID

ϕ

ENERGY STORAGE

$\eta\phi\varepsilon_s$

$E_{out_s} = \eta\phi$

$$\varepsilon_g = \frac{\varepsilon_r + \eta\varepsilon_s\phi}{1 - \phi + \phi\eta} \quad \left[\frac{kWh_e \ \text{embodied}}{kWh_e \ \text{generated}}\right]$$

$$\varepsilon_c = \frac{\varepsilon_r}{(1 - \phi)} \quad \left[\frac{kWh_e \ \text{embodied}}{kWh_e \ \text{generated}}\right]$$

Theoretical Framework

$$\varepsilon_c = \frac{\varepsilon_r}{(1-\phi)} \quad \left[\frac{kWh_e \text{ embodied}}{kWh_e \text{ generated}}\right]$$

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$$EROI_g = \frac{1-\phi+\eta\phi}{\frac{1}{EROI}+\frac{\eta\phi}{ESOI_e}} \quad \left[\frac{kWh_e \text{ generated}}{kWh_e \text{ embodied}}\right]$$

To Store or Curtail?

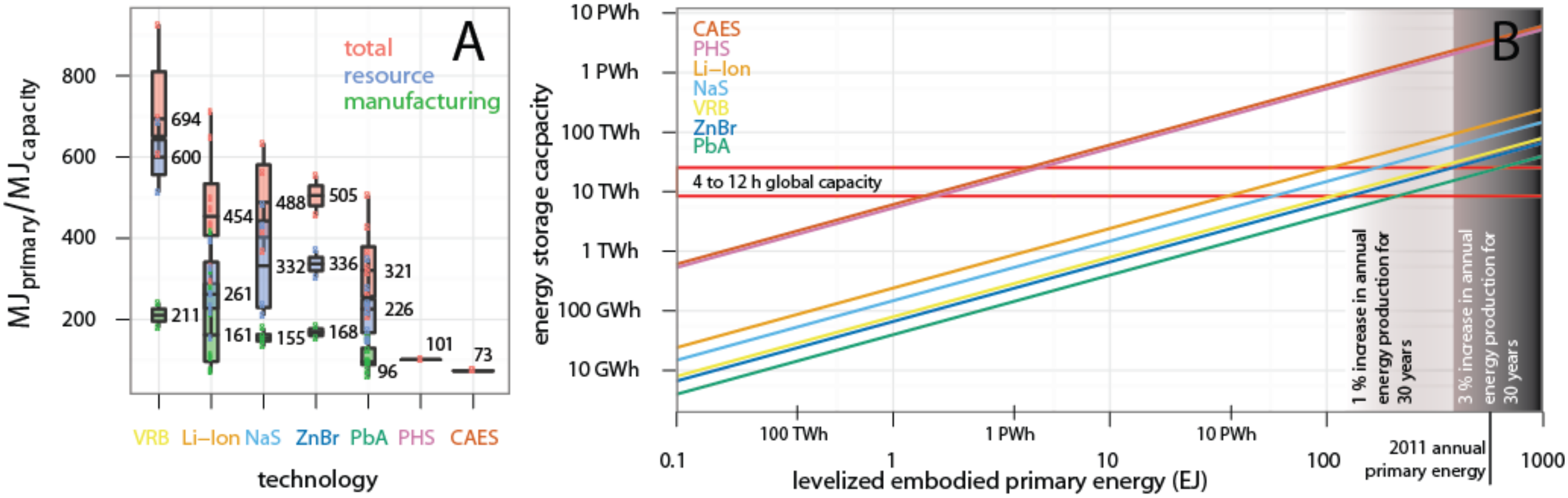
- At breakeven $\varepsilon_c = \varepsilon_g$

$$\frac{\varepsilon_r}{(1-\phi)} = \frac{\varepsilon_r + \phi\eta\varepsilon_s}{1-\phi+\eta\phi}$$

$$\frac{\varepsilon_r}{\varepsilon_s} = 1-\phi$$

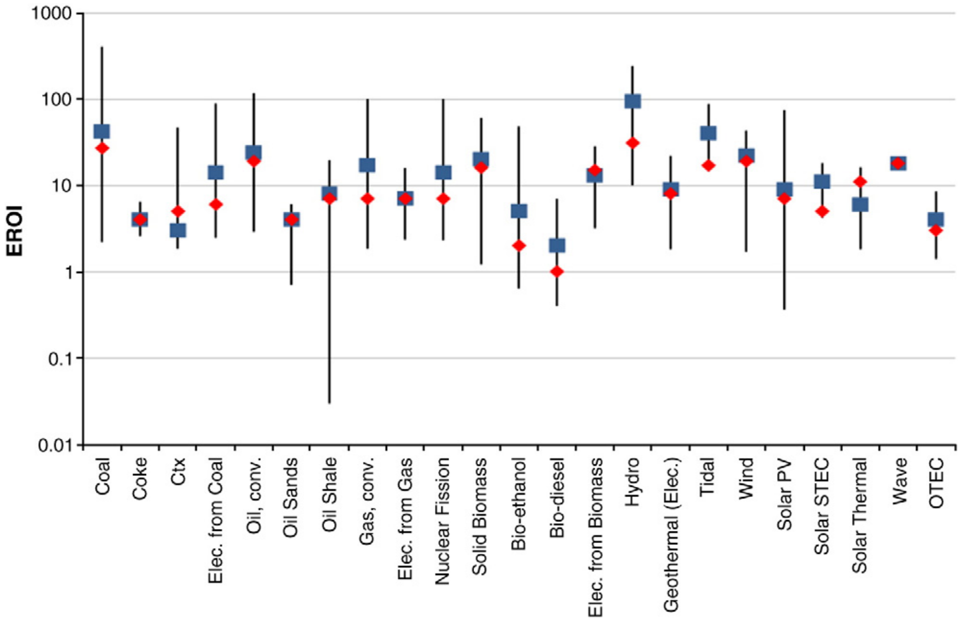
$$\boxed{\frac{ESOI_e}{EROI} \Rightarrow \begin{cases} \text{store if } > 1-\phi \\ \text{curtail if } < 1-\phi. \end{cases}}$$

Embodied Energy for Grid Storage



Data assimilated from: Rydh et al., 1999, 2005; Denholm 2004, Argonne, 2010

EROI



Dale, Krumdieck and Bodger, 2012

EROIe of Solar Technologies

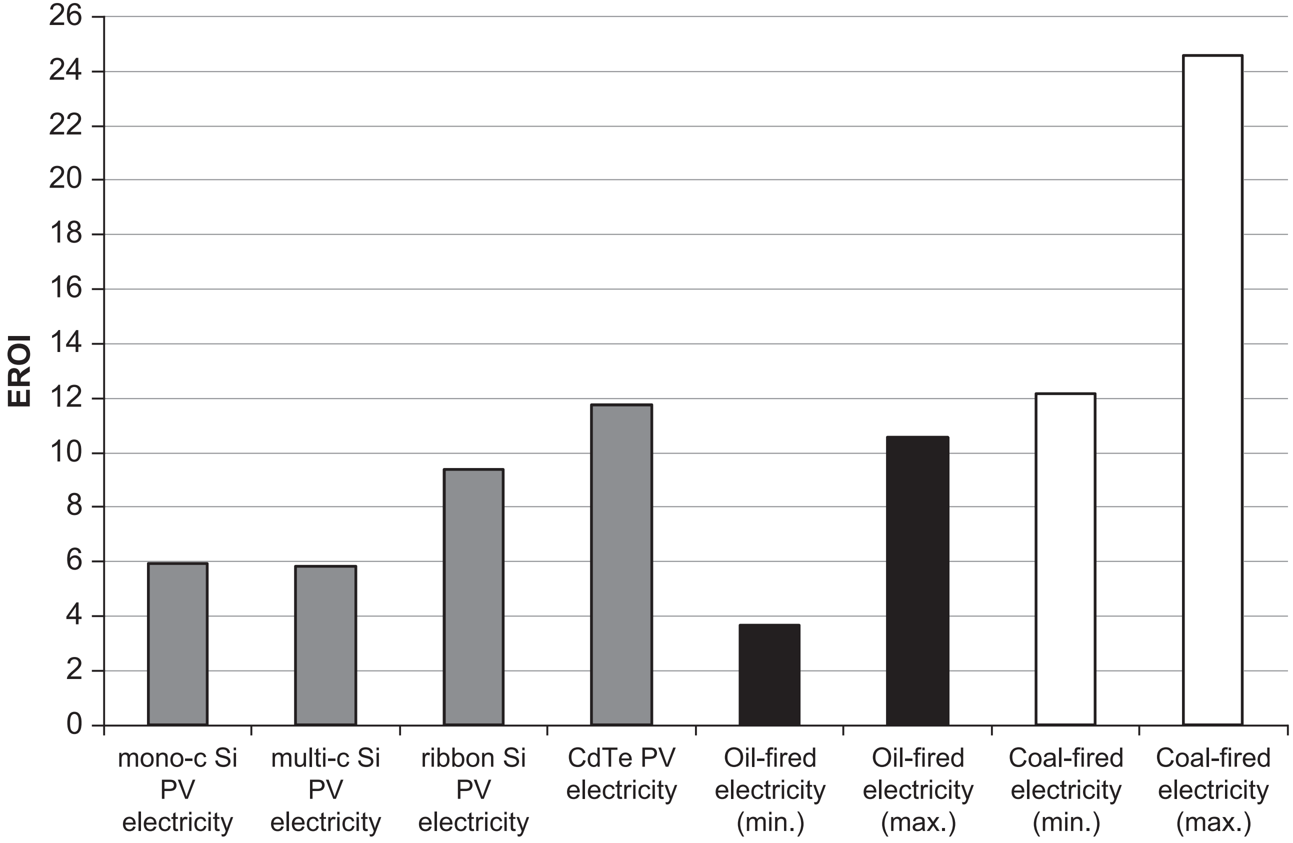
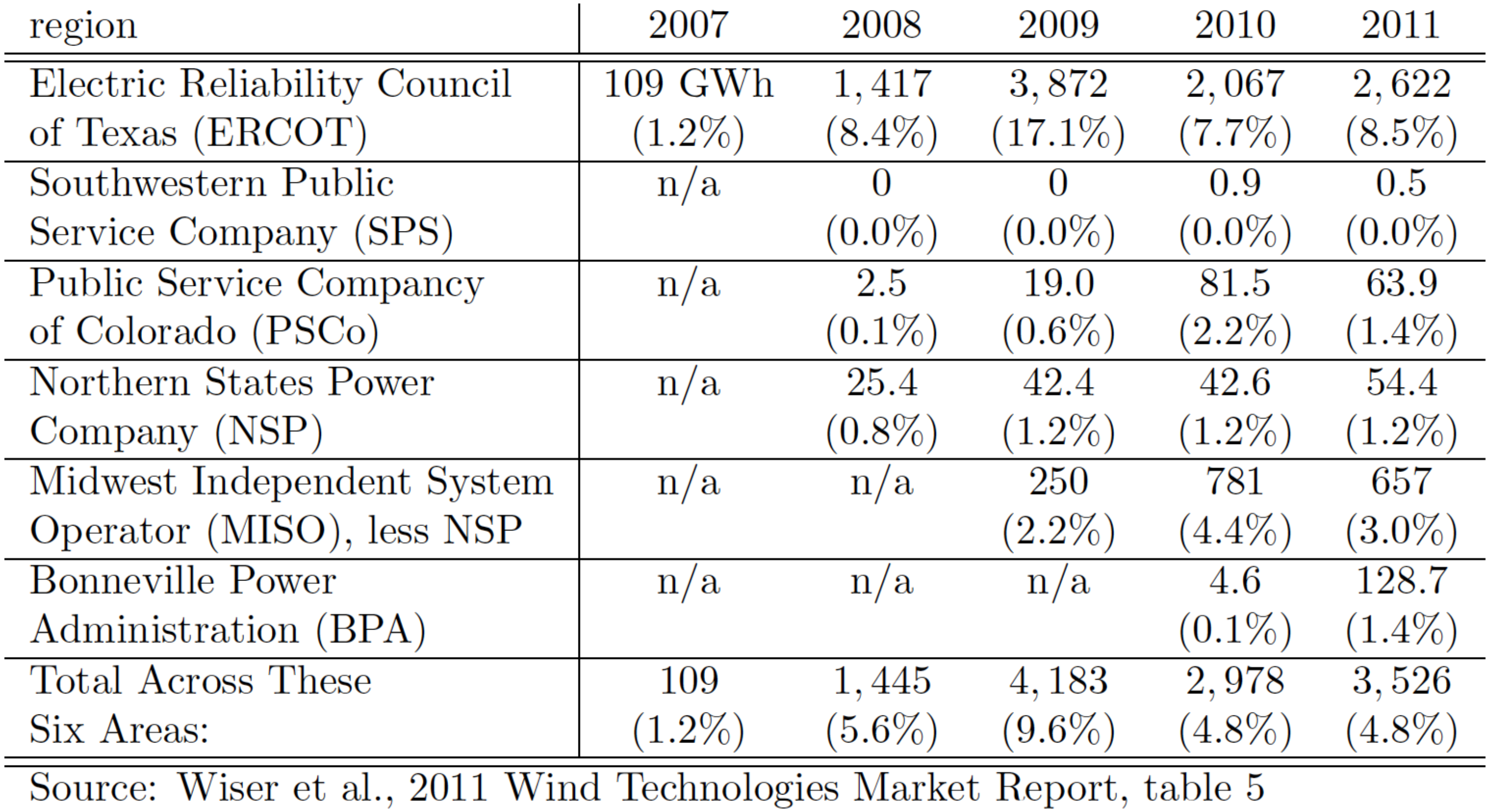


Fig. 2. $EROI_{el}$ of PV electricity, compared to the $EROI_{el}$ of oil- and coal-fired thermal electricity (Eq. (2)).

To Store or Curtail?

- Energy lost with curtailment vs energy lost through building and operating storage technologies

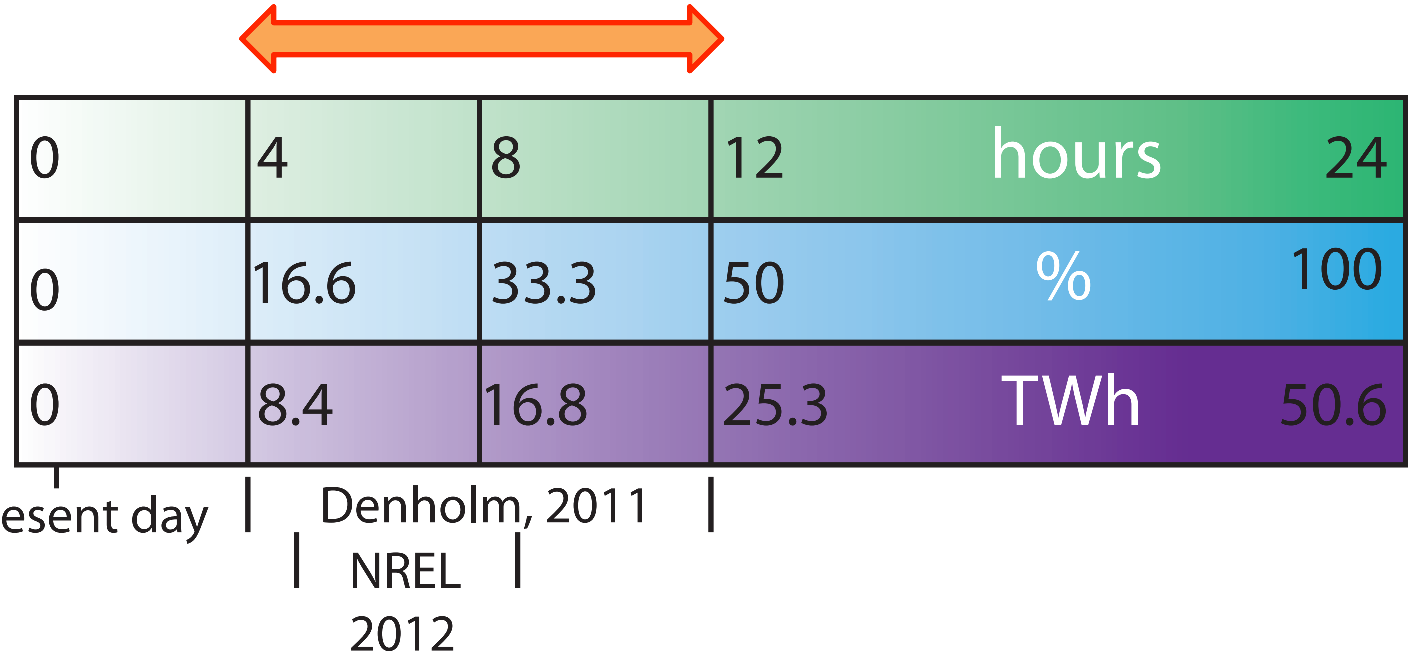


region	2007	2008	2009	2010	2011
Electric Reliability Council of Texas (ERCOT)	109 GWh (1.2%)	1,417 (8.4%)	3,872 (17.1%)	2,067 (7.7%)	2,622 (8.5%)
Southwestern Public Service Company (SPS)	n/a	0 (0.0%)	0 (0.0%)	0.9 (0.0%)	0.5 (0.0%)
Public Service Compancy of Colorado (PSCo)	n/a	2.5 (0.1%)	19.0 (0.6%)	81.5 (2.2%)	63.9 (1.4%)
Northern States Power Company (NSP)	n/a	25.4 (0.8%)	42.4 (1.2%)	42.6 (1.2%)	54.4 (1.2%)
Midwest Independent System Operator (MISO), less NSP	n/a	n/a	250 (2.2%)	781 (4.4%)	657 (3.0%)
Bonneville Power Administration (BPA)	n/a	n/a	n/a	4.6 (0.1%)	128.7 (1.4%)
Total Across These Six Areas:	109 (1.2%)	1,445 (5.6%)	4,183 (9.6%)	2,978 (4.8%)	3,526 (4.8%)

Source: Wiser et al., 2011 Wind Technologies Market Report, table 5

Can we build enough storage to supplement variable electricity supply?

- How much storage might society need?



0	4	8	12	hours	24
0	16.6	33.3	50	%	100
0	8.4	16.8	25.3	TWh	50.6

Budischak, et al., 2013 – 0%
Weisbach, et al., 2013 – 1000%

How much storage exists today?

0.2 % of average daily global electricity consumption

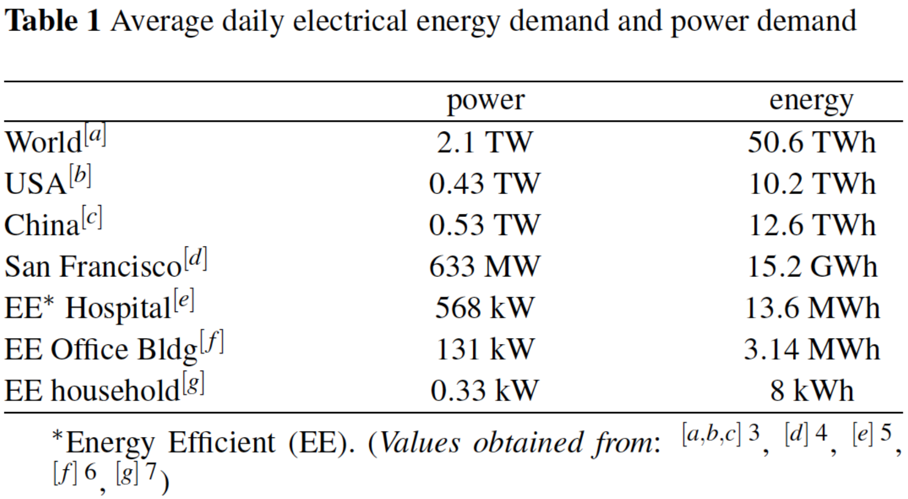


Table 1 Average daily electrical energy demand and power demand

	power	energy
World[a]	2.1 TW	50.6 TWh
USA[b]	0.43 TW	10.2 TWh
China[c]	0.53 TW	12.6 TWh
San Francisco[d]	633 MW	15.2 GWh
EE* Hospital[e]	568 kW	13.6 MWh
EE Office Bldg[f]	131 kW	3.14 MWh
EE household[g]	0.33 kW	8 kWh

*Energy Efficient (EE). (*Values obtained from*: [a,b,c] 3, [d] 4, [e] 5, [f] 6, [g] 7)

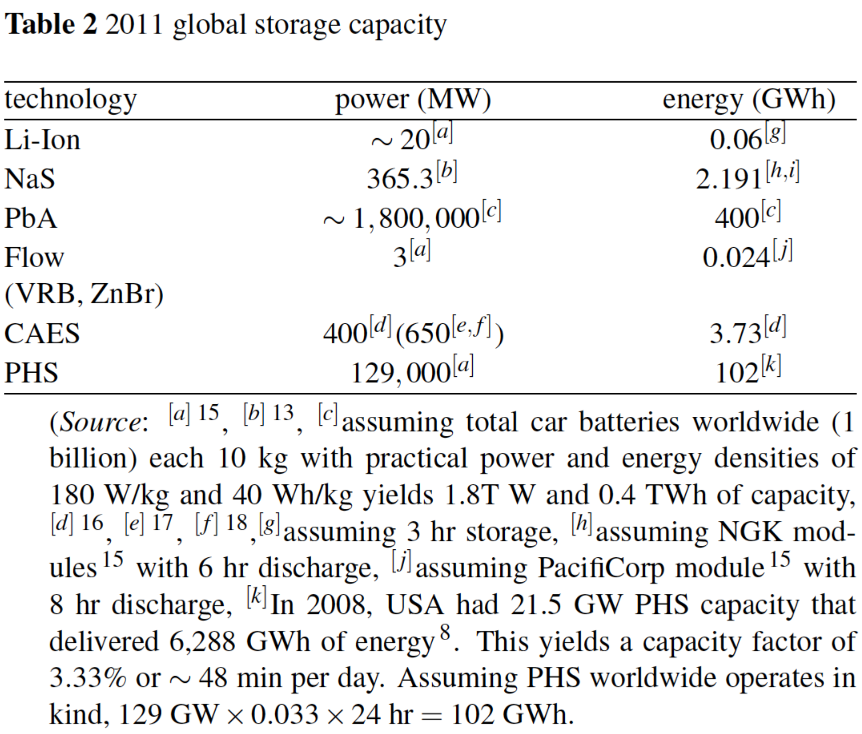
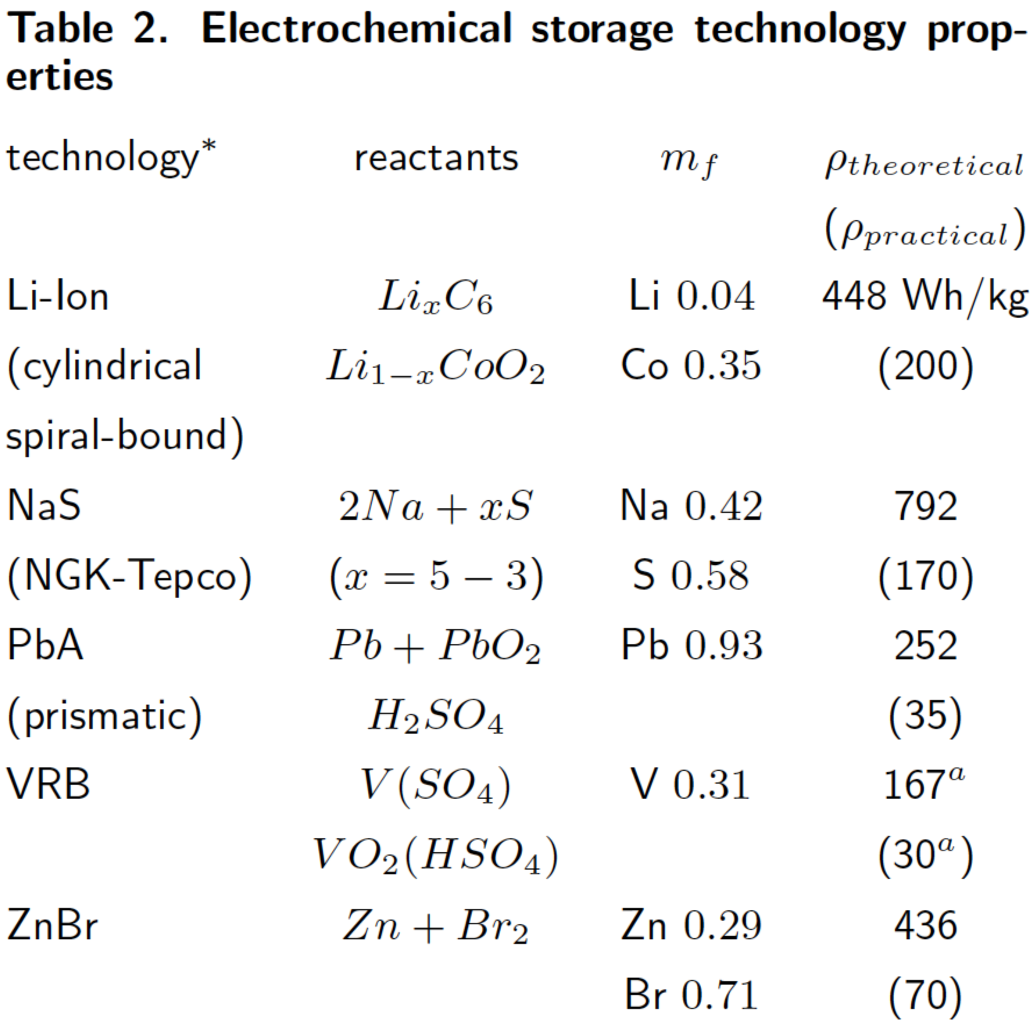


Table 2 2011 global storage capacity

technology	power (MW)	energy (GWh)
Li-Ion	~ 20[a]	0.06[g]
NaS	365.3[b]	2.191[h,i]
PbA	$\sim 1,800,000$[c]	400[c]
Flow (VRB, ZnBr)	3[a]	0.024[j]
CAES	400[d] (650[e,f])	3.73[d]
PHS	129,000[a]	102[k]

(*Source*: [a] 15, [b] 13, [c]assuming total car batteries worldwide (1 billion) each 10 kg with practical power and energy densities of 180 W/kg and 40 Wh/kg yields 1.8T W and 0.4 TWh of capacity, [d] 16, [e] 17, [f] 18,[g]assuming 3 hr storage, [h]assuming NGK modules 15 with 6 hr discharge, [j]assuming PacifiCorp module 15 with 8 hr discharge, [k]In 2008, USA had 21.5 GW PHS capacity that delivered 6,288 GWh of energy 8. This yields a capacity factor of 3.33% or $\sim$ 48 min per day. Assuming PHS worldwide operates in kind, 129 GW $\times$ 0.033 $\times$ 24 hr $=$ 102 GWh.

Backup 6: ESP Calculation Data



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technology*	reactants	m_f	$\rho_{theoretical}$ $(\rho_{practical})$
Li-Ion (cylindrical spiral-bound)	Li_xC_6 $Li_{1-x}CoO_2$	Li 0.04 Co 0.35	448 Wh/kg (200)
NaS (NGK-Tepco)	$2Na + xS$ $(x = 5 - 3)$	Na 0.42 S 0.58	792 (170)
PbA (prismatic)	$Pb + PbO_2$ H_2SO_4	Pb 0.93	252 (35)
VRB	$V(SO_4)$ $VO_2(HSO_4)$	V 0.31	167[a] (30[a])
ZnBr	$Zn + Br_2$	Zn 0.29 Br 0.71	436 (70)

scatter plots with embodied energy and price