MAKING GOOD ENERGY CHOICES: THE ROLE OF ENERGY SYSTEMS ANALYSIS

Professor Sally M. Benson
Department of Energy Resources Engineering
Co-Director, Precourt Institute for Energy
Director, Global Climate and Energy Project

Thanks to my extraordinary post-docs and graduate students

- Charlie Barnhart
- Michael Cabajales-Dale
- Matt Pellow
- Chris Emmott
- Markus Felgenhauer

For deepening my understanding of the energy system…

The Energy Transition

- Rapid changes are are taking place in the global energy system
  - Pollution concerns
  - Climate change motivated reduction in greenhouse gas emissions
  - Lower cost renewable energy
  - Plentiful and low cost natural gas
  - Cheap oil
  - Security concerns
- Rapid changes are likely to continue for many decades

How Do We Make Good Choices?

- What's the best kind of battery for grid storage?
- What's better – natural gas peakers or battery storage?
- How much should we subsidize renewable energy?
- Batteries or fuel cells for transportation?
- For new technologies, what aspects need to improve the most: efficiency, lifetime, materials, or cost?
- What are the metrics we should use to decide that one technology is better than another?

Costs May Not Provide All the Answers

- Un-priced externalities (e.g. local environmental impacts of mining materials for energy devices)
- Government subsidies mask true costs
- Early-stage technologies are too immature to accurately estimate costs
- Co-benefits are not reflected in costs
- Short term supply excess and deficits
- …

Energy Systems Analysis Can Help

- Beyond component costs…
- Consider interactions and tradeoffs between different parts of the energy system
  - e.g. impact of electric cars on the electricity grid
- Consider co-benefits of various technologies
  - e.g. pollution reduction benefits of renewables
- Consider the effects of multiple metrics on technology performance
  - e.g. roundtrip efficiency, cycle life, and depth of discharge of a battery

Energy Systems Analysis Is Valuable at Many Levels

Integrated assessment models

Economy-wide global or regional macroeconomic models of the energy system (e.g. IGSM, GCAM, Message)

Bottoms Up Technology Integration Models

Geographically or technological integrated energy systems models (e.g. VICUS integrating electricity and transportation sectors)

Life cycle analysis

Full life cycle, materials, manufacturing, use, recycle or disposal (e.g. GREET)

Component Technology Models or Metrics

Technology systems models (e.g. IECM) or metrics (e.g. ESOI)

Three Illustrative Examples

- Sustainable growth of the PV and wind industries
- Grid scale electricity storage
  - What's better for grid scale storage?
  - Should we store or curtail excess renewable energy?
  - How do we make batteries better for grid scale storage?
  - Can we sustain growth of the
- Natural gas or energy storage for backing up the electrical grid?

And if there is time, some recent work on BEVs or FCVs for transportation.

Net Energy Analysis: Basic Idea

- It takes energy to make, operate and dispose/recycle the devices/systems needed to produce energy.
- For a device/system to be useful to the global energy system:

  Energy output >> total energy inputs

Barnhart and Benson, 2013. On the importance of reducing the energetic and material demands of electrical energy storage. Energy and Environmental Science, DOI: 10.1039/c3ee24040a.

M. Dale and S.M. Benson, 2013. The Energy Balance of the Photovoltaic (PV) Industry - Is the PV industry a net energy provider? Environ. Sci. Technol. 2013, 47, 3482−3489.

Barnhart, Dale, Brandt, and Benson, 2013. The energetic implications of curtailing or storing wind and solar generated electricity. Energy and Environmental Science, DOI: 10.1039/c3ee41973h.

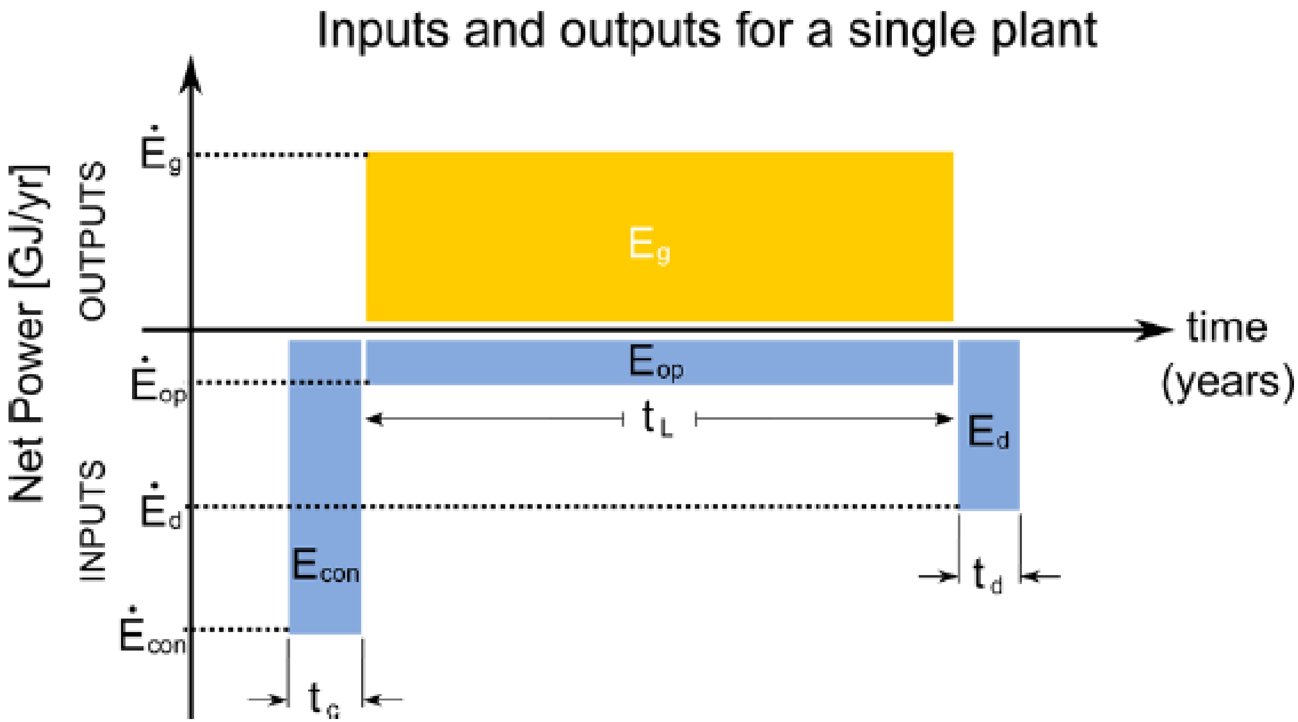
Carbajales-Dale, M., Barnhart, C. J., & Benson, S. M. (2014). Can we afford storage? A dynamic net energy analysis of renewable electricity generation supported by energy storage. *Energy & Environmental Science*, *7*(5), 1538-1544.

Carbajales-Dale, M., Barnhart, C. J., Brandt, A. R., & Benson, S. M. (2014). A better currency for investing in a sustainable future. *Nature Climate Change*, *4*(7), 524-527.

Pellow, M. A., Emmott, C. J., Barnhart, C. J., & Benson, S. M. (2015). Hydrogen or batteries for grid storage? A net energy analysis. *Energy & Environmental Science*, *8*(7), 1938-1952.

Example: Photovoltaic Energy

Illustration of Net Energy Concepts for a Renewable Energy Device



$$\dot{E}_{con} = Power\ for\ construction\ (W)$$

$$\dot{E}_{op} = Power\ for\ operation\ (W)$$

$$\dot{E}_{d} = Power\ for\ decomission\ (W)$$

$$\dot{E}_{g} = Power\ generated\ (W)$$

$$t_c = construction\ time\ (s)$$

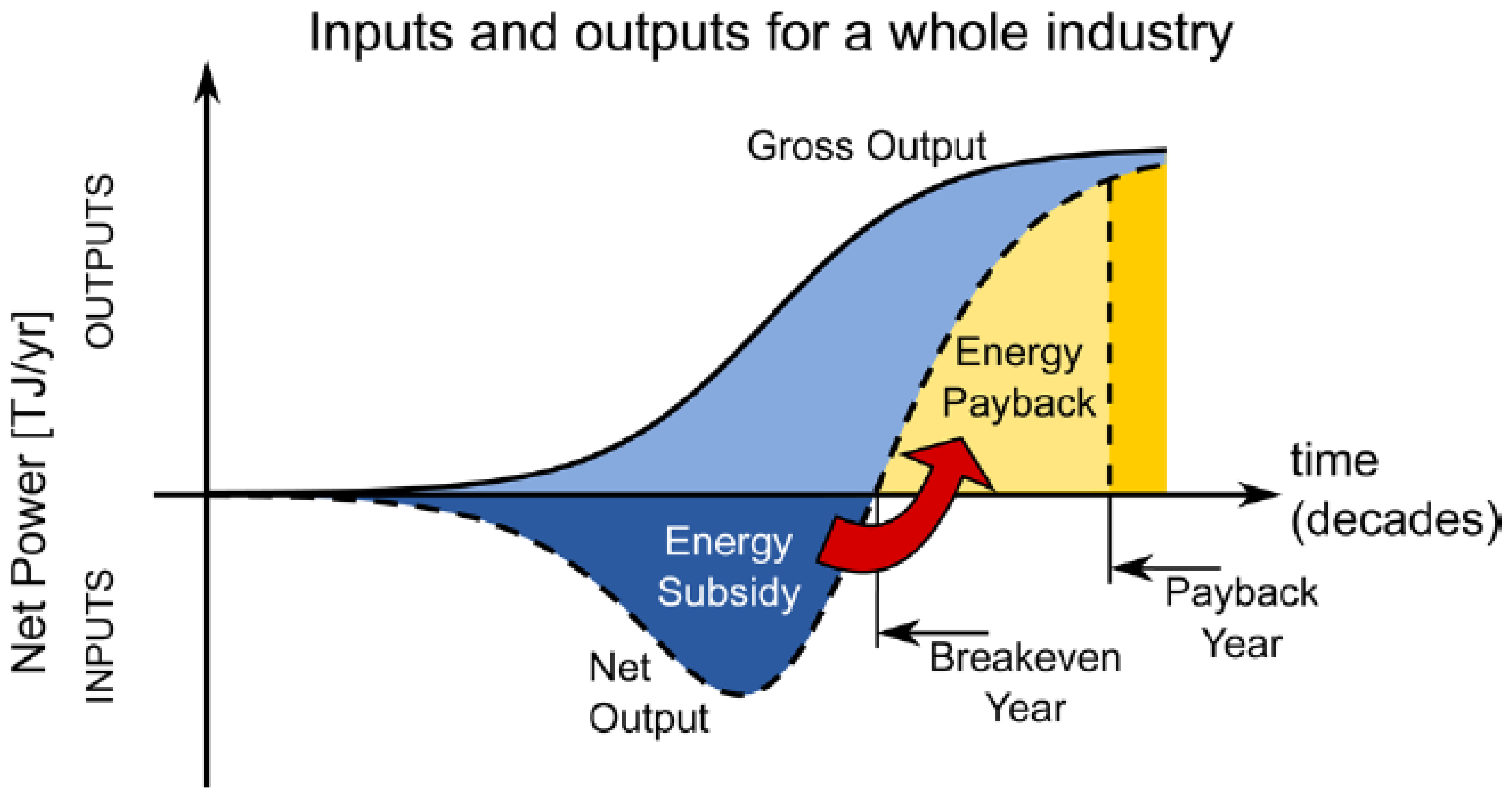
$$t_L = operational\ lifetime\ (s)$$

$$t_d = decomission\ time\ (s)$$

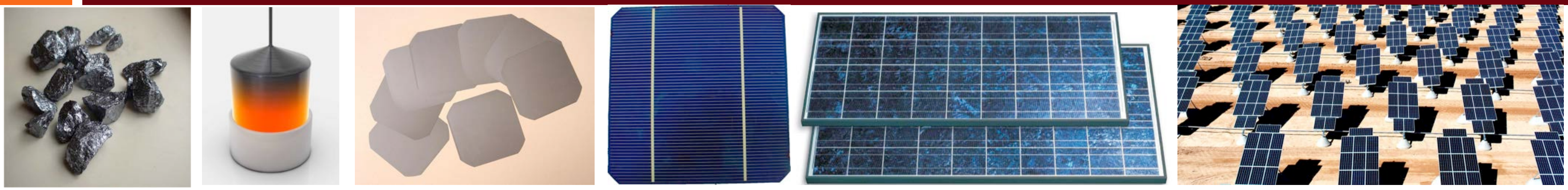
Definitions

- Embodied energy: Amount of energy to manufacture and install a device
- Cumulative energy demand (CED): total energy inputs over the life cycle
- Energy return on investment (EROI): the sum of the energy outputs compared to the cumulative energy demand
- Energy payback time (EPBT): time for the cumulative energy outputs to be greater the energy inputs

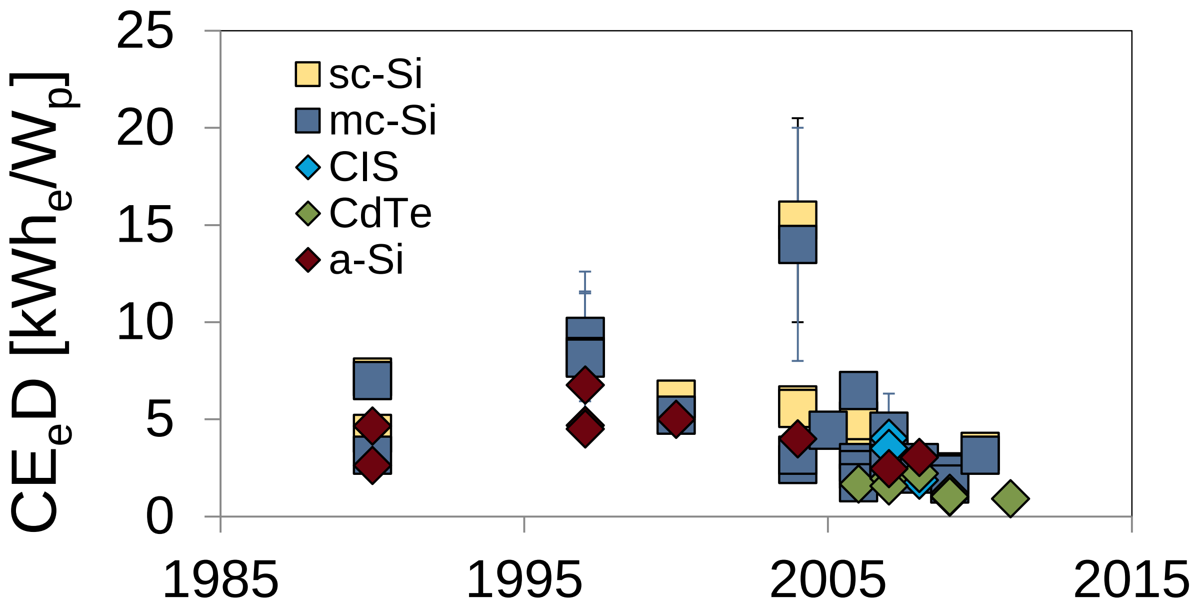
Industry Level Net Energy



Cumulative Energy Demand for PV



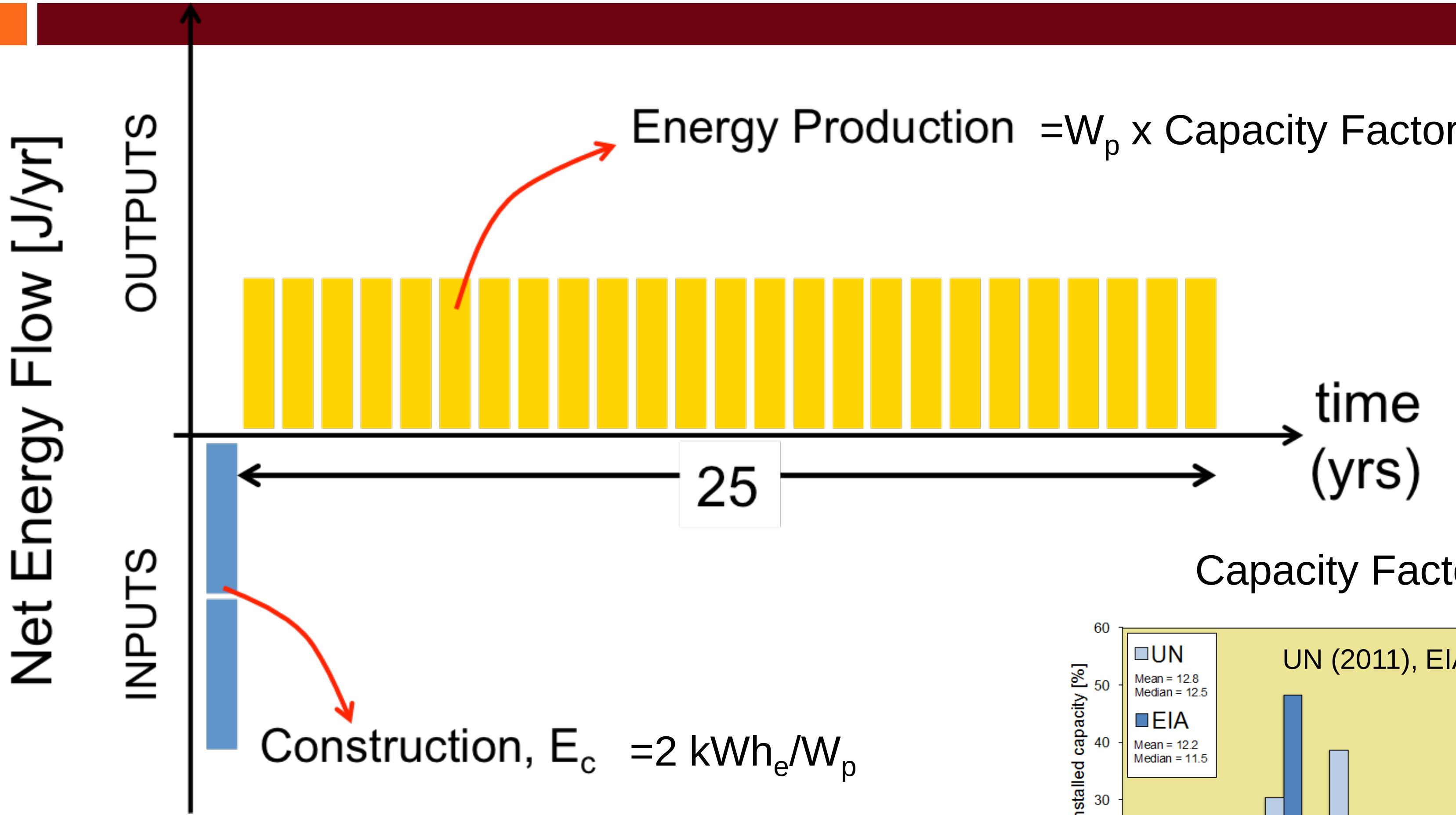
Poly-Si | Ingot | Wafer | Cell | Module | System



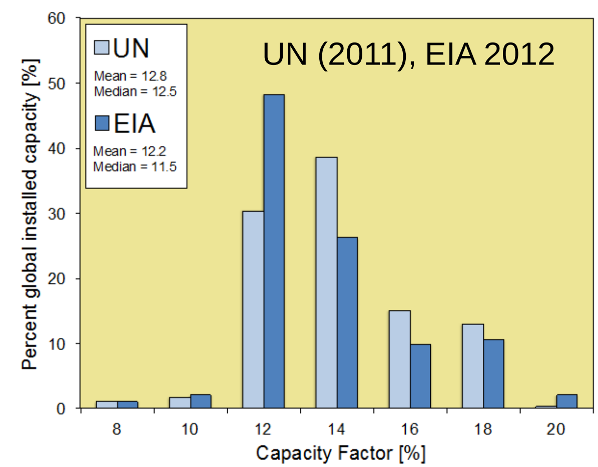
Kreith (1990)
Prakash (1995)
Kato (1997)
Keolian (1997)
Alsema (2000)
Frankl (2001)
Knapp (2001)
Mathur (2002)
GEMIS (2002)
Gürzenich (2004)
Krauter (2004)
Battisti (2005)
Fthenakis (2006)
Muneer (2006)
Mason (2006)
Kannan (2006)
Mohr (2007)
Pacca (2007)
Raugei (2007)
Ito (2008)
Stoppato (2008)
Roes (2009)
Fthenakis (2009)
Raugei (2009)
Zhai (2010)
Nishimura (2010)
Held (2011)
Laleman (2011)

In 2013 it took about 2 kWh_e to make a 1 W_p silicon PV panel.

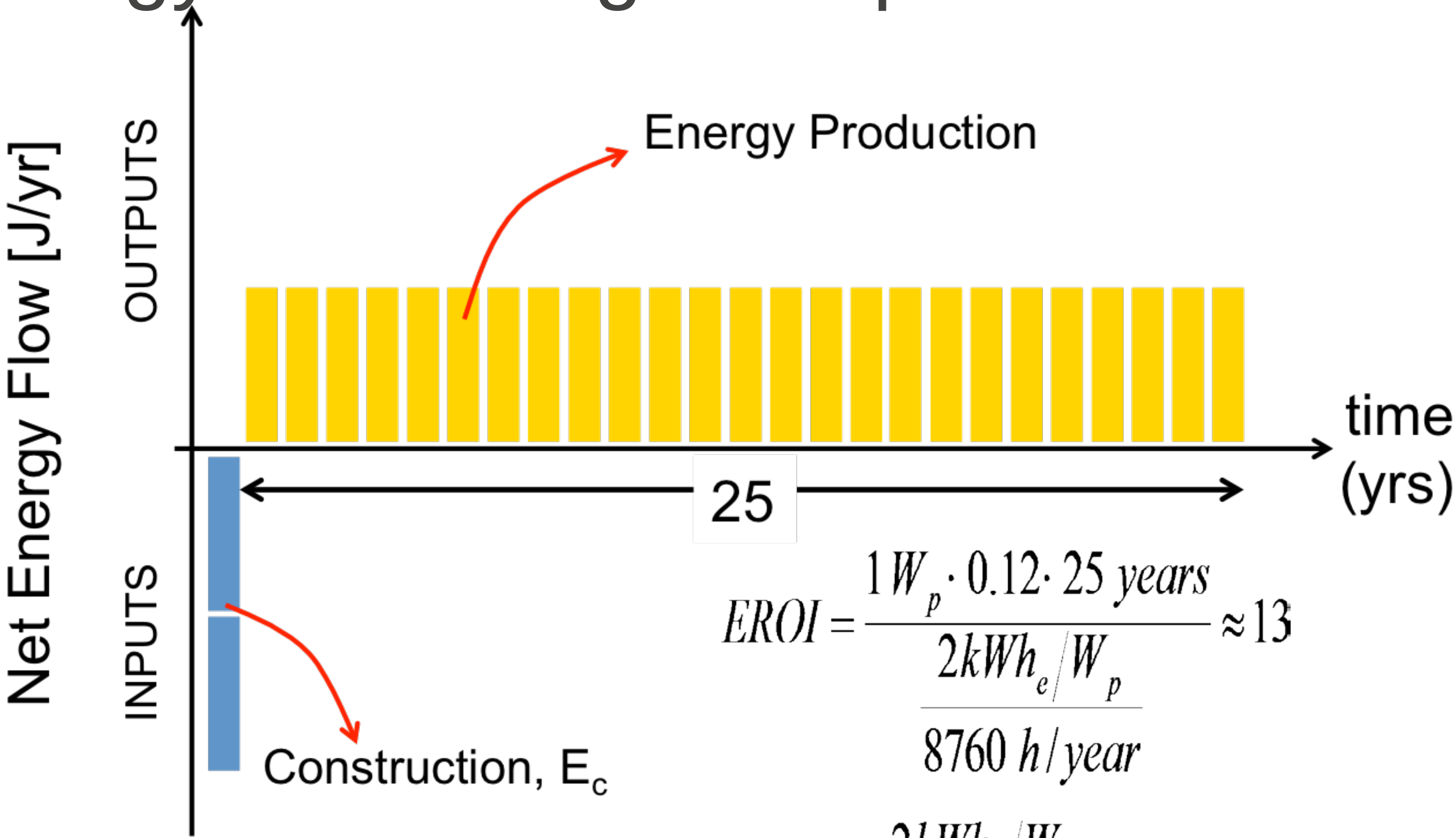
Energy flows: single PV panel



Capacity Factor



Energy flows: single PV panel

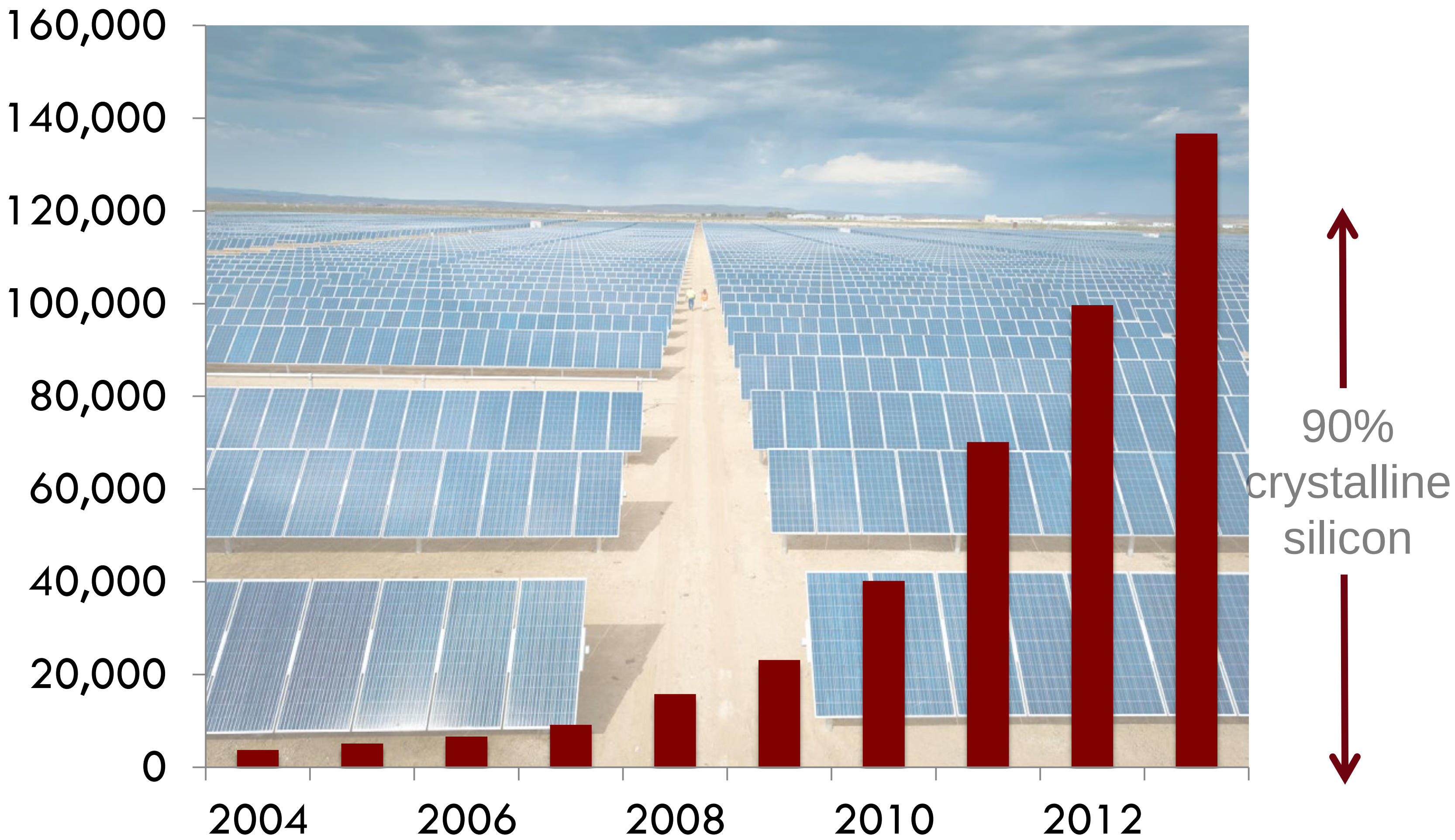


$$EROI = \frac{1\,W_p \cdot 0.12 \cdot 25\ years}{\frac{2kWh_e / W_p}{8760\ h/year}} \approx 13$$

$$EPBT = \frac{\frac{2kWh_e / W_p}{8760\ h/year}}{1\,W_p \cdot 0.12} \approx 2$$

Energetically, a PV panel is a good investment.

And, the PV Industry is Growing Rapidly



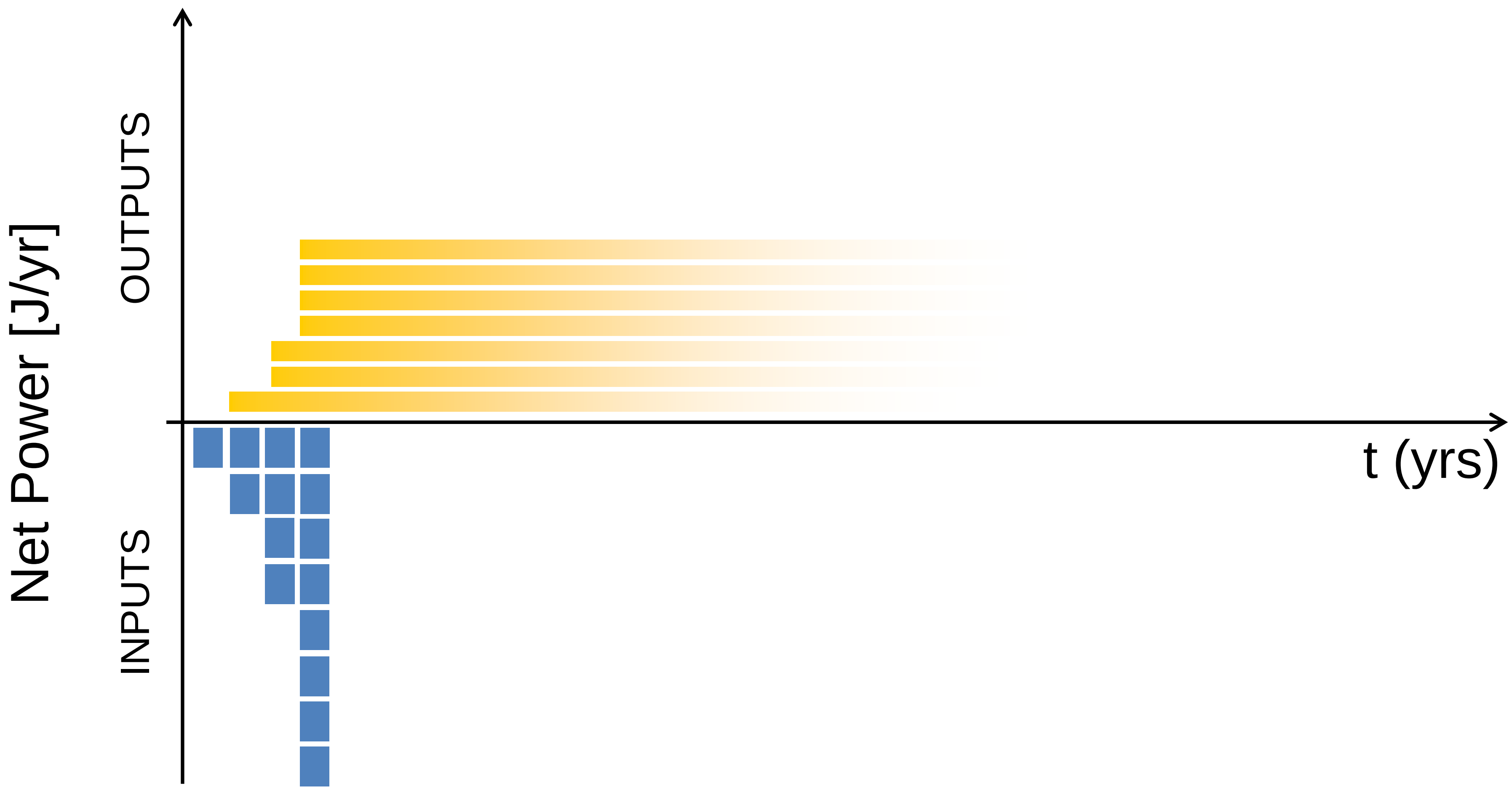
DOE (2008), EPIA (2011), EIA (2012), UN (2012)

Energy flows for PV industry – 100% growth rate

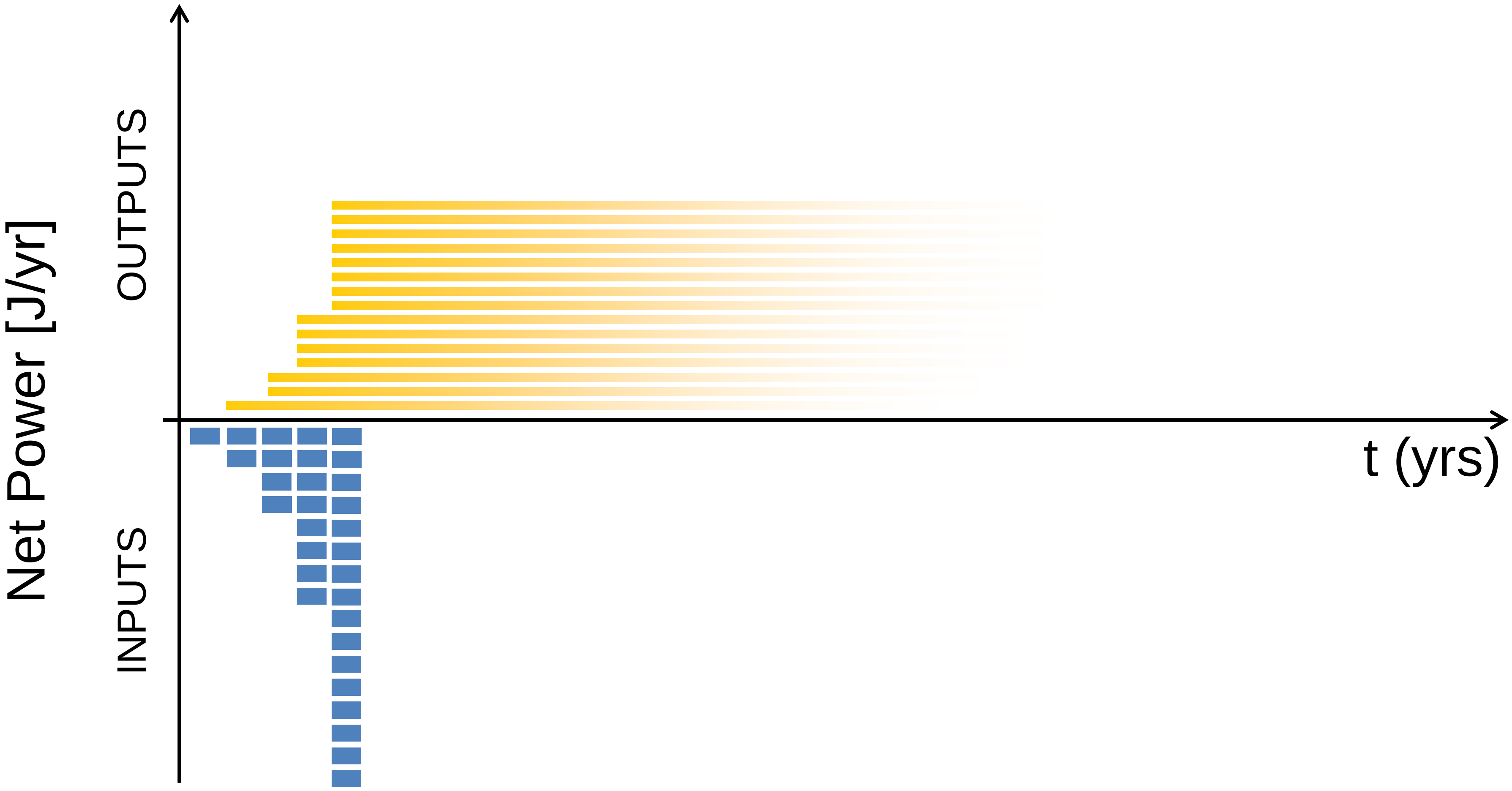
Energy flows for PV industry – 100% growth rate

Energy flows for PV industry – 100% growth rate

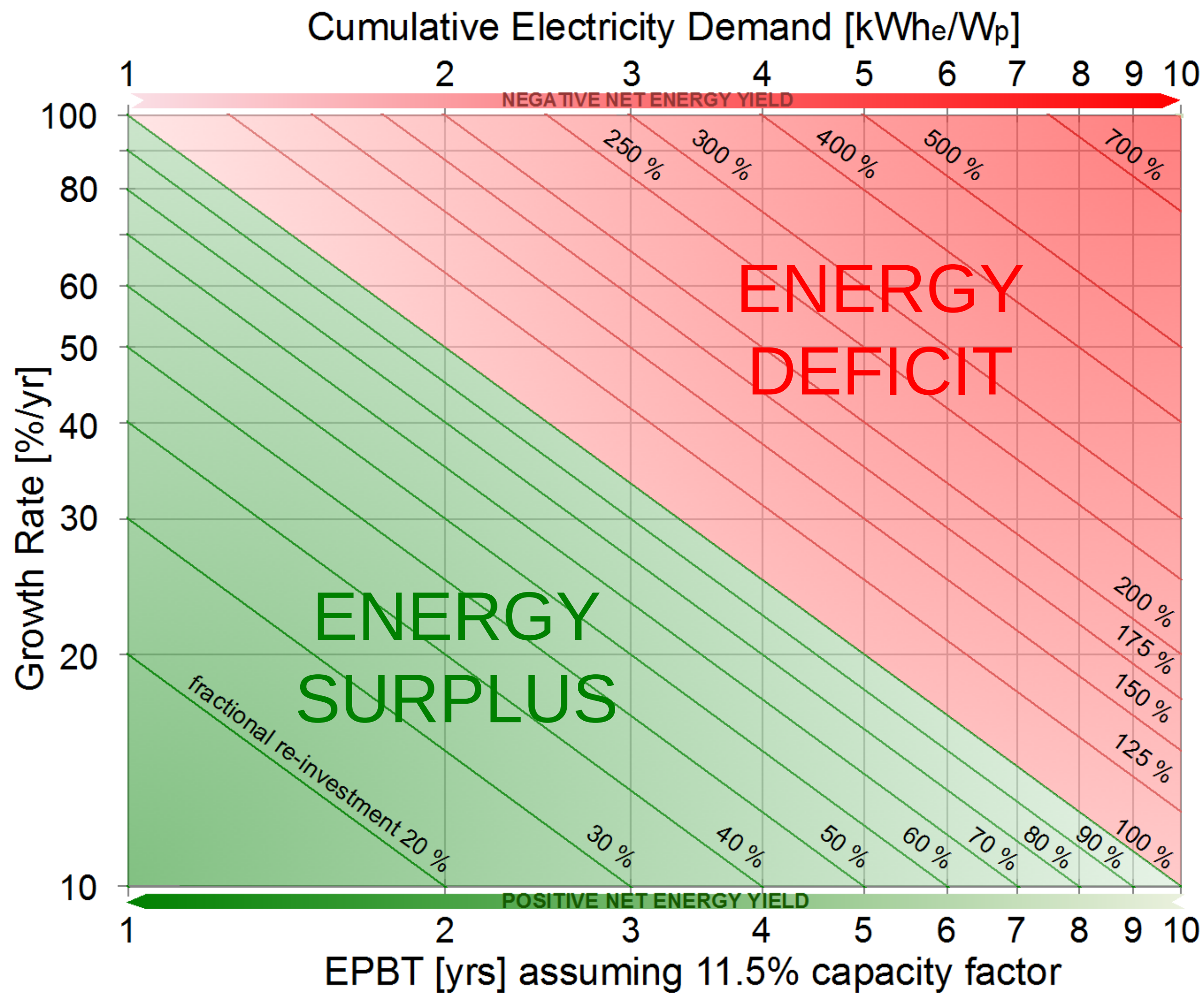
Energy flows for PV industry – 100% growth rate



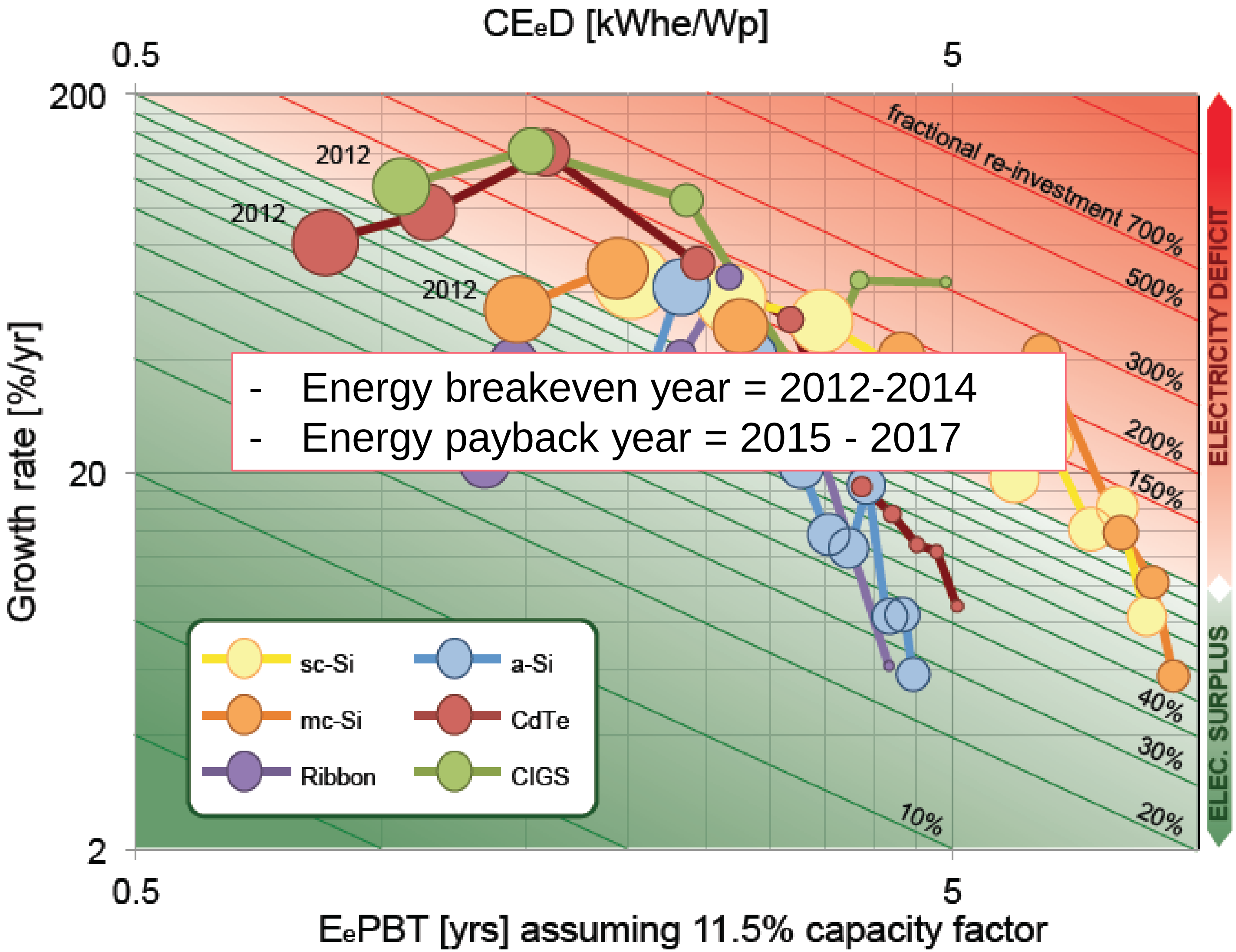
Energy Flows for PV industry – 100% Growth rate



A Growing Industry May be a Net Energy Sink or Source

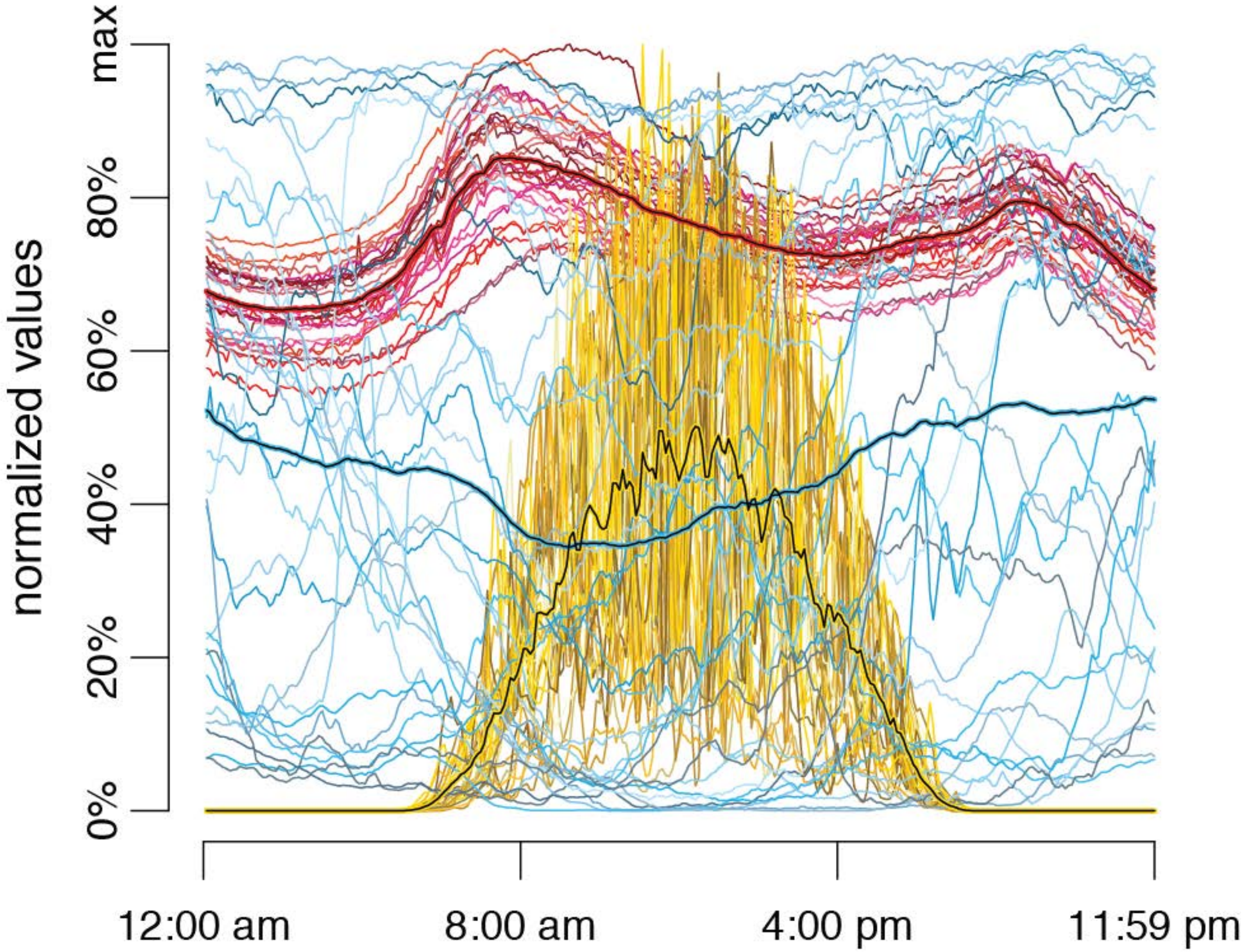


The PV Industry Is Now a Net Energy Producer



- Energy breakeven year = 2012-2014
- Energy payback year = 2015 - 2017

Managing the Variability of Renewable Energy

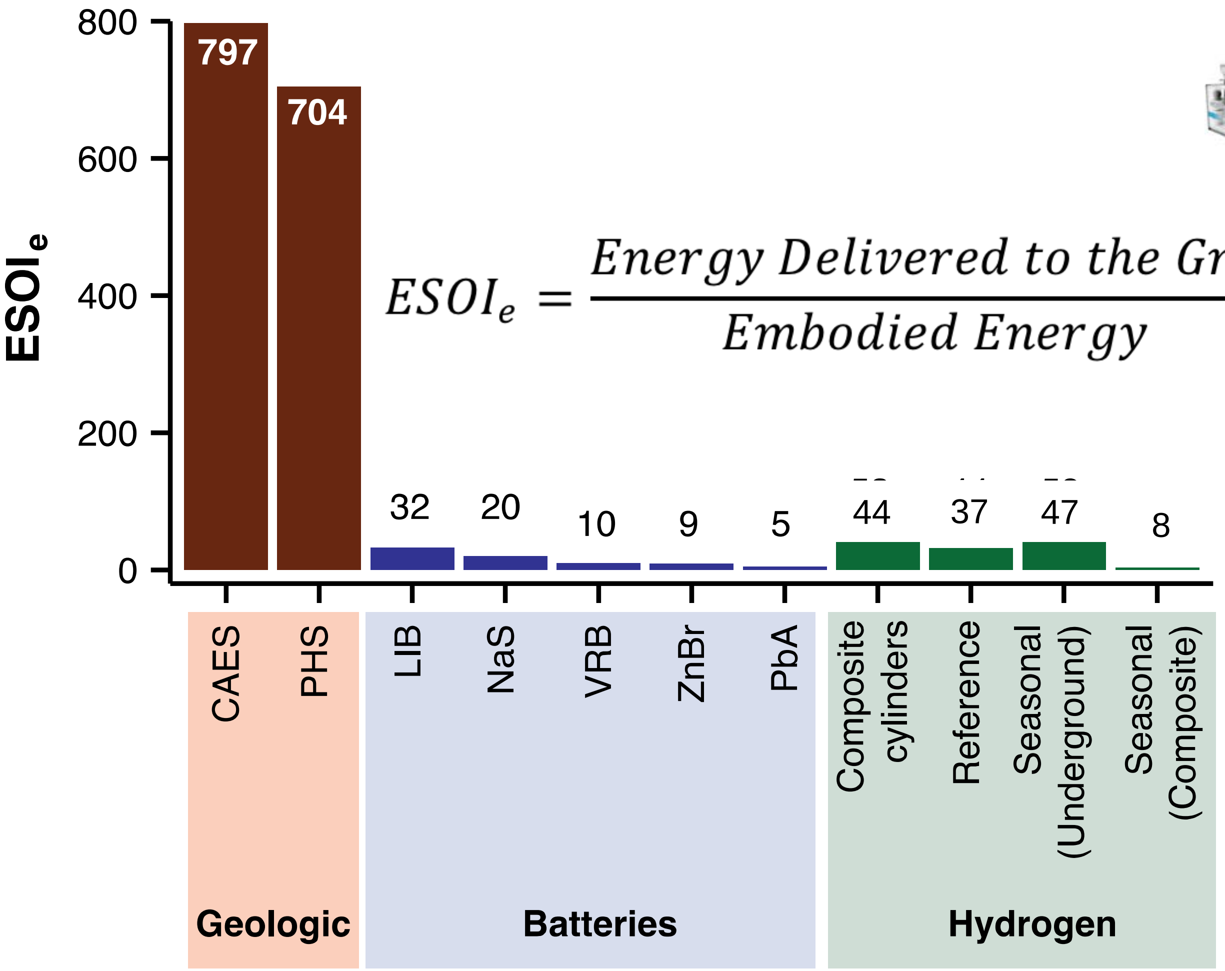


BPA demand, solar insolation and wind data, 5 minute intervals, April 2010

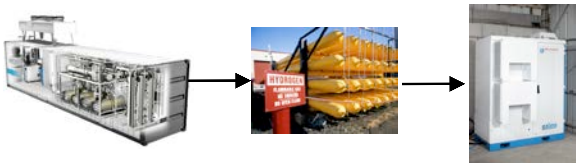
Energy Storage for Managing Variable Energy Resources

- Pumped hydropower (PHS)
- Compressed air energy storage
- Batteries
  - Lithium Ion (Li-Ion)
  - Sodium Sulfer (NaS)
  - Vanadium redox flow battery (VRB)
  - Zinc Bromine (ZnBr)
  - Lead-Acid (PbA)
- Hydrogen
  - Alkaline water electrolyzer, compressed hydrogen storage, and PEM Fuel Cell

A New Metric: Energy Stored on Energy Invested (ESOI)



$$ESOI_e = \frac{Energy\ Delivered\ to\ the\ Grid}{Embodied\ Energy}$$



Pellow, M. A., Emmott, C. J., Barnhart, C. J., & Benson, S. M. (2015). Hydrogen or batteries for grid storage? A net energy analysis. *Energy & Environmental Science*, *8*(7), 1938-1952.

But, the Round Trip Efficiency for Hydrogen Is Much Worse

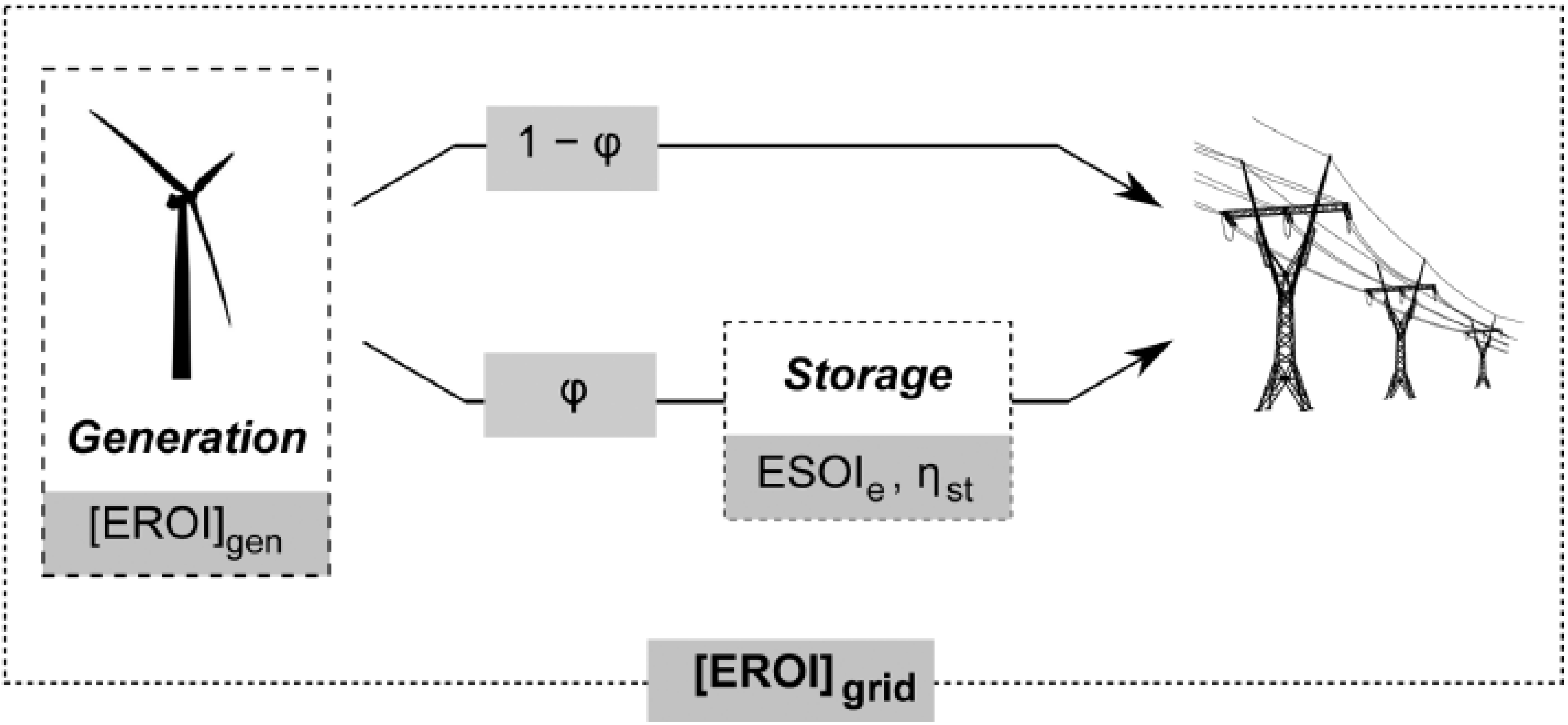
	E_{out}^{life} (10^6 MJ)	E_{emb}^{life} (10^6 MJ)	E_{in}^{life} (10^6 MJ)	$ESOI_e$	η_{st}
RHFC[a]	592	9.92	1,973	59	0.30
LIB[b]	677	64	752	35	0.83

η_{st} = full system round trip efficiency

Why is the efficiency for the RHFC so low?

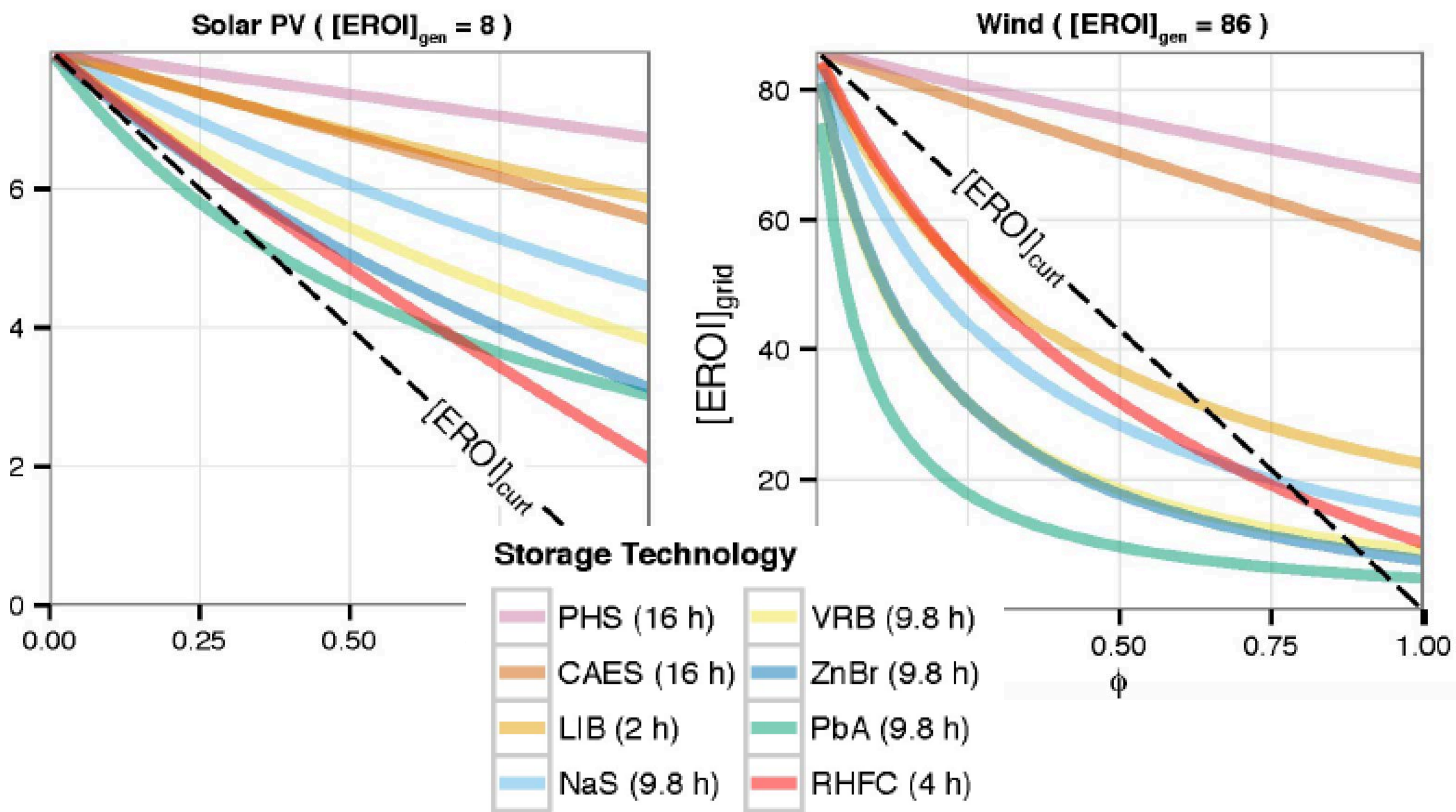
$$\eta_{st} = \eta_{lyz} \cdot \eta_{comp} \cdot \eta_{fc} = 0.7 \cdot 0.89 \cdot 0.47 = 0.3$$

How Do We Weight the Relative Importance of ESOI and Efficiency?



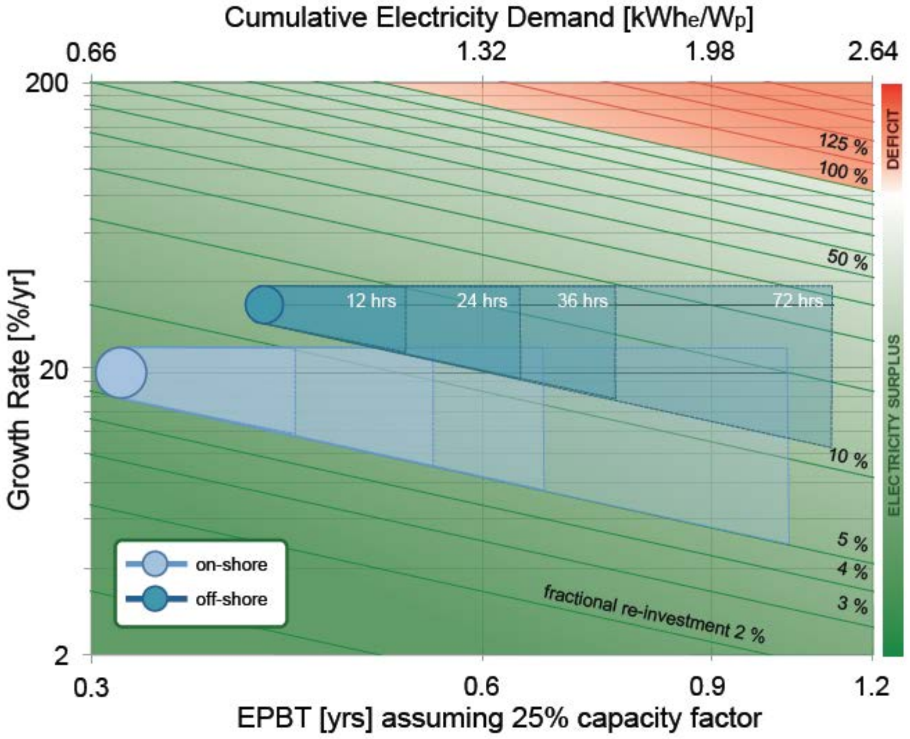
$$[\text{EROI}]_{\text{grid}} = \frac{1 - \phi + \eta_{\text{st}}\phi}{\dfrac{1}{[\text{EROI}]_{\text{gen}}} + \dfrac{\phi}{\text{ESOI}_{\text{e}}}}$$

Is It Worth "Paying for Storage?" and Which Technology is Better?

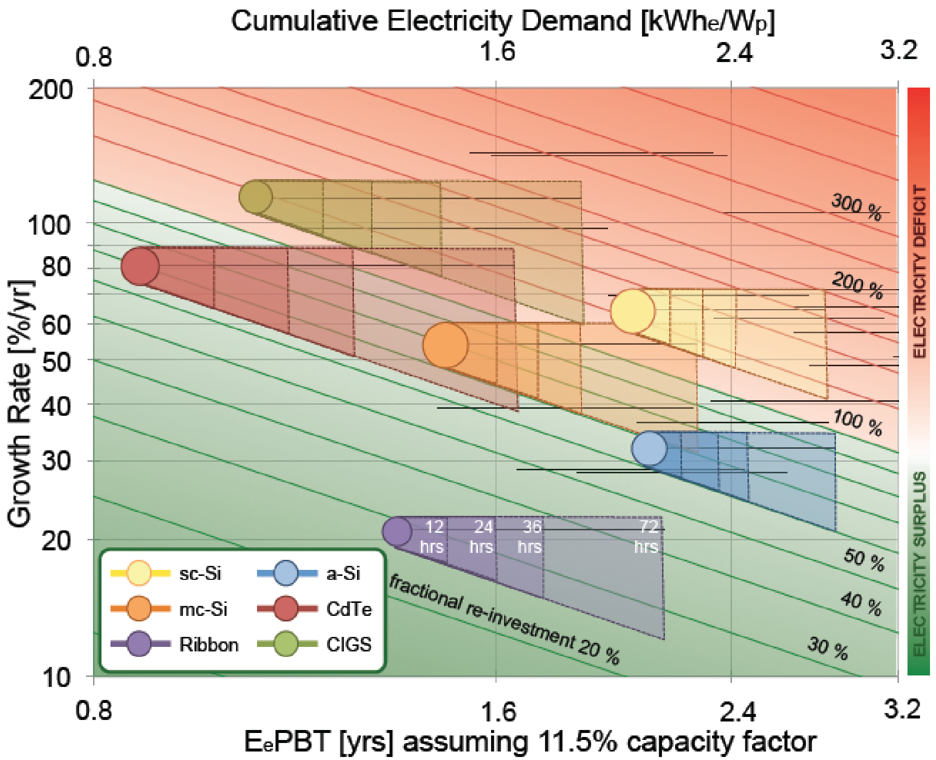


Can We Afford Energy Storage in a Growing Renewable Energy System?

Wind



Solar



Carbajales-Dale, M., Barnhart, C. J., & Benson, S. M. (2014). Can we afford storage? A dynamic net energy analysis of renewable electricity generation supported by energy storage. *Energy & Environmental Science*, *7*(5), 1538-1544.

How Do You Make A Battery Better for Grid Scale Storage?

$$ESOI = \frac{\eta D \lambda}{CTG}$$

where

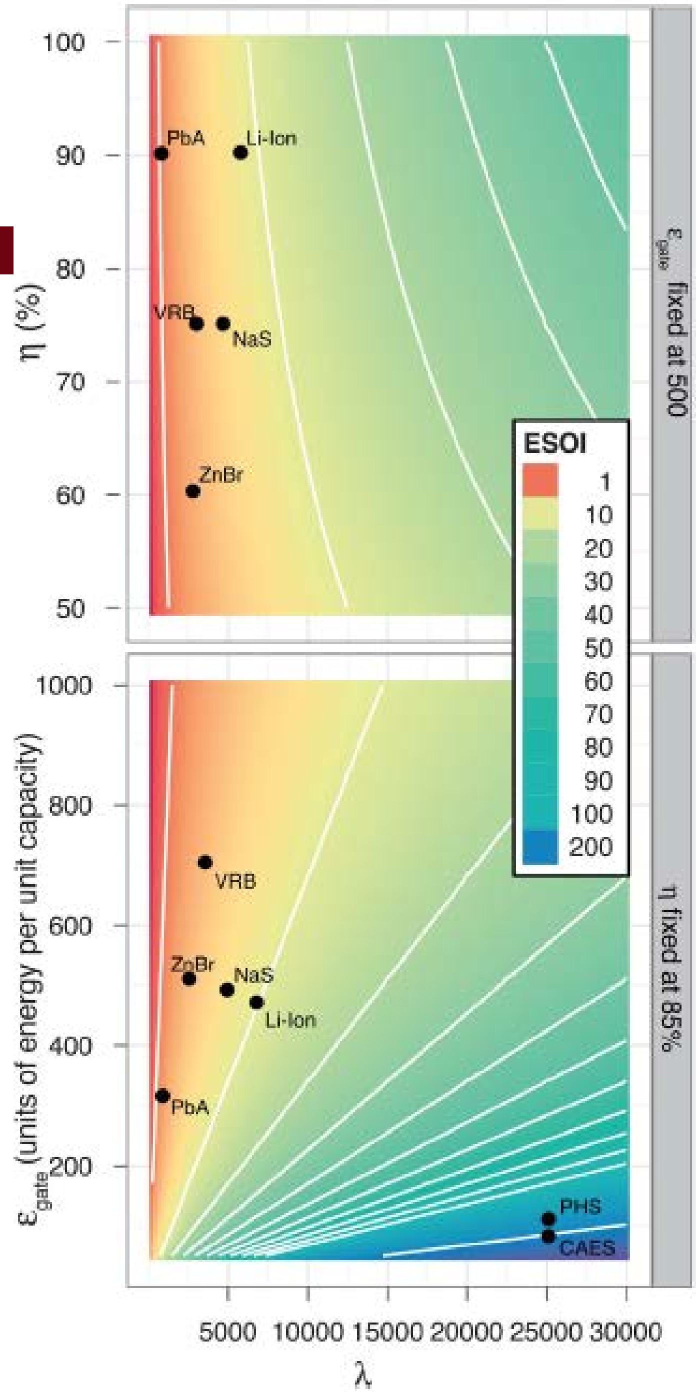
$\eta = efficiency$

$D = depth\ of\ discharge$

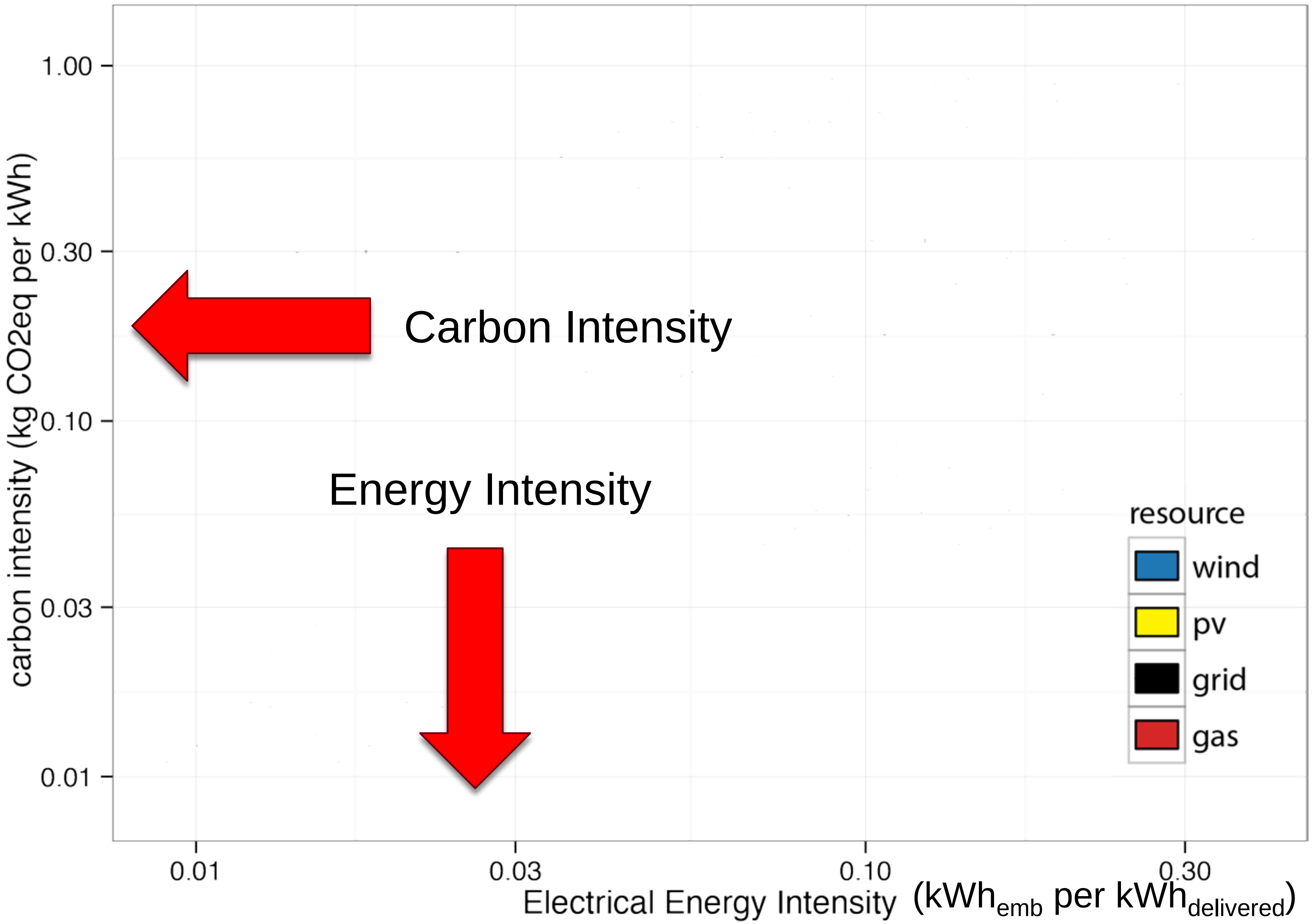
$\lambda = cycle\ life$

$$CTG = \frac{Cradle\ to\ gate\ embodied\ energy(MJ)}{Storage\ capacity(MJ)}$$

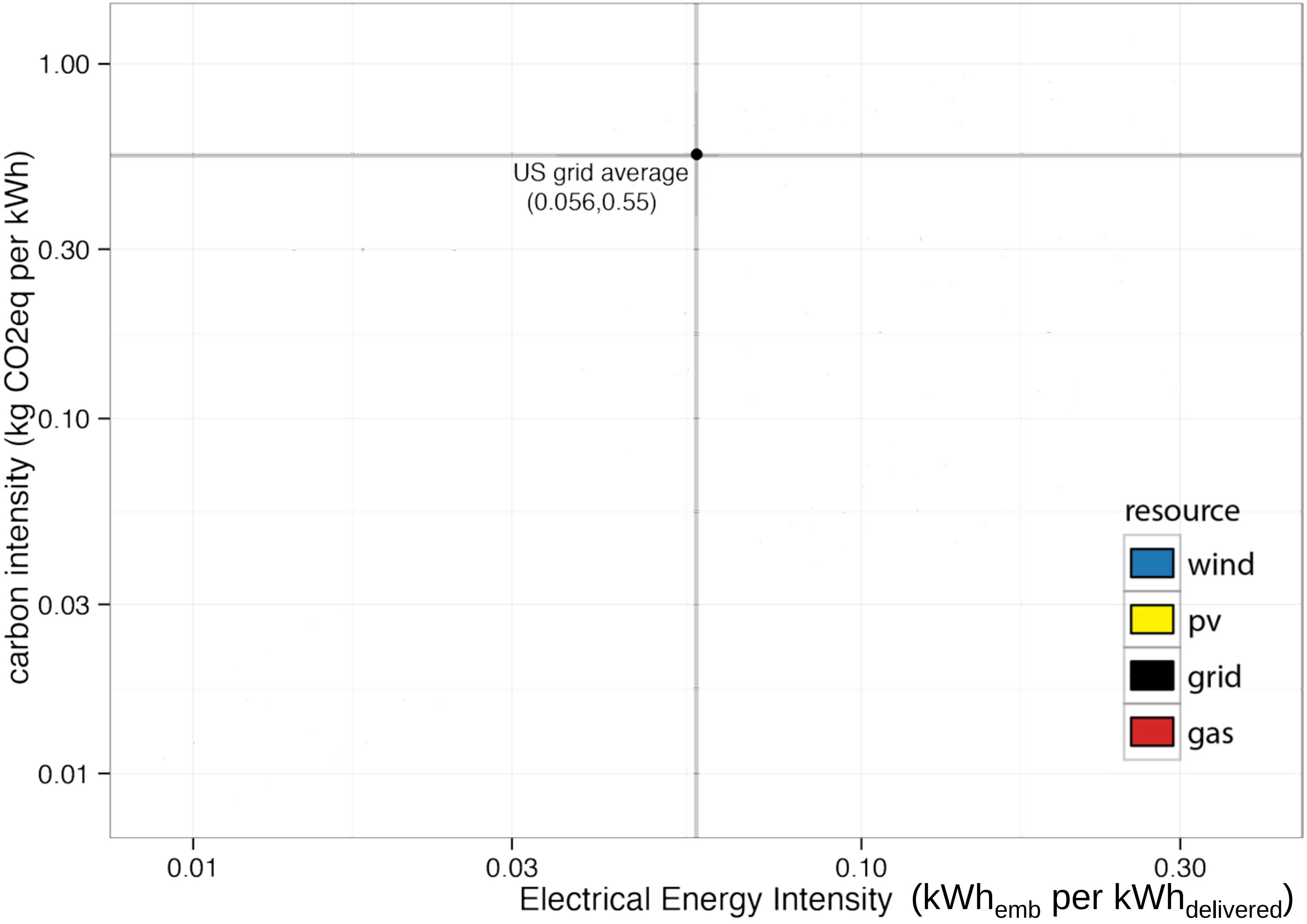
Increase the cycle life of the battery!



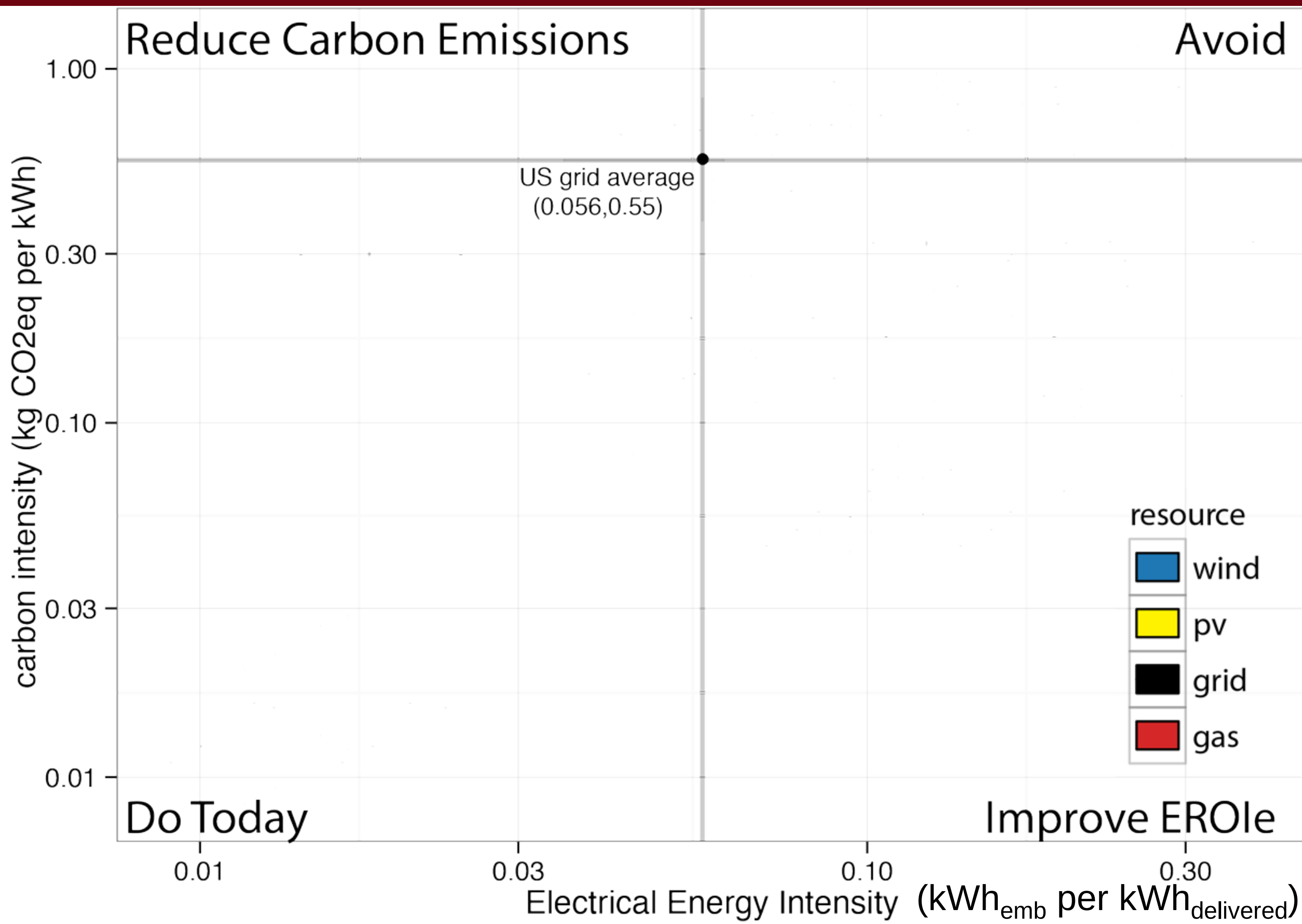
How Do Storage Options Compare to Natural Gas Generation?



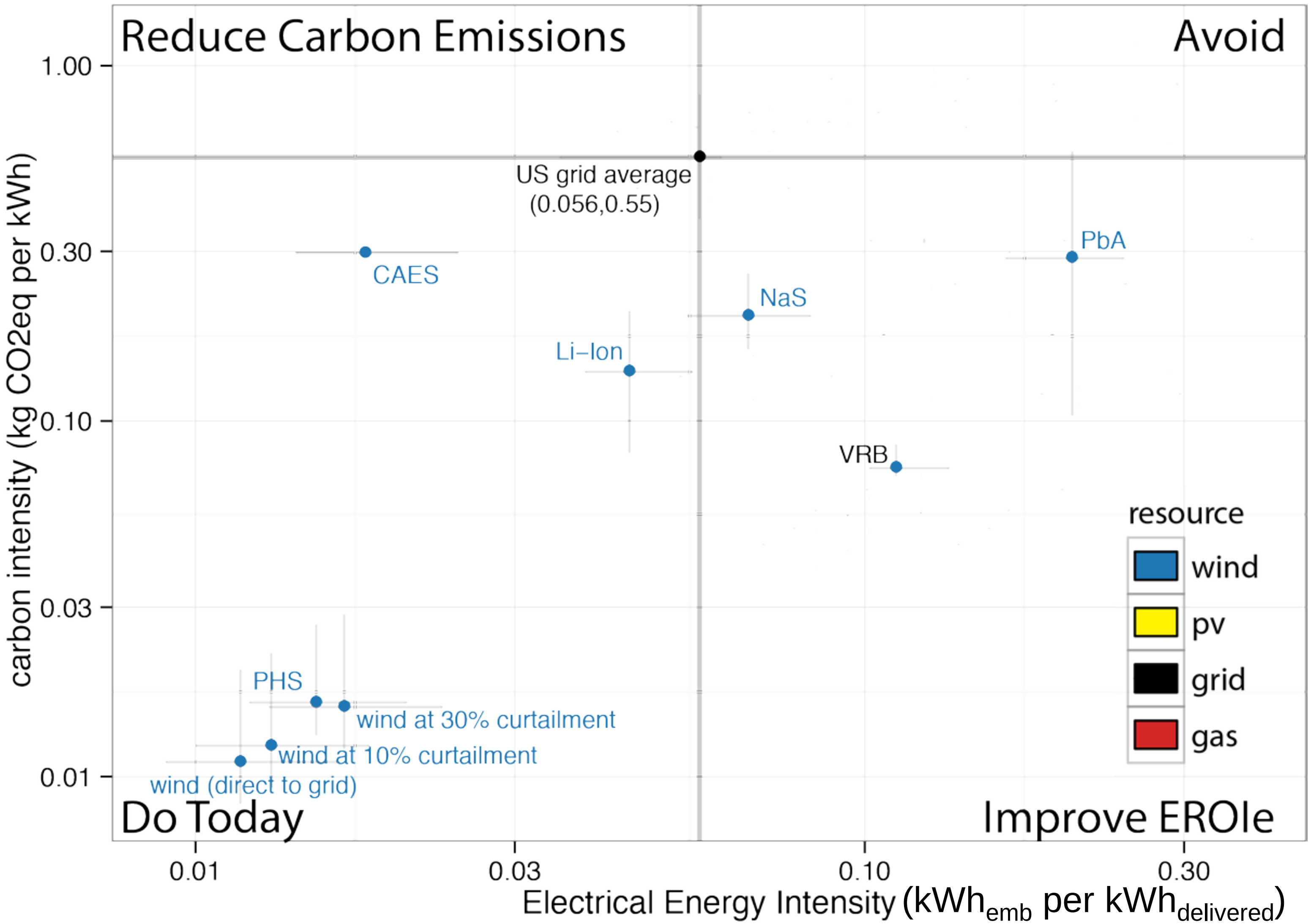
Compare Options to U.S. Grid Average



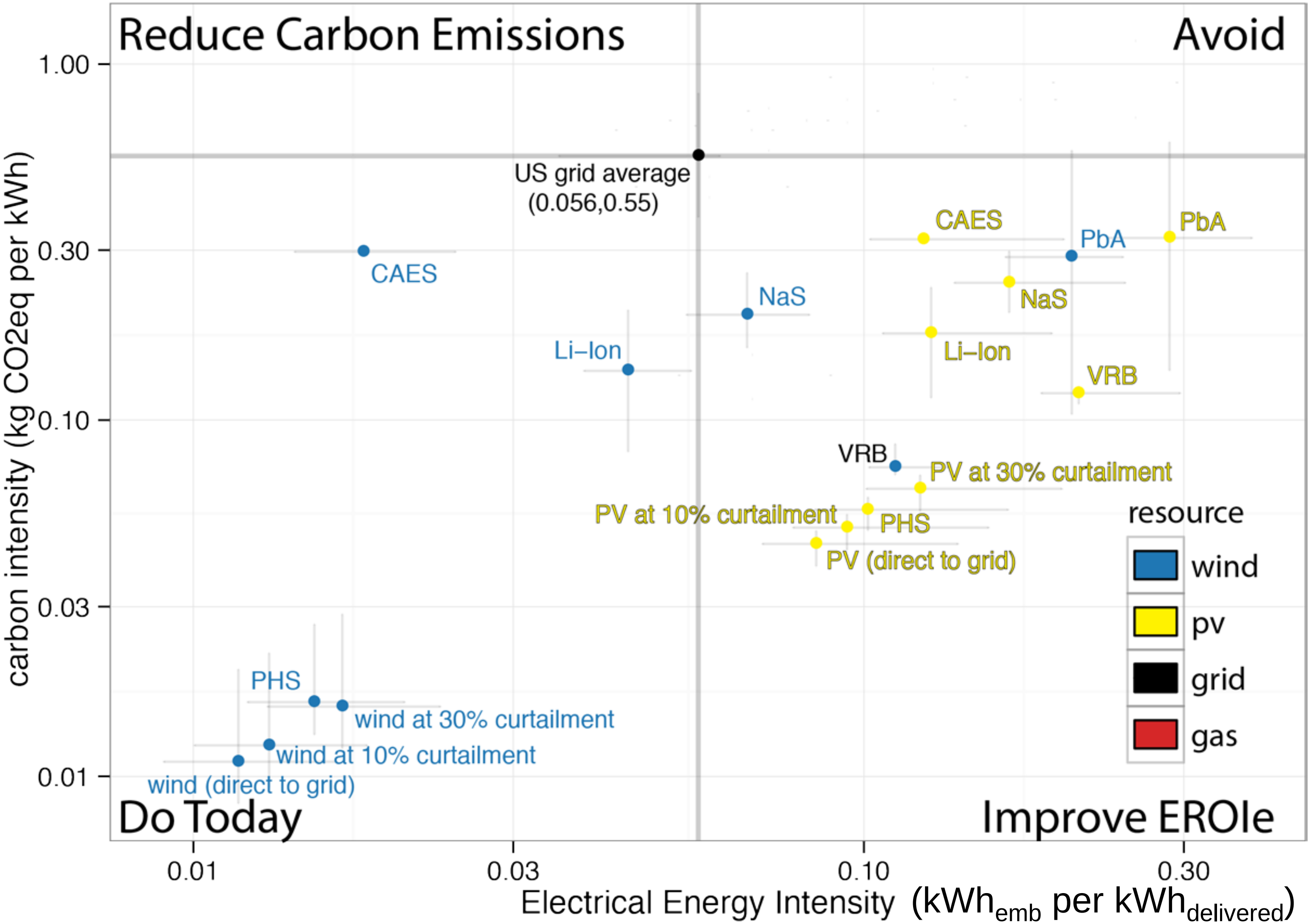
Identify Paths to Improvement



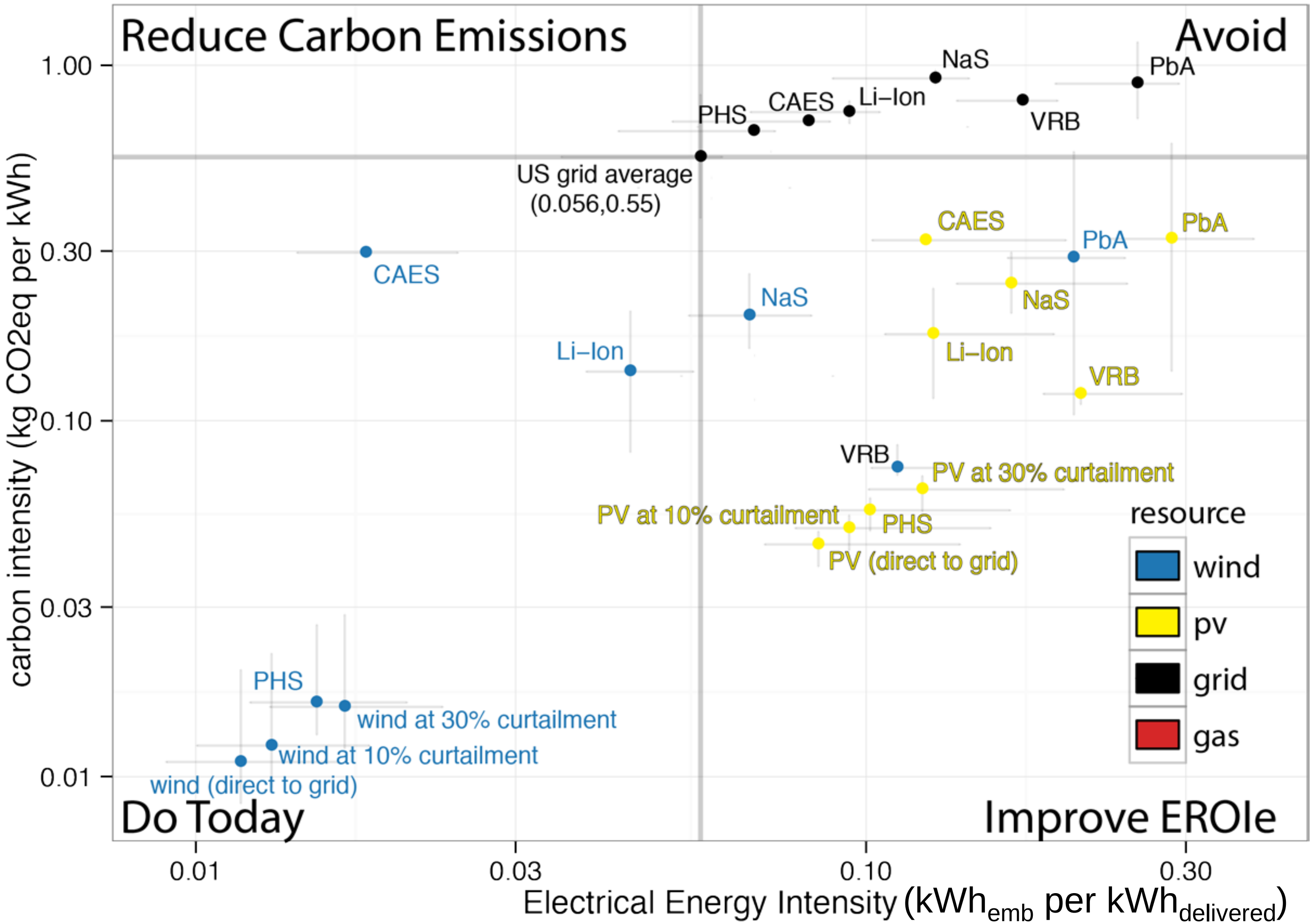
Wind With Some Storage Is Much Better than the Grid Average



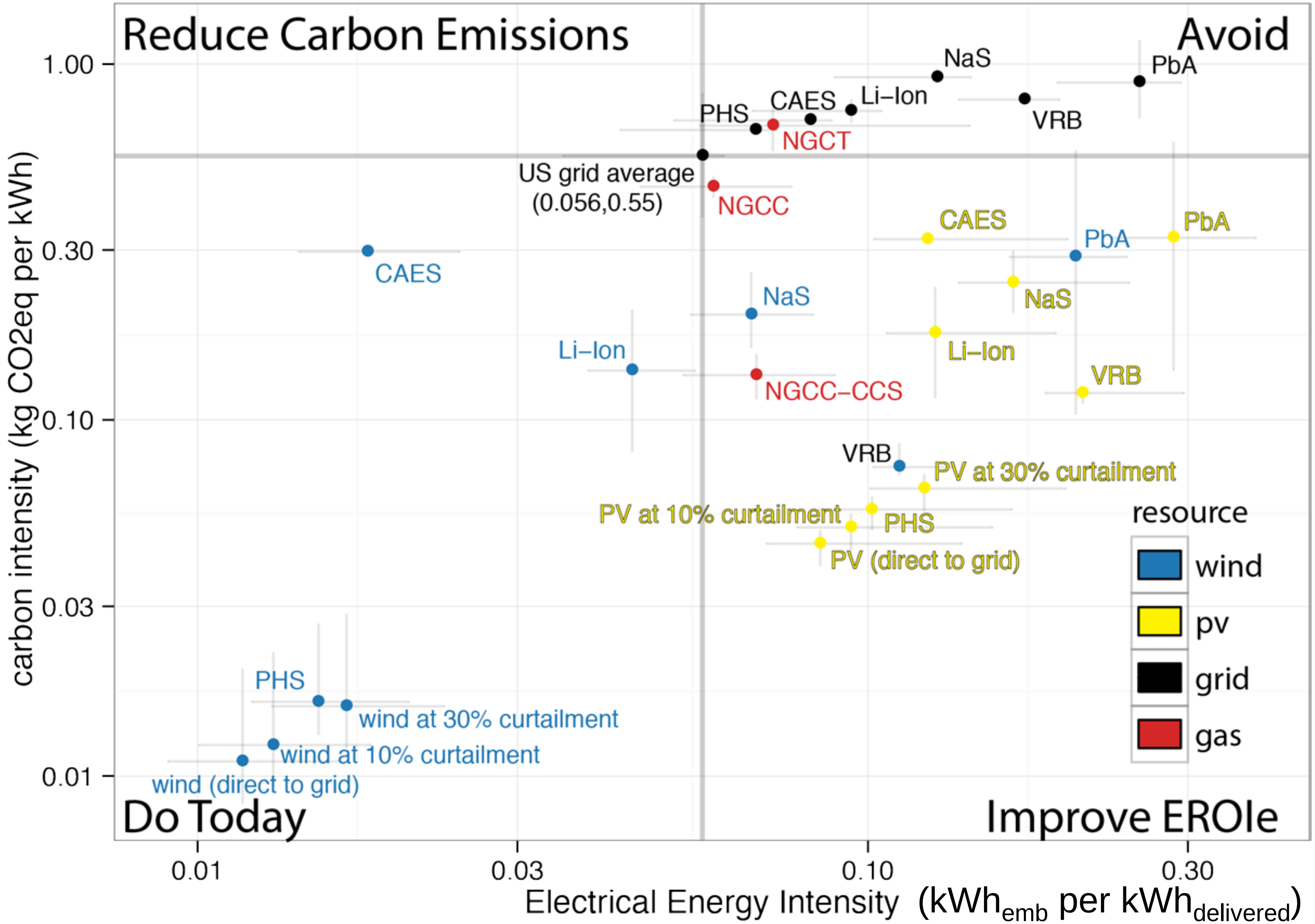
Solar PV With Storage Has Higher Energy Intensity But Lower Carbon Intensity



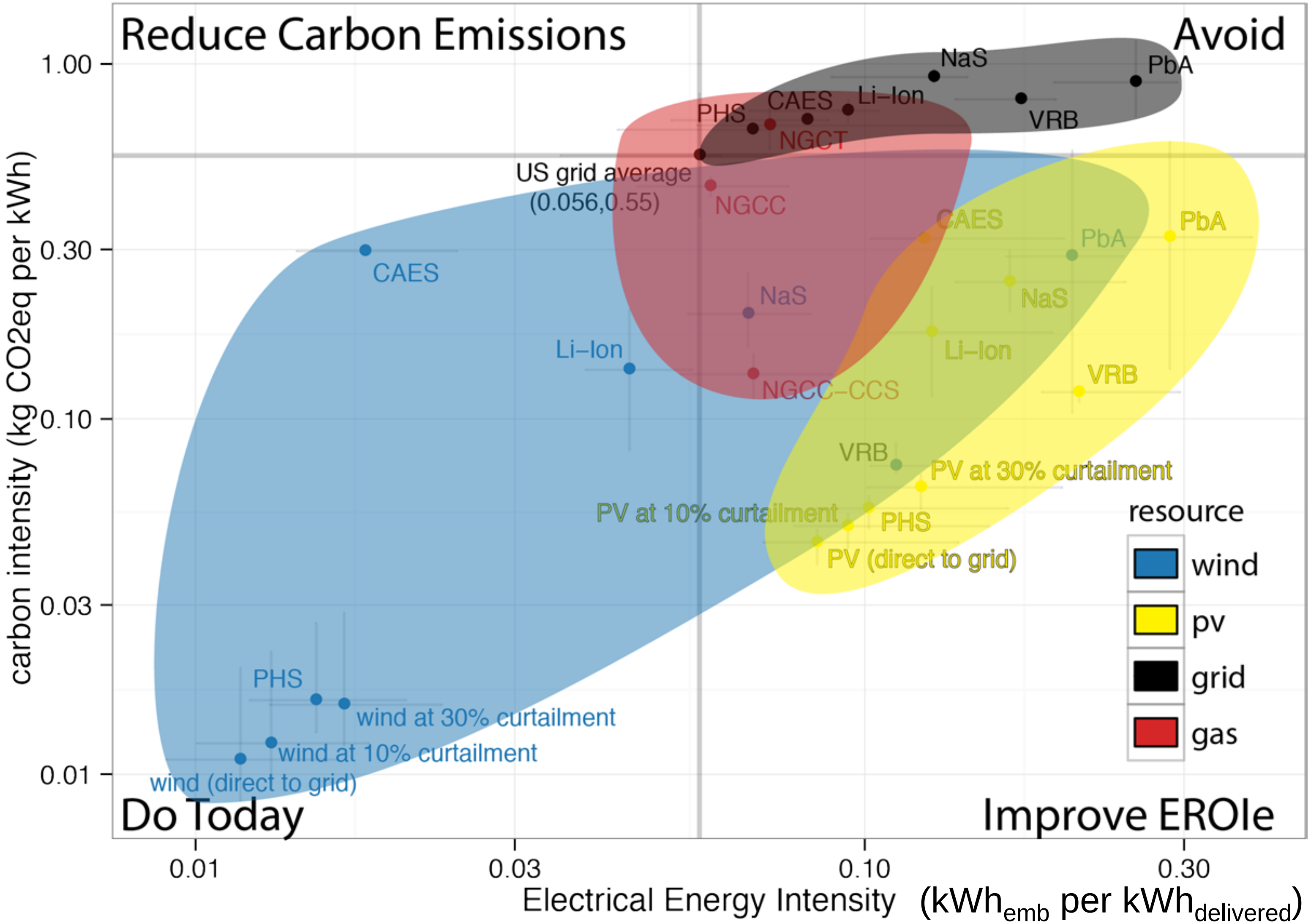
Avoid Storing Grid Power



Natural Gas… Mixed Story, NGCCS is Interesting



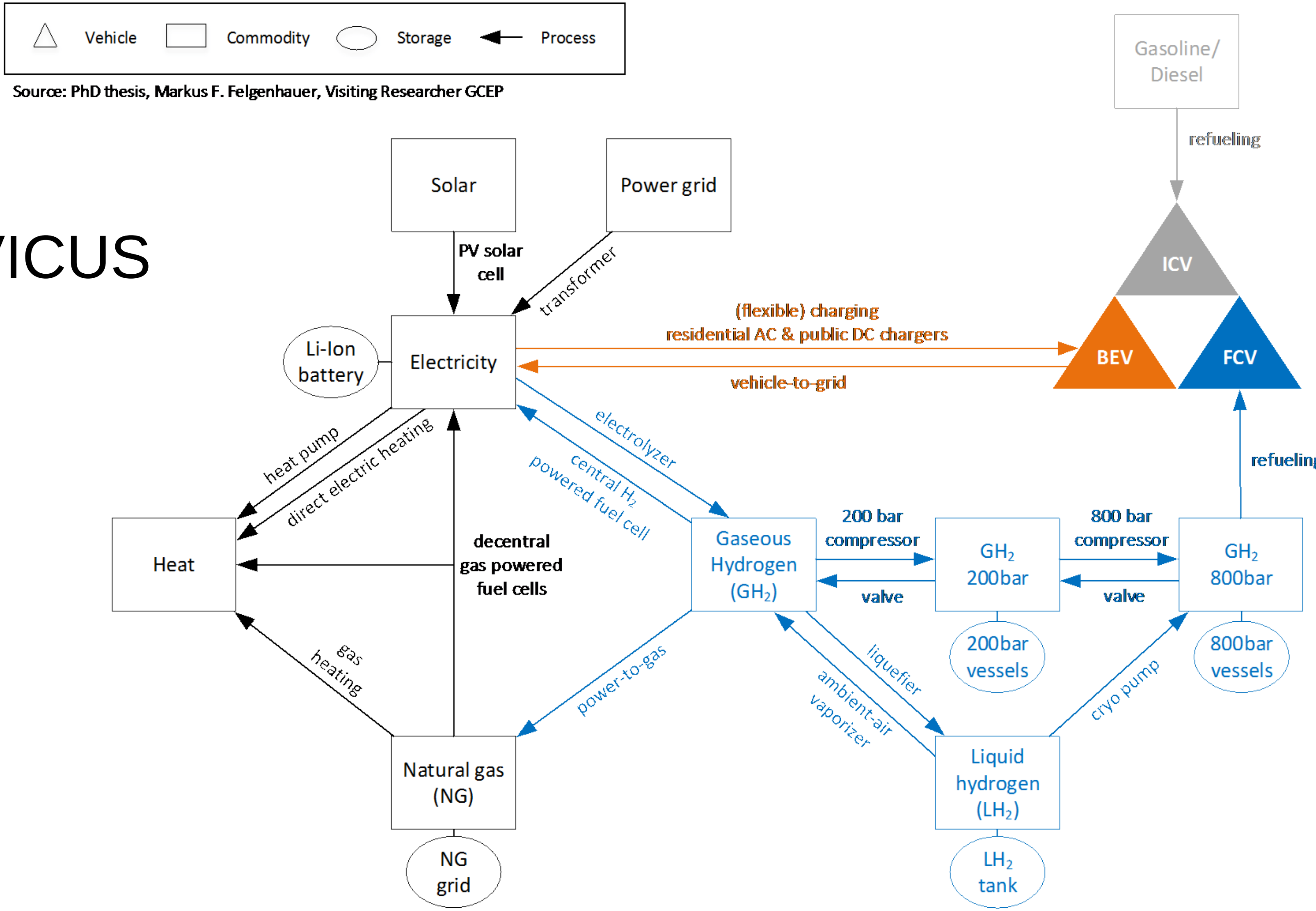
Helping Make Better Energy Choices



Summary

- Energy systems analysis provide new perspectives on energy technologies and systems
  - … beyond cost
- Provide a valuable tool during the global energy system transition
  - Solar and wind are net energy producers
  - Pumped hydro and CAES are good options for storage
  - Other forms of storage are energetically expensive
  - Li-Ion batteries are better than hydrogen for storage today
    - Batteries need to last longer
    - The hydrogen system needs to be more efficient
  - Natural gas generation provides a better option than some (not all) alternatives for managing the variability of renewable energy

What's better, BEVs or FCVs?



Source: PhD thesis, Markus F. Felgenhauer, Visiting Researcher GCEP

VICUS

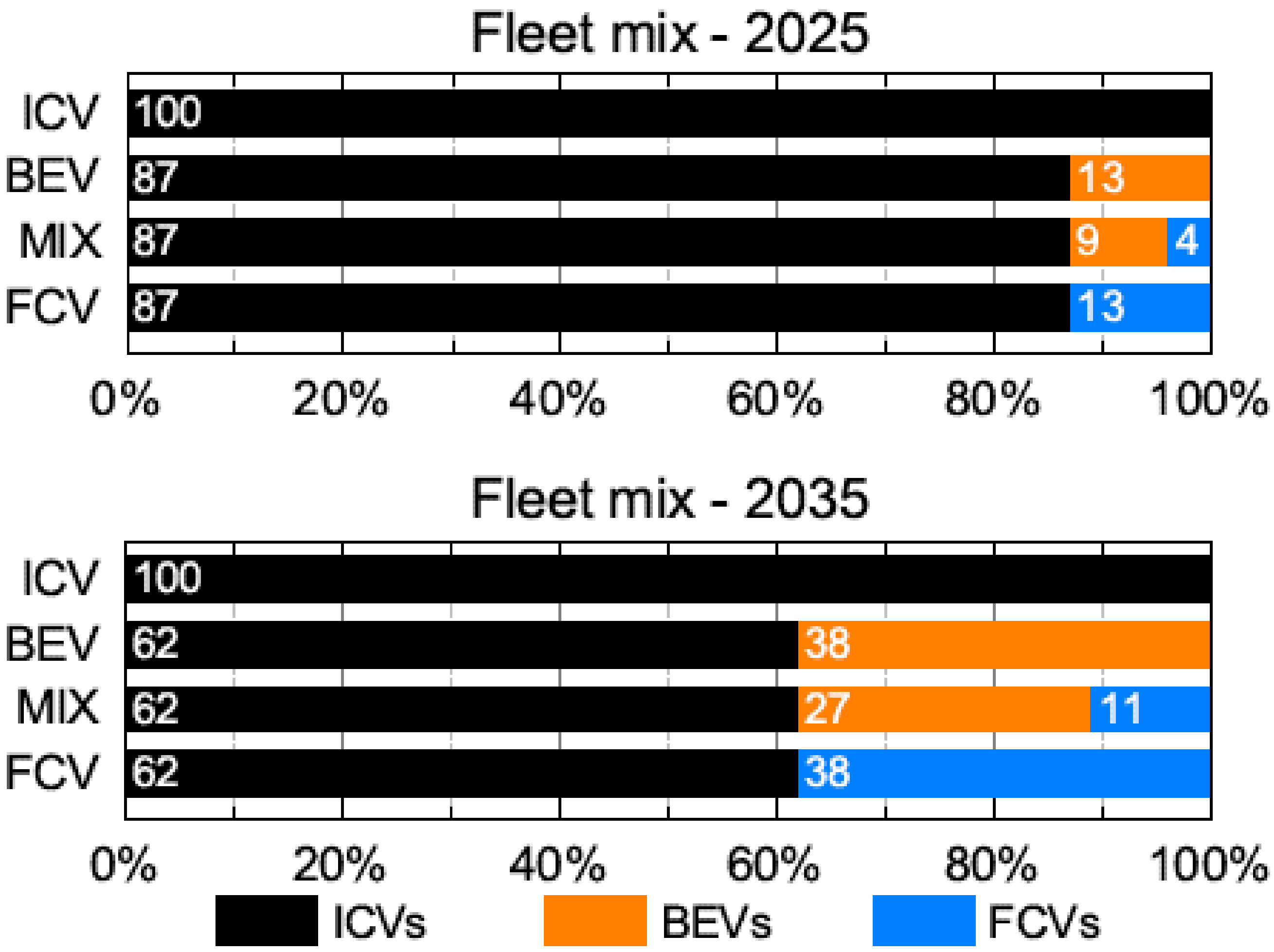
Evaluating co-benefits in the economic and emissions tradeoffs of battery and fuel cell vehicles

Markus F. Felgenhauer * † ‡, Matthew A. Pellow †, Sally M. Benson † § ¶ and Thomas Hamacher ‡

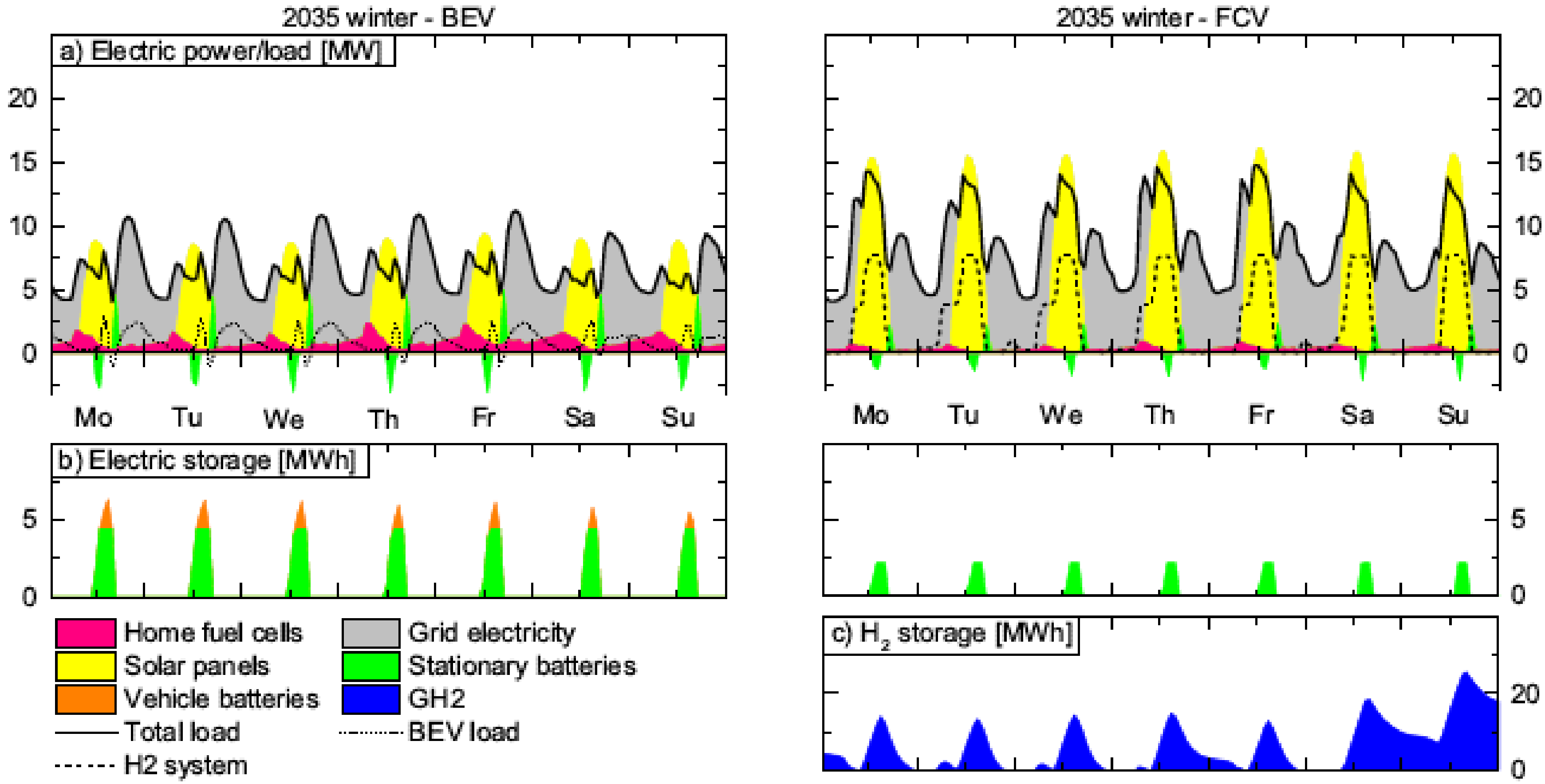
*BMW Group, Development Total Vehicle, Energy Management, Munich, 80788, Germany, †Stanford University, Global Climate & Energy Project, Stanford, CA 94305, USA, §Stanford University, Precourt Institute for Energy, Stanford, CA 94305, USA, ¶Stanford University, Department of Energy Resource Engineering, Stanford, CA 94305, USA, and ‡Technical University of Munich, Renewable and Sustainable Energy Systems, Munich, 80333, Germany

Submitted to Proceedings of the National Academy of Sciences of the United States of America

Los Alto Hills Case Study



Los Alto Hills Case Study



BEVs are much more cost effective