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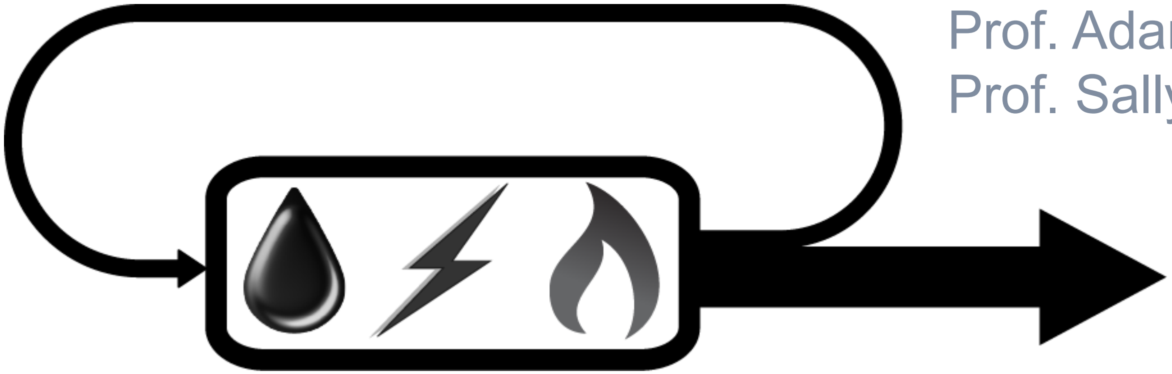
GLOBAL CLIMATE AND ENERGY PROJECT
STANFORD UNIVERSITY

ENERGY 101 TUTORIAL

Net Energy Analysis of Renewables

Charlie Barnhart

Standing on the Shoulders of…
Prof. Mik Dale
Prof. Adam Brandt
Prof. Sally Benson



Think, Pair, Share ---Then Poll

On average, who 'consumes' more energy per day?

Vegan driving a Ford 150 Raptor (11 MPG)

Cyclist on a Paleodiet

Think, Pair, Share ---Then Poll

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Vegan driving a Ford
150 Raptor (11 MPG)

Text 620572 to 37607

Cyclist on a Paleodiet

Text 620573 to 37607

Transportation

- Ford F150 Raptor fuel economy is 11 MPG
  - (This is equivalent to 4.7 km per liter)
- Each American drives about 10,000 miles per year
  - (This is equivalent to 44 km per day)

$$\frac{energy}{day} = \frac{\frac{distance}{day}}{\frac{distance}{fuel}} \times \frac{energy}{fuel}$$

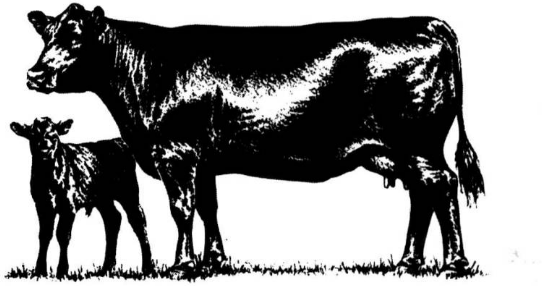
$$\frac{energy}{day} = \frac{\frac{44\ \text{km}}{\text{day}}}{\frac{4.7\ \text{km}}{\text{liter}}} \times \frac{10\ \text{kWh}}{\text{liter}} = \frac{94\ \text{kWh}}{\text{day}}$$

Diet

Modern agriculture is the use of land to convert petroleum into food.
-Albert Bartlett

- Thermodynamic Minimum: 2600 kcal per day
  - ~3 kWh per day
- Dairy?
  - Add 1.5 kWh per day

- Eggs?
  - Add 1 kWh per day



- Meat?
  - Add 8 kWh per day, 16 kWh per day if beef
- Energy consumed in fertilizer and farming?
  - 2 kWh per day

Average person: 12 kWh per day
Vegan: 5 kWh per day
Paleodieter: 20 kWh per day

cf. MacKay www.withouthotair.com

The Results

On average, who 'consumes' more energy per day?

Diet: 5 kWh / day

Truck: 94 kWh /day

Total: 99 kWh /day

Diet:

Base: 20 kWh / day

Additional 1300 kcal for cycling: 10 kWh / day

Total: 30 kWh / day

How else do we ‘consume’ energy?

- Think, Pair, Share

Energy for goods and services

Lighting

Wireless devices

Cleaning

Refrigerating

Cooking

Computing

Cooling

Traveling

Communicating

Visiting Friends in Seattle

Eating

Drinking

Defense

Shipping

What about energy for energy?

Collecting Firewood, S. Africa

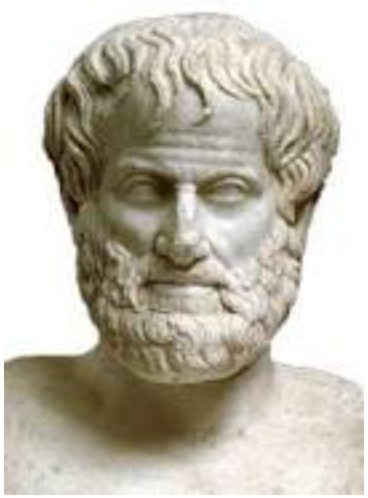
Coal Mining, PRB, Wyoming

Thunderhorse Oil Platform, GOM

Wind Turbine Blade

Silicon Ingot

What is the function of the energy industry?



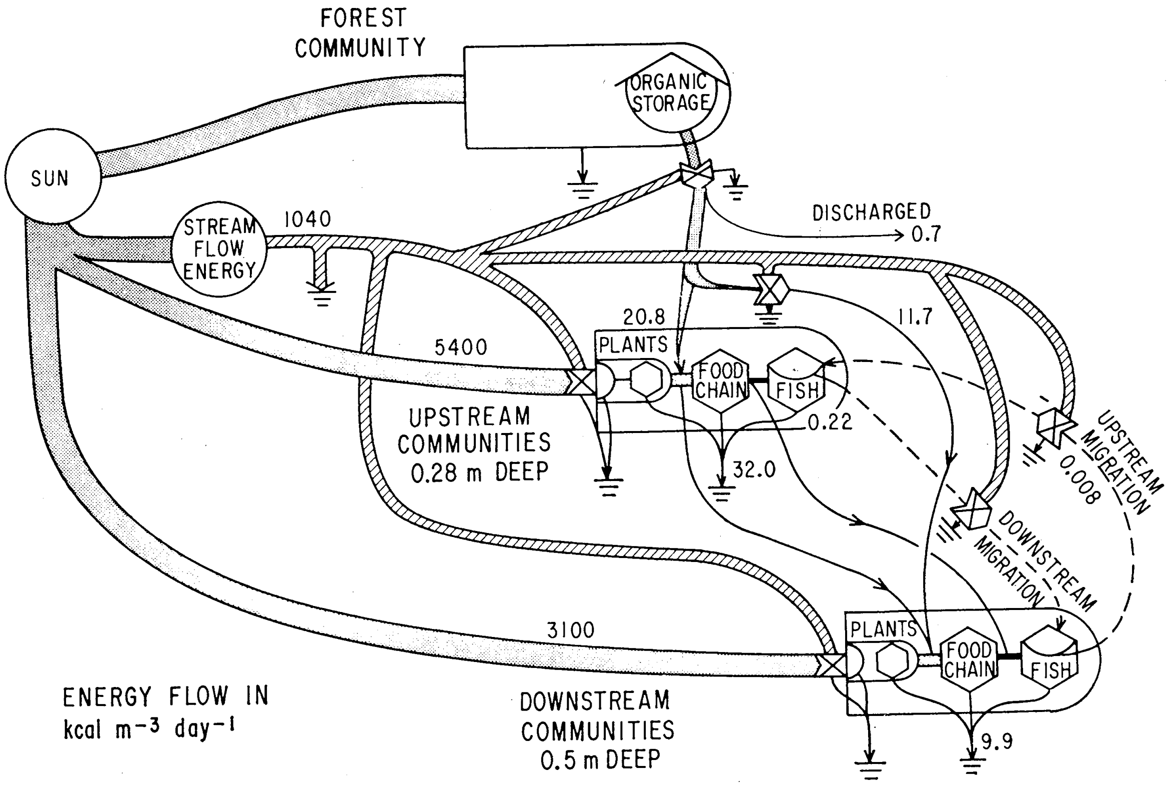
Fundamentally, the energy industry takes labor, capital, and energy inputs and consumes them in an effort to deliver usable energy to society. A functioning energy industry delivers more energy to society than it consumes.

Biological systems-scale efficiency metrics

- Early work in systems-scale energy efficiencies inspired by biologists and ecologists

Hall (1972): Why do fish migrate? Is the extra energy they expend in migrating paid back in access to more food?

Work expended to move upstream repaid
≈ 25 times in food



Source: Hall (1972) *Migration and metabolism in a temperate stream ecosystem*

Life in general

Energy Invested

Energy Returned

Energy Surplus

Energy Deficit

Early human “energy industries”

- Early human societies were historically subject to energy return limitations
  - Hunter and gatherers (on average) must capture and gather more calories than they expend on hunting and gathering
  - Agriculturalists must grow more calories than the effort expended in growing their food

Source: Smil (1994) Energy in human history

An Analogy: Financial Analysis

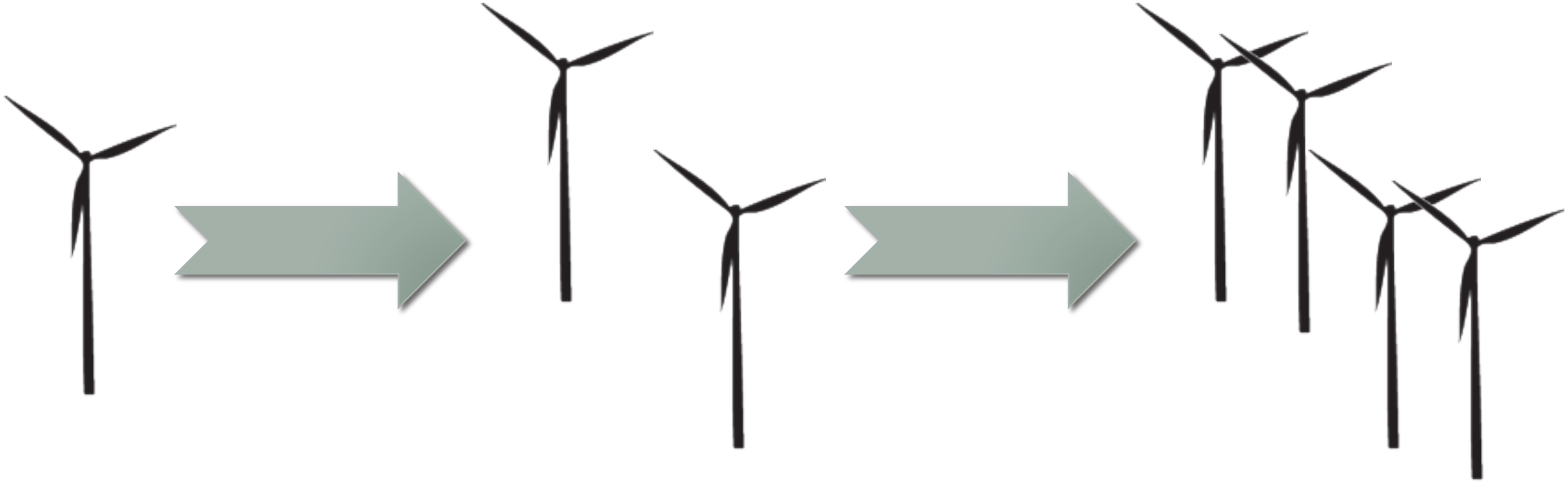
- You have to invest money to make money
- To be profitable you need to make more money than you invest.
- Investments with high rates of return are better than investments with lower rates of return.
- Investments that are more profitable and have shorter breakeven times are easier to grow quickly.

How do these ideas apply to energy systems?

Net Energy Analysis (Macroenergetics)

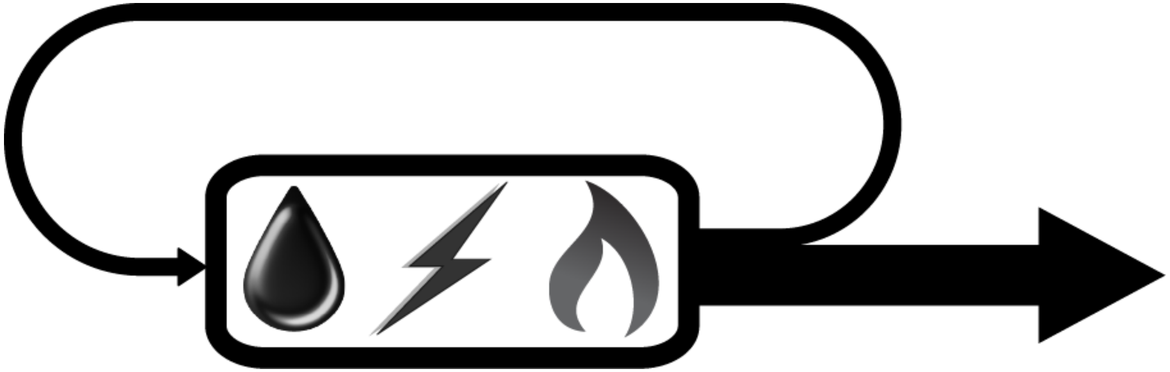
- It takes energy to make, operate and decommission the devices and systems needed to produce energy.
- For a device or system to be useful to the global energy system:

Energy Output > Total Energy Inputs



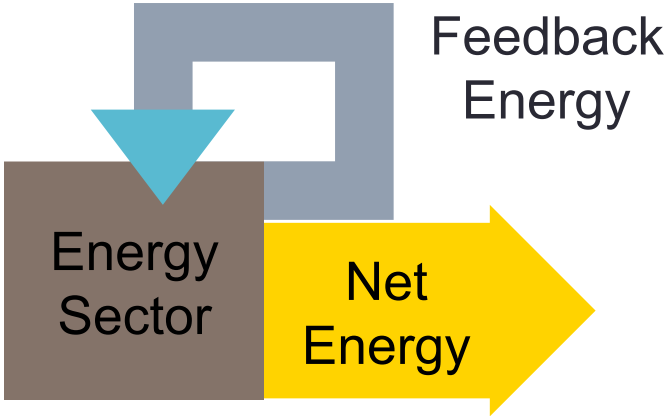
General insights from net energy analysis

1. A primary energy resource must provide more energy to society than that consumed in extracting, processing, and distributing the energy
2. Energy resources that do not meet this criterion are either "subsidized" by other energy resources or are uneconomic
3. Net energy returns will decrease as the quality of the resource declines
4. Net energy returns will increase as technologies improve



Net Energy and Society

- Industrial Revolution was fuelled by easily accessible (i.e. cheap) and abundant fossil fuels;
- Rapid and large payback led to ‘upward growth spiral’ of increasing energy supply;
- Historically the energy sector has required very low energy investment (<10% of gross production);
- This leaves lots of net energy available to society to do things we like – hot showers, cold beer, fast cars…



Net Energy Analysis

Net Energy Analysis (NEA) is the **means** to **account** for **embodied energy**:

- **Definitions**:
  - Net energy analysis is “determination of the **amount of primary energy, direct and indirect**, that is **dissipated** in **producing** a **good or service** and delivering it to the market” (Peet, 1992)

- **Energy return ratios**, e.g. energy-return-on-investment (EROI), tell us how many times a given investment of energy will pay back:

- **Energy payback time** (EPBT) tells us how quickly a given energy investment will be paid back.

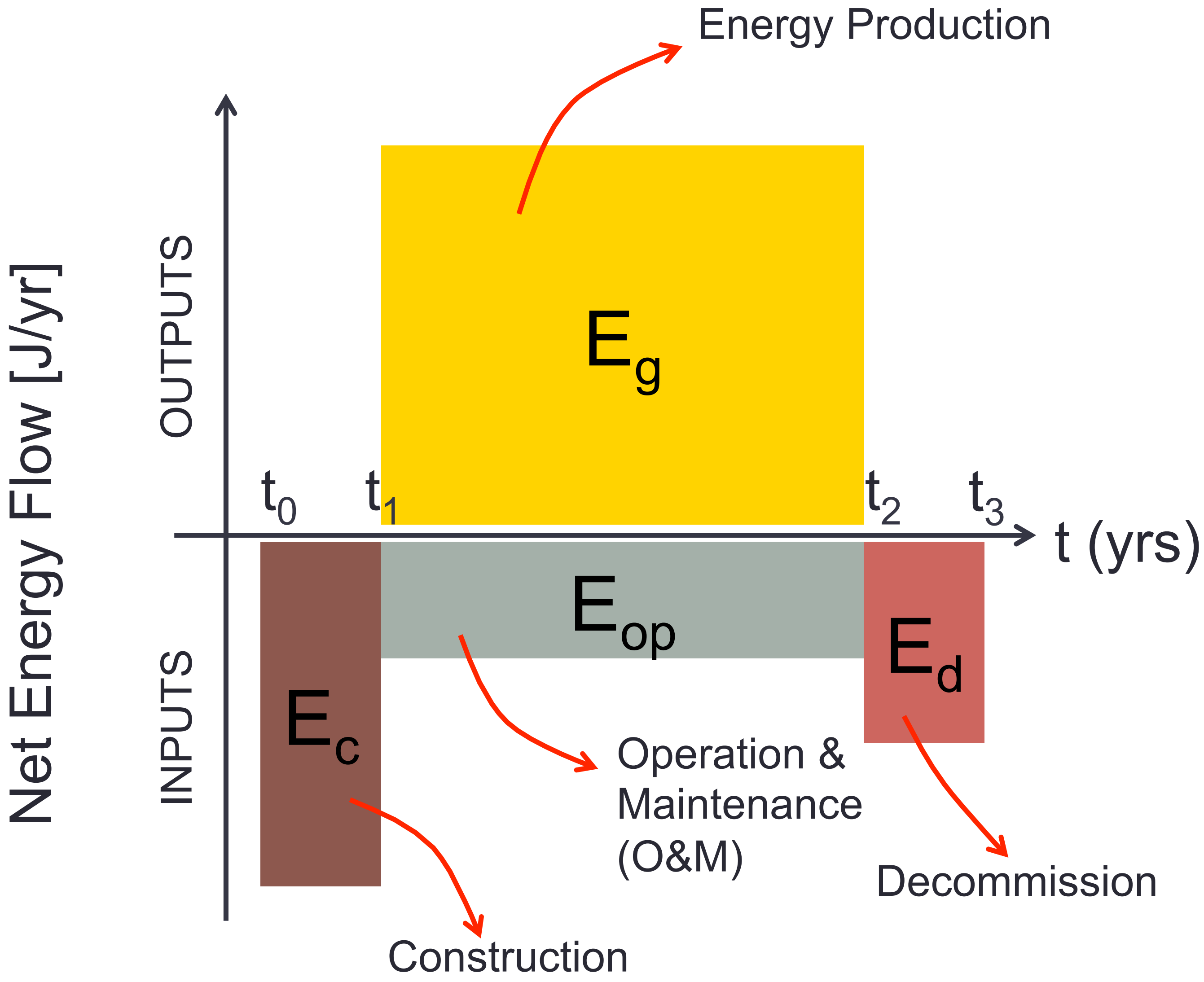
The concept of “energy returns”

- Energy return ratios (ERRs) compare the amount of energy produced by an energy system to that which it consumes

$$\text{ERR} = \frac{\text{Energy outputs}}{\text{Energy inputs}}$$

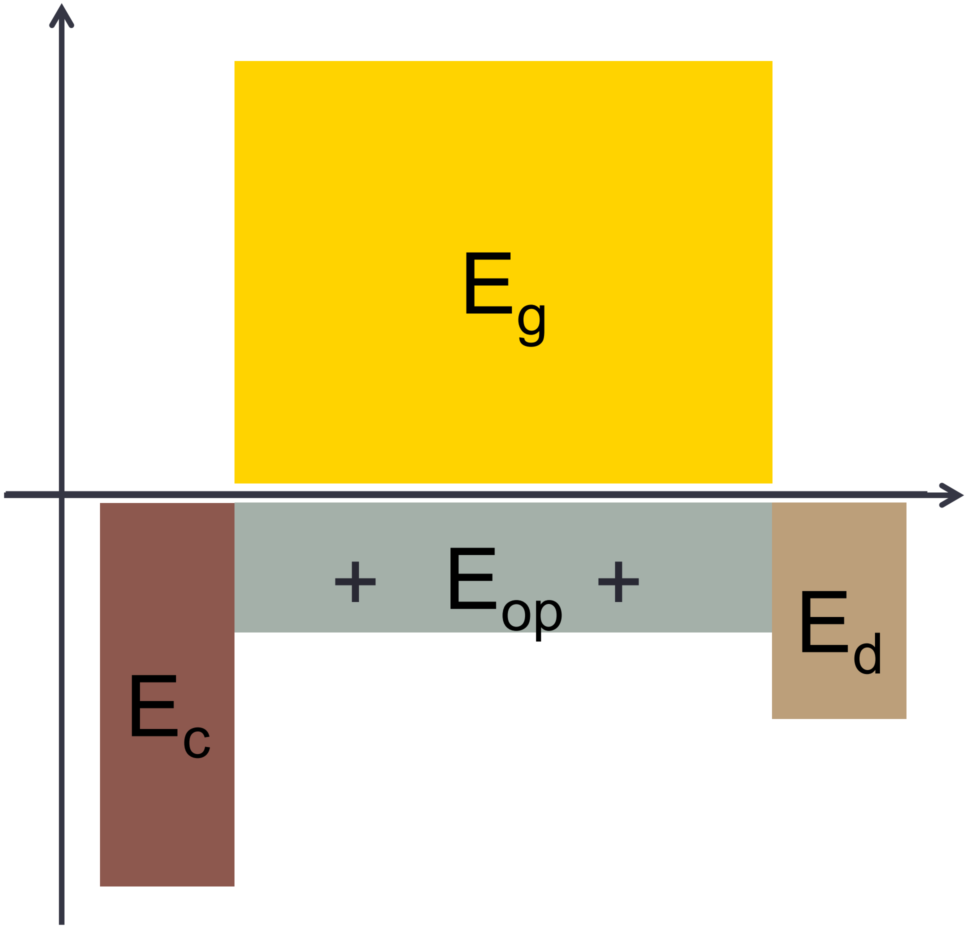
*ERR ≥ 1 for successful extractive industry

Energy flow for single plant



Energy Return on Investment (EROI)

EROI =



Energy Payback Time (EPBT)

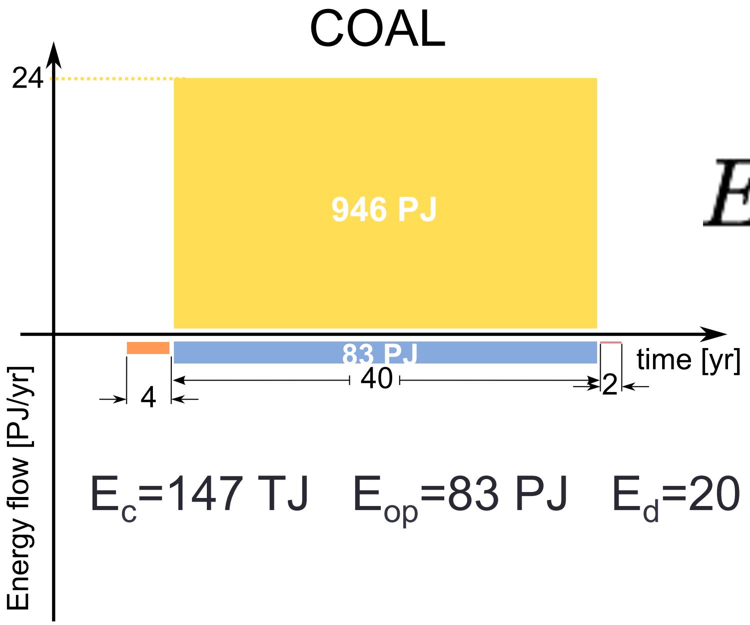
- The time an energy production technology takes to pay back all of the energy inputs.
- Has dimensions of time (often years).
- Definition:

$$EPBT = \frac{\text{Energy}_{in}}{\text{Annual Energy}_{out}}$$

- In terms of diagram:

$$EPBT = \frac{E_c + E_{op} + E_d}{\dot{E}_g}$$

Example 1: Coal



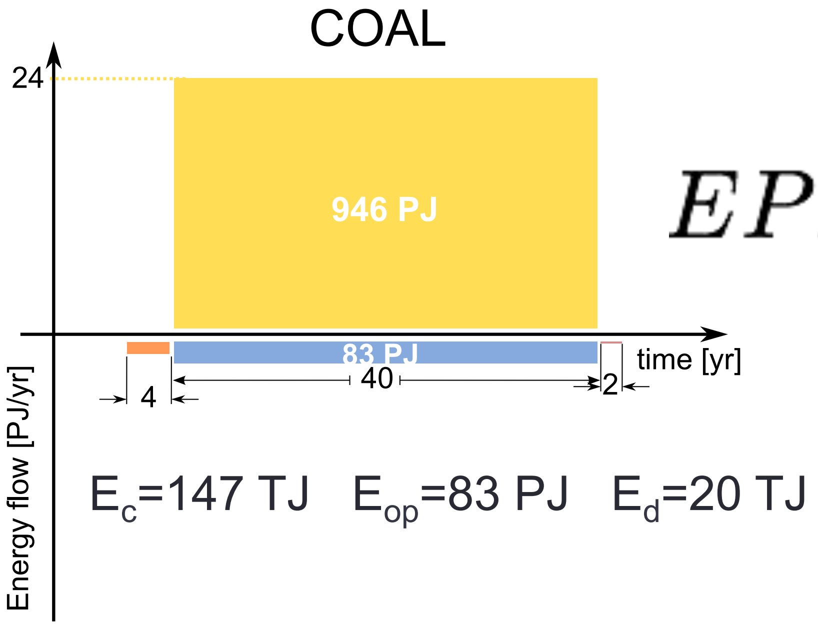
E_c=147 TJ E_{op}=83 PJ E_d=20 TJ

$$EROI = \frac{E_g}{E_c + E_{op} + E_d}$$

Data from White & Kulcinski (2000).

$$EROI = \frac{946}{0.147 + 83 + 0.02} = 11$$

Example 1: Coal



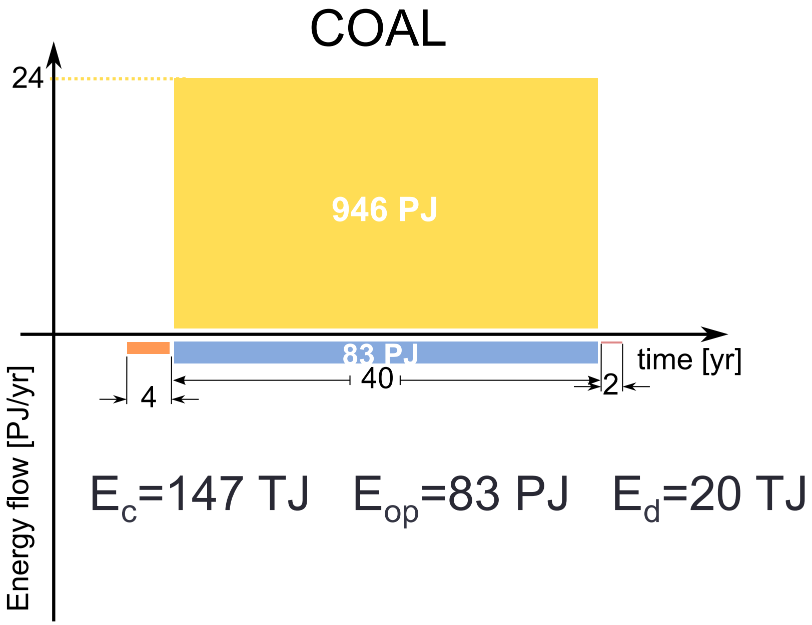
E_c=147 TJ E_{op}=83 PJ E_d=20 TJ

$$EPBT = \frac{E_c + E_{op} + E_d}{E_g/t_g}$$

Data from White & Kulcinski (2000).

$$EPBT = \frac{0.147 + 83 + 0.02}{24} = 3.5$$

Example 1: Coal



E_c=147 TJ E_{op}=83 PJ E_d=20 TJ

Data from White & Kulcinski (2000).

EROI = 11
EPBT = 3.5 yrs

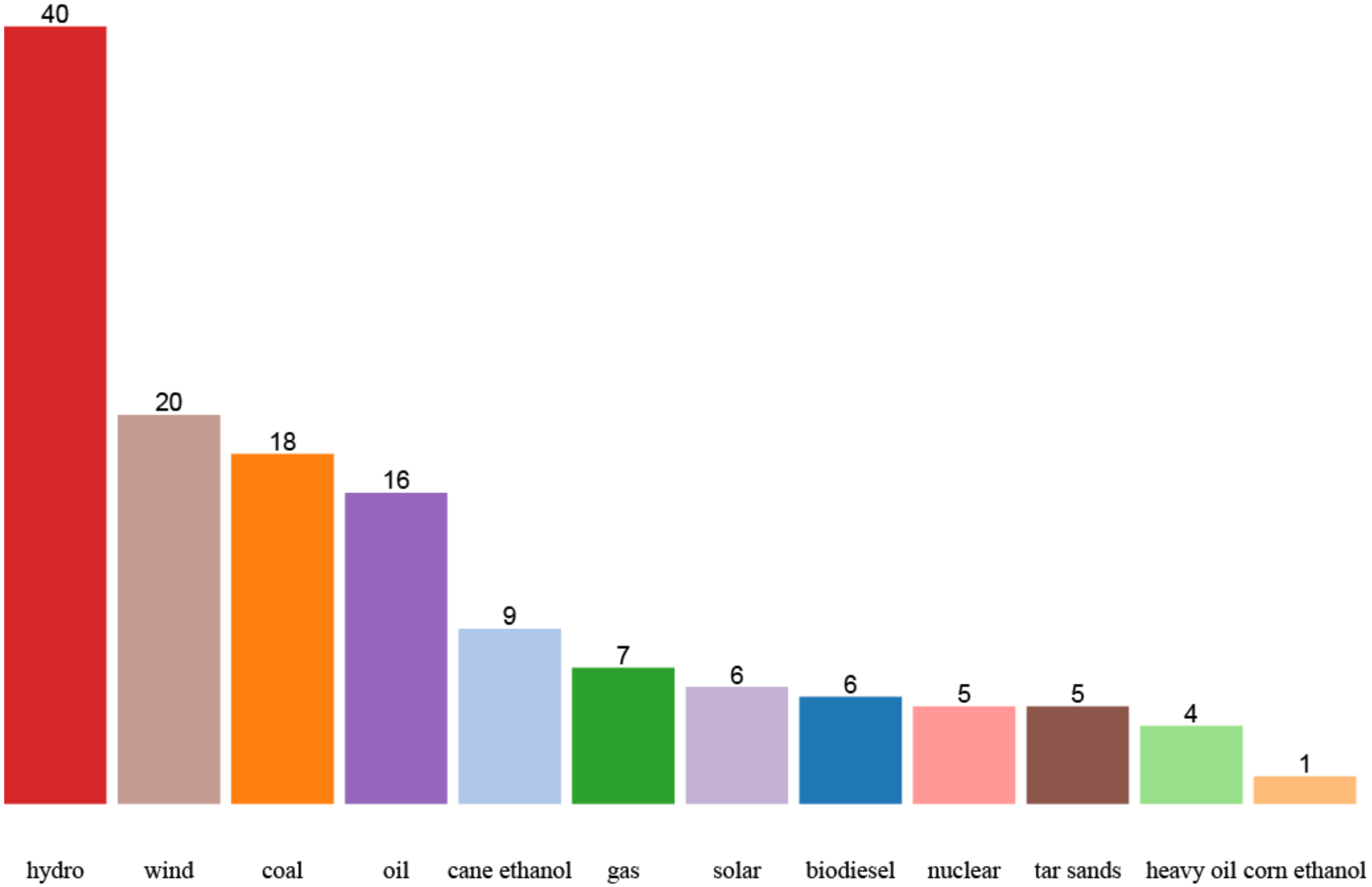
- Non-renewable technologies have large O&M costs, normally associated with fuel cycle;
- Renewable technologies often have large up-front costs associated with construction and installation.

Pop Quiz---Poll

- Which resource, on average, today, has the highest EROI?
  - Wind? 761392
  - Solar? 761393
  - Oil? 761394
  - Coal? 761395
  - Natural Gas? 761396

  - Text Answer Code to 37607

Primary EROI



Cleveland, Cutler J., Robert Costanza, Charles A.S. Hall, and Robert Kaufmann (1986)

Think, Pair, Share

- What might be some issues, problems and caveats associated with NEA?

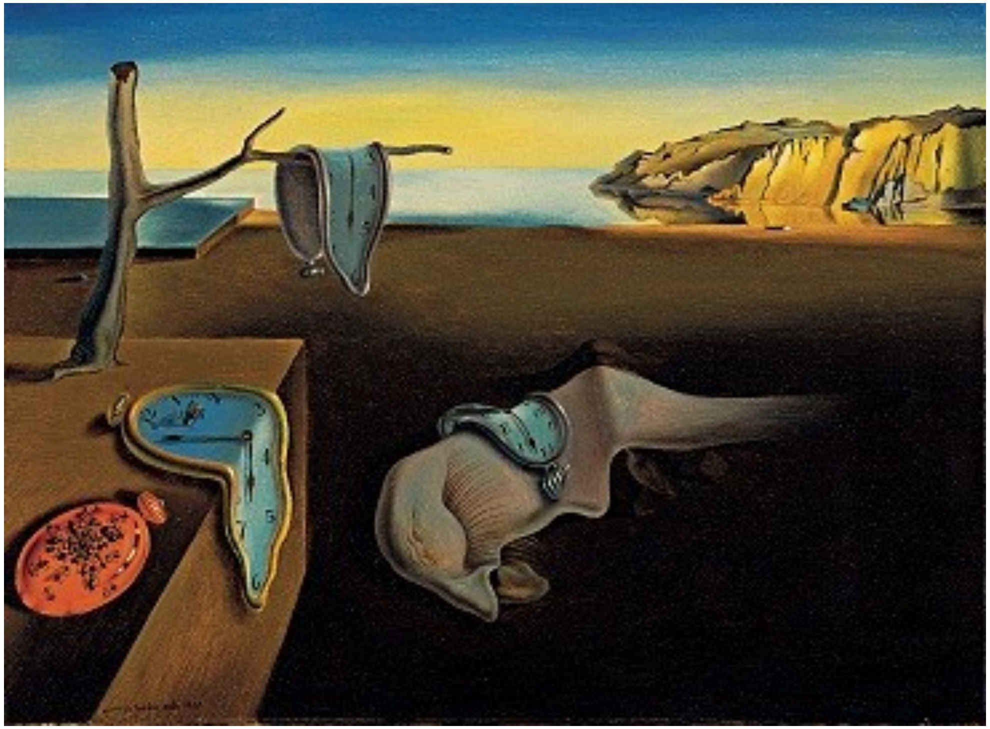
Problems with NEA

- Measuring total energy input is very difficult
  - Requires knowledge of many processes, embodied energy
- System boundaries often not commensurate between studies
- Metrics often poorly defined
  - What is meant by total outputs?
  - How are different energy types aggregated?
- Results can be overemphasized

Simple definitions, complex implementation

- Definitions for ERRs are easy to state qualitatively, difficult to define quantitatively
  - Energy products are produced in complex "pathways"
  - Indirect energy consumption can occur in dozens of other industries
  - System boundary considerations loom large and are difficult to standardize
- We are working (Brandt, Dale 2012; Brandt Dale Barnhart 2013) to standardize methodologies

5 Minute Break



Athabascan Tar Sands

Brandt A.R., J. Englander and S. Bharadwaj (2013). The energy efficiency of oil sands extraction: Energy return ratios from 1970 to 2010. *Energy*

Boundary Considerations

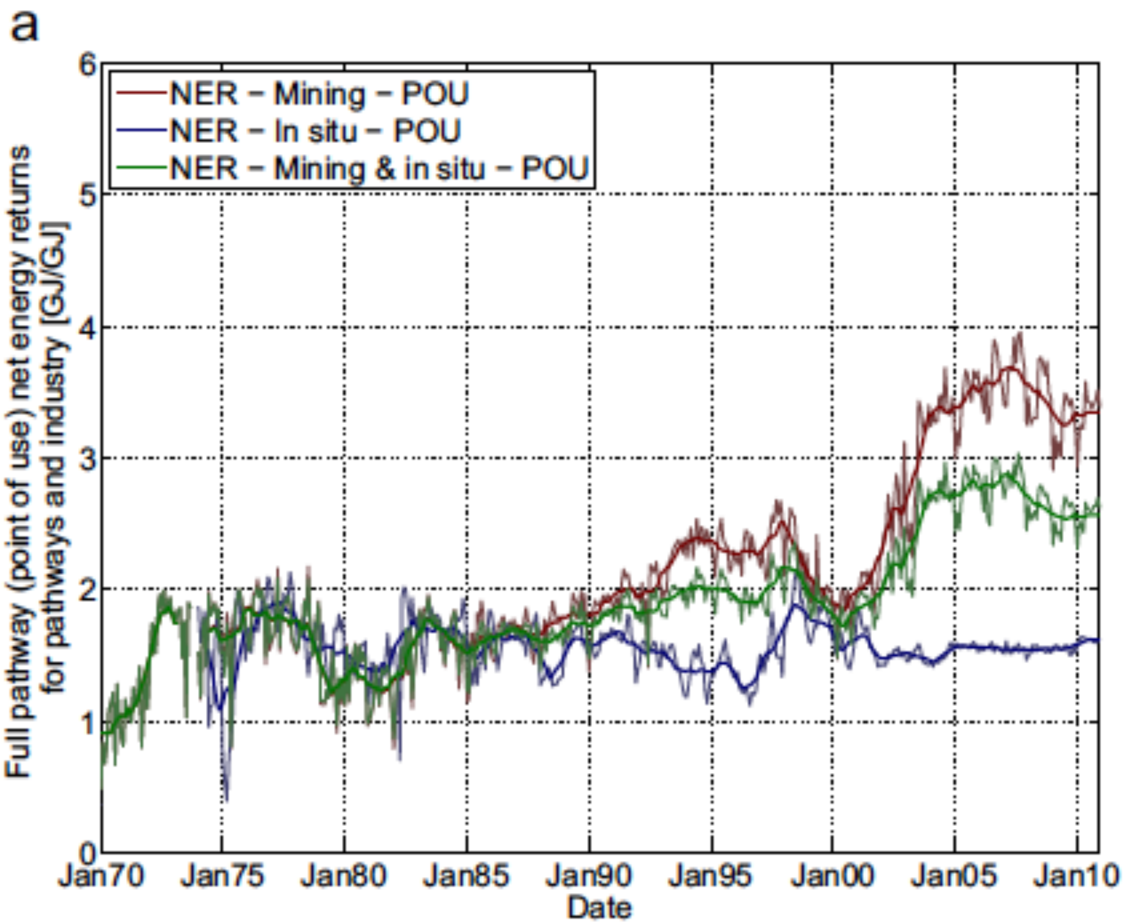
- Net Energy Ratio

$$\frac{\text{energy outputs}}{\text{all energy inputs}}$$

- Net External Energy Ratio

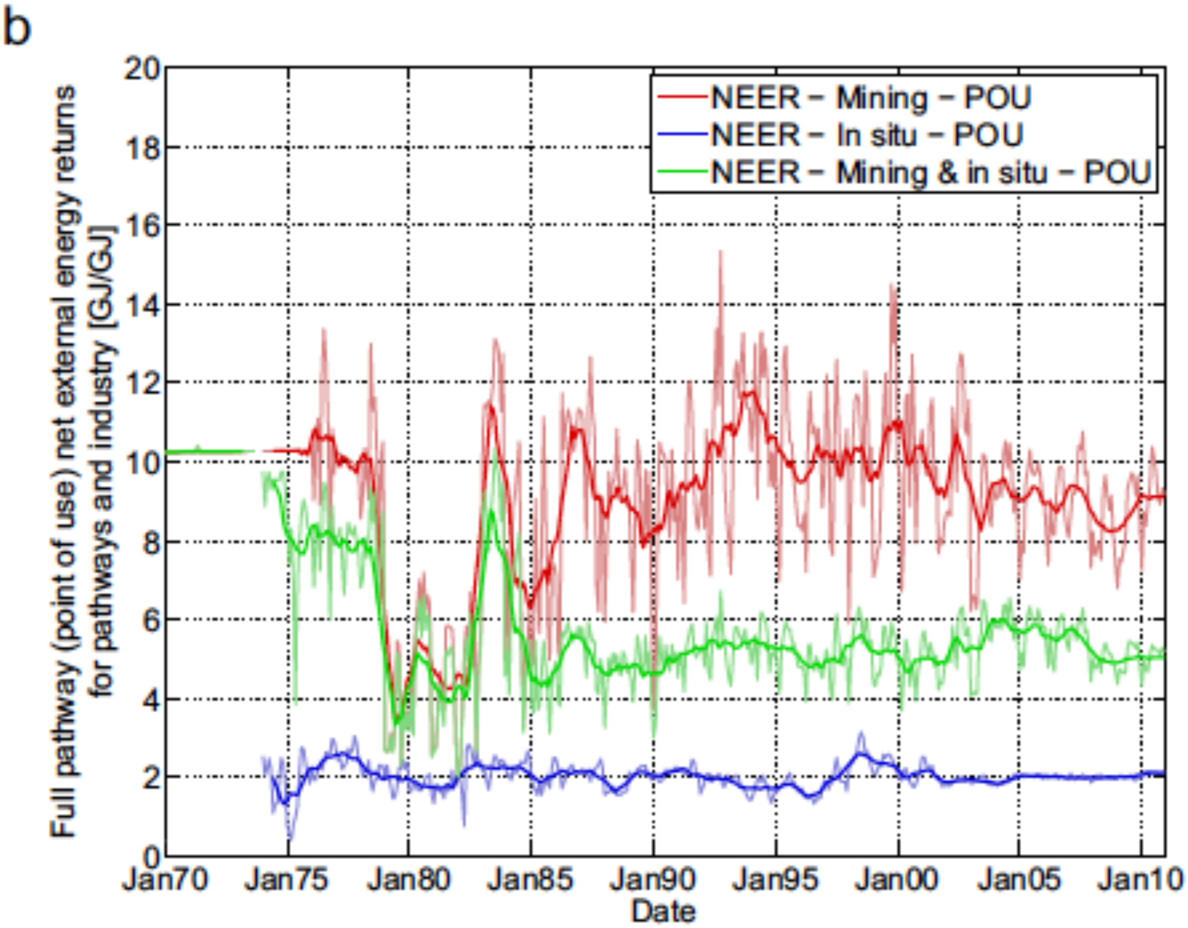
$$\frac{\text{energy outputs}}{\text{societal energy inputs}}$$

Net Energy Ratio (NER)



NER, EROI = 3.25 GJ/GJ

Net External Energy Ratio (NEER)



NEER = 10 GJ/GJ

The PV Industry

PV—A dynamic energy industry

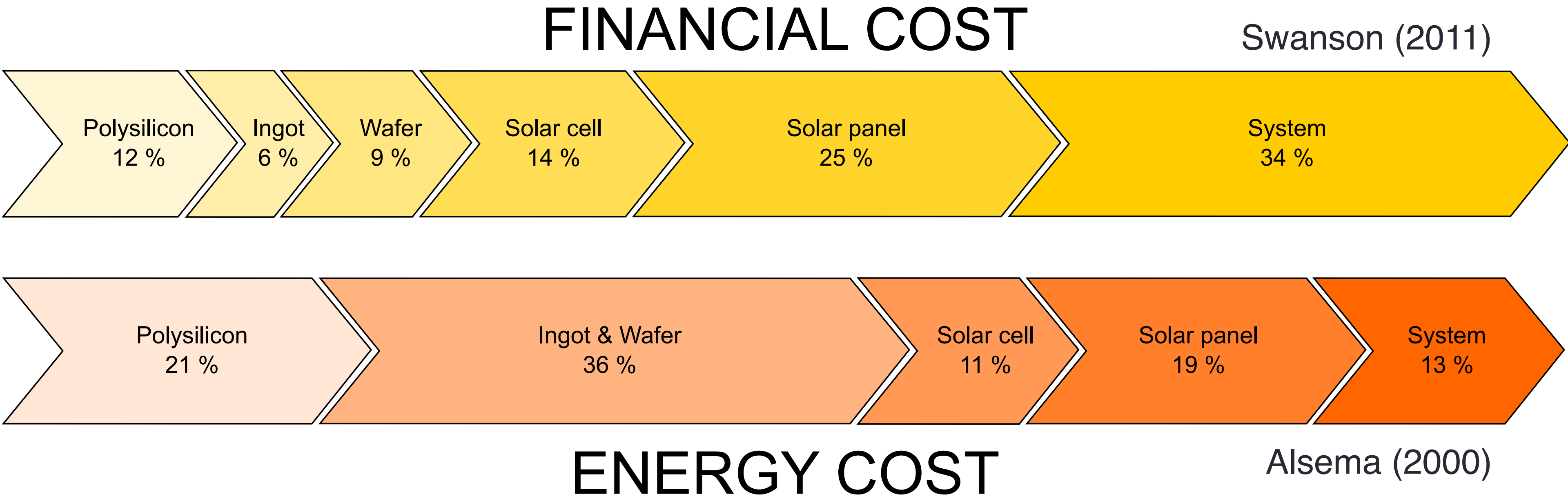
- Amortized metrics such as 'cumulative energy demand' (CED) may disguise the costs of rapid scale-up or transition to alternative energy sources

- Timing of material and energy inputs and outputs is important

- Most renewables require 'up-front' payment of majority of energy costs

- Fossil fuels have larger operating costs

Energy Inputs for PV Manufacturing



FINANCIAL COST

Swanson (2011)

Polysilicon 12 %

Ingot 6 %

Wafer 9 %

Solar cell 14 %

Solar panel 25 %

System 34 %

Polysilicon 21 %

Ingot & Wafer 36 %

Solar cell 11 %

Solar panel 19 %

System 13 %

ENERGY COST

Alsema (2000)

- E. A. Alsema, Progress in Photovoltaics: Research and Applications 8, 17 (2000)
- Swanson, R. (2011) The Silicon Photovoltaic Roadmap, Stanford Energy Seminar Nov 14, 2011

Energy flows industry growing at 100% per year

EPBT = 2 yrs

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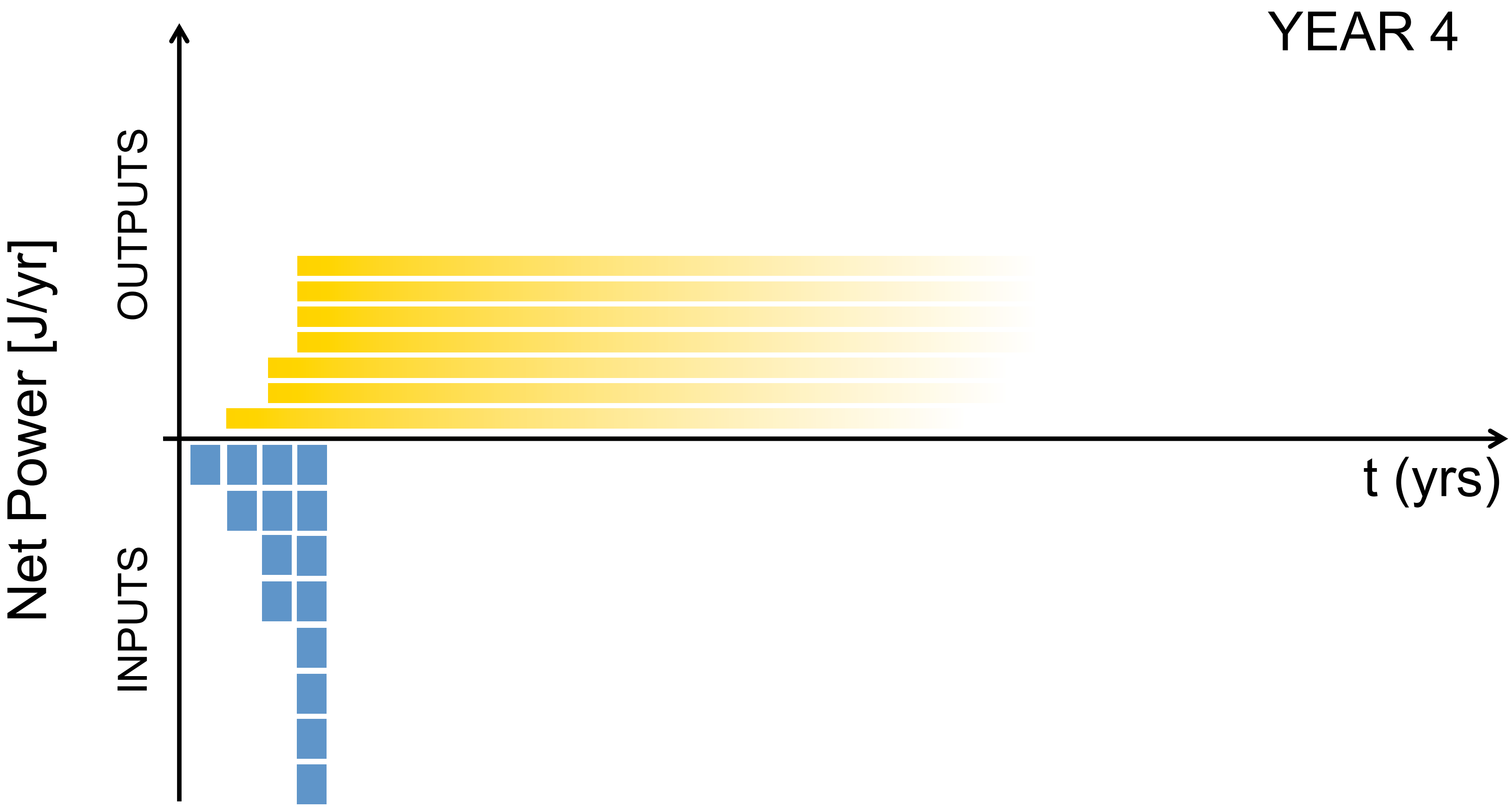
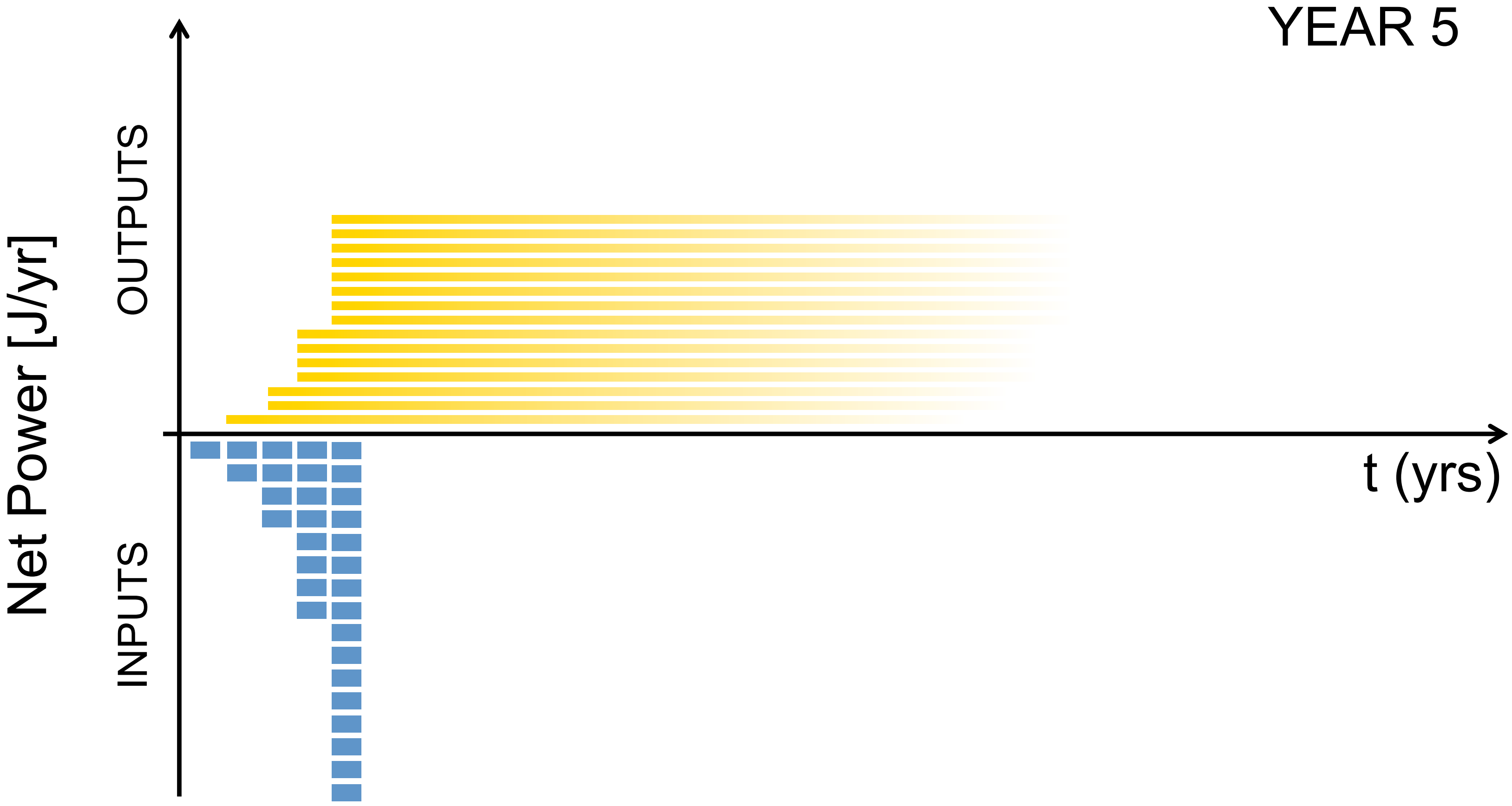


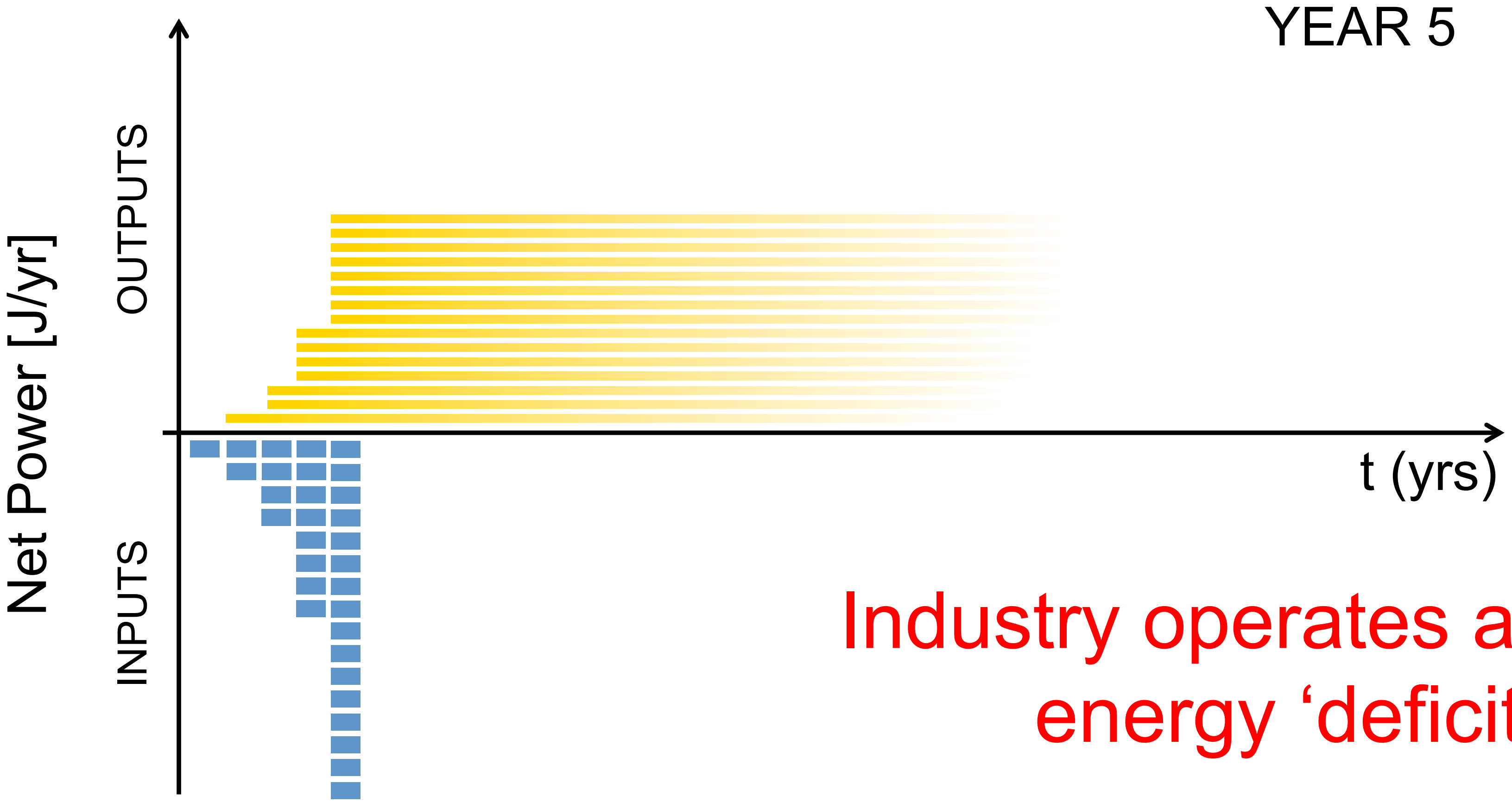
Energy flows industry growing at 100% per year

EPBT = 2 yrs



Energy flows industry growing at 100% per year

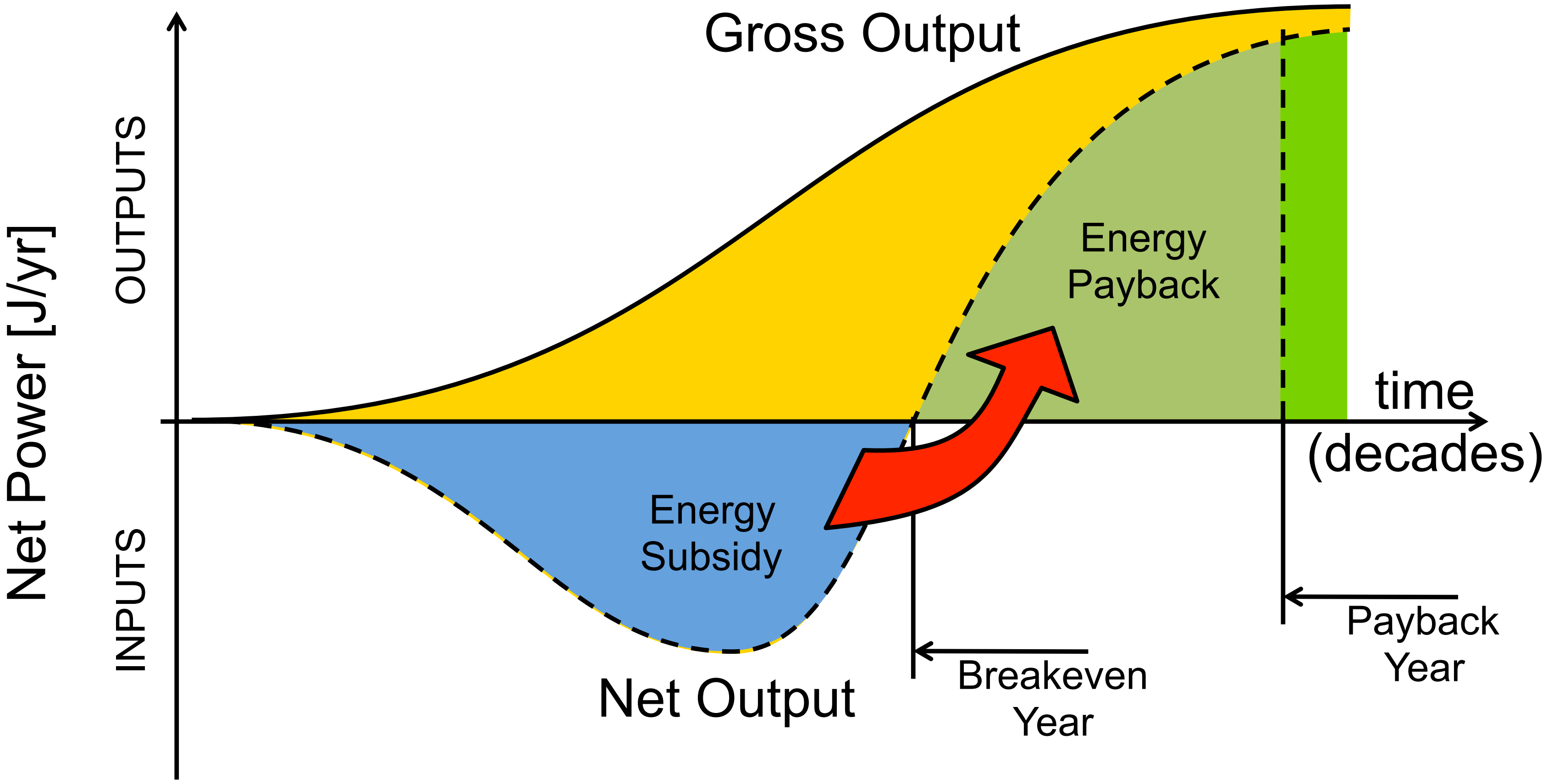
EPBT = 2 yrs



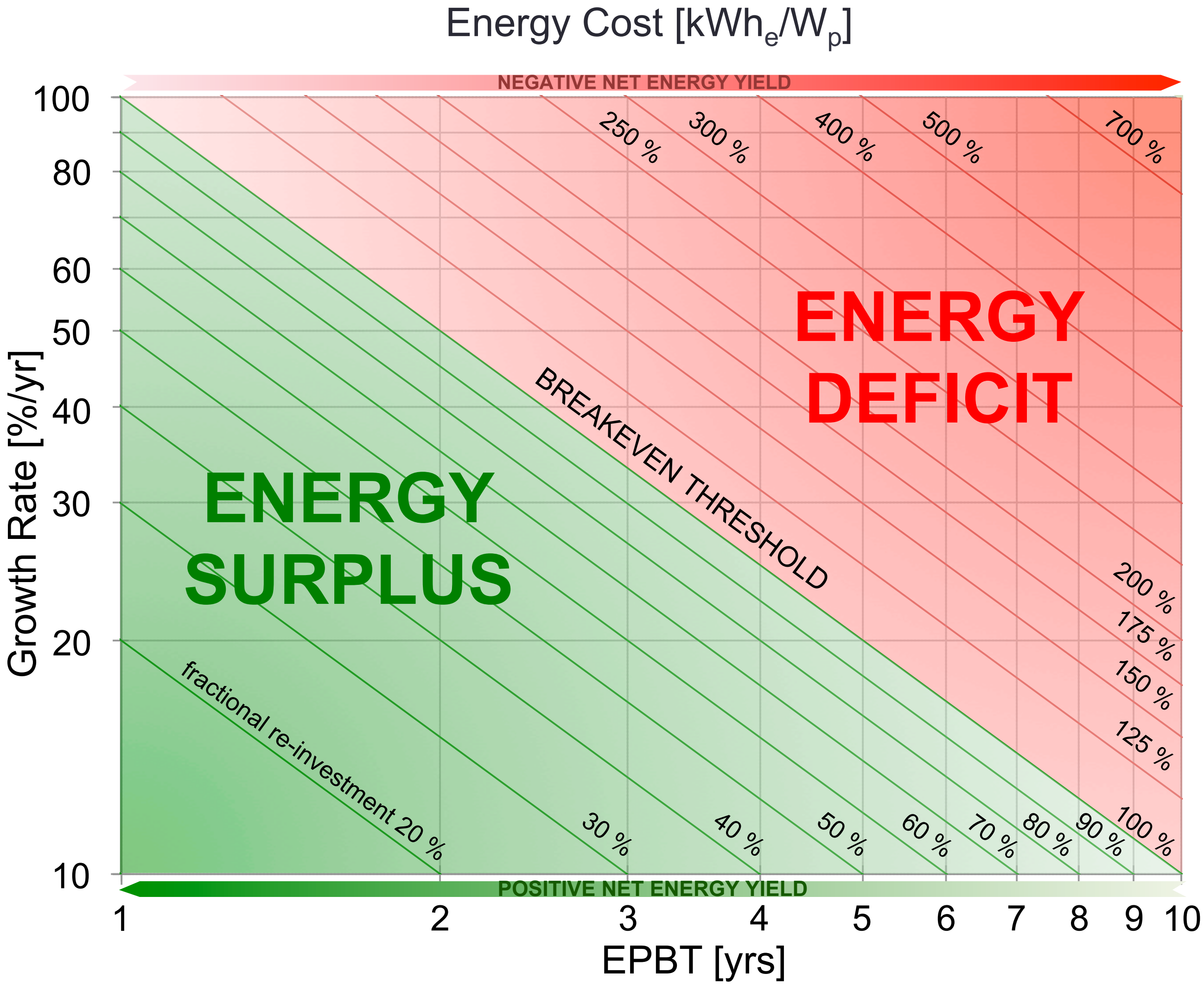
Industry operates at energy ‘deficit’

Energy flows for growing industry

Growing industry requires ‘**start-up capital**’



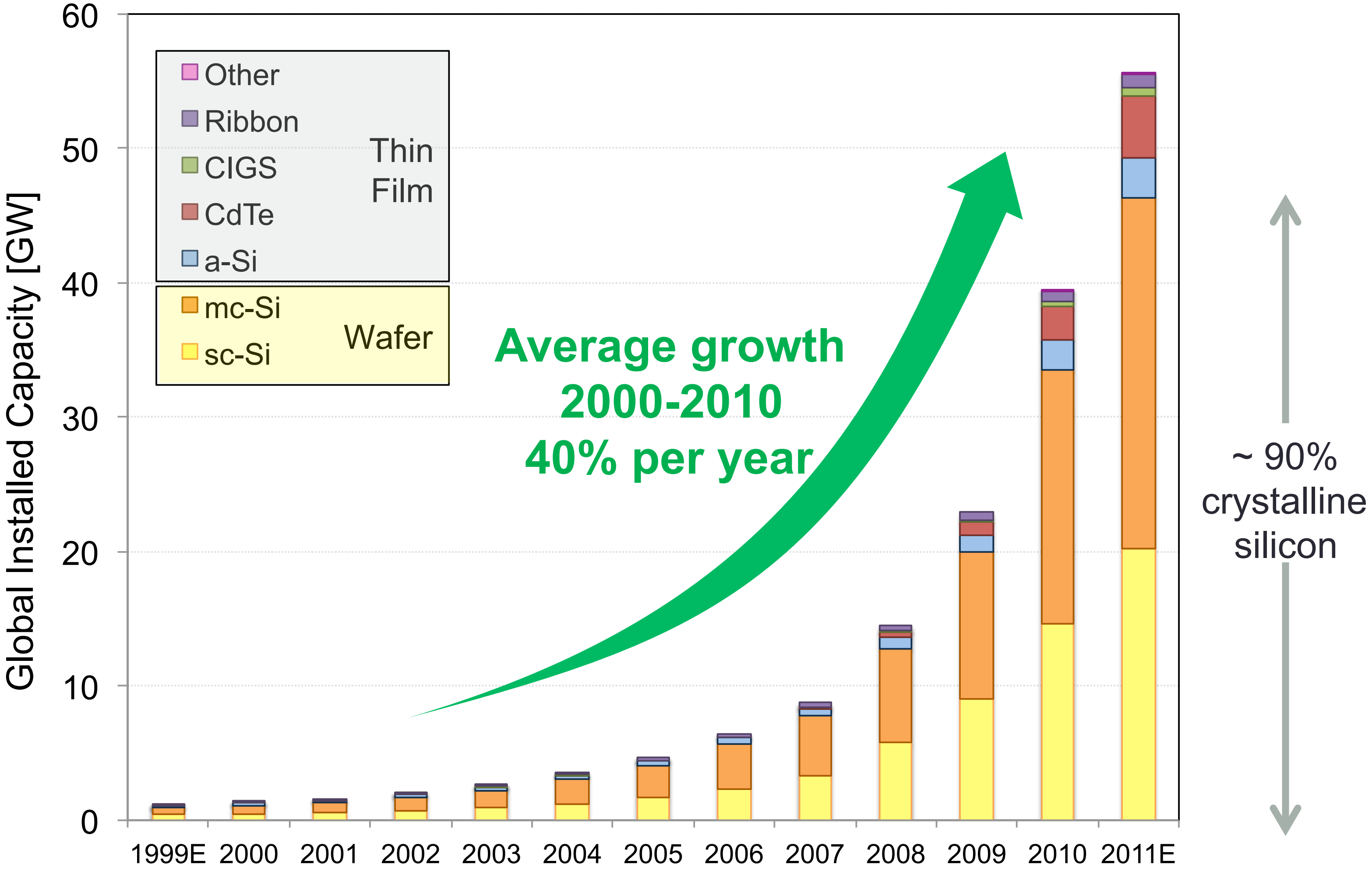
Net energy yield, growth and energy cost



Energy Balance of the PV Industry

- Industry growth rates [%/yr]
- Capacity factor (or load factor) of PV systems [%]
- Energetic cost (CED) of PV systems [kWh_e/W_p]

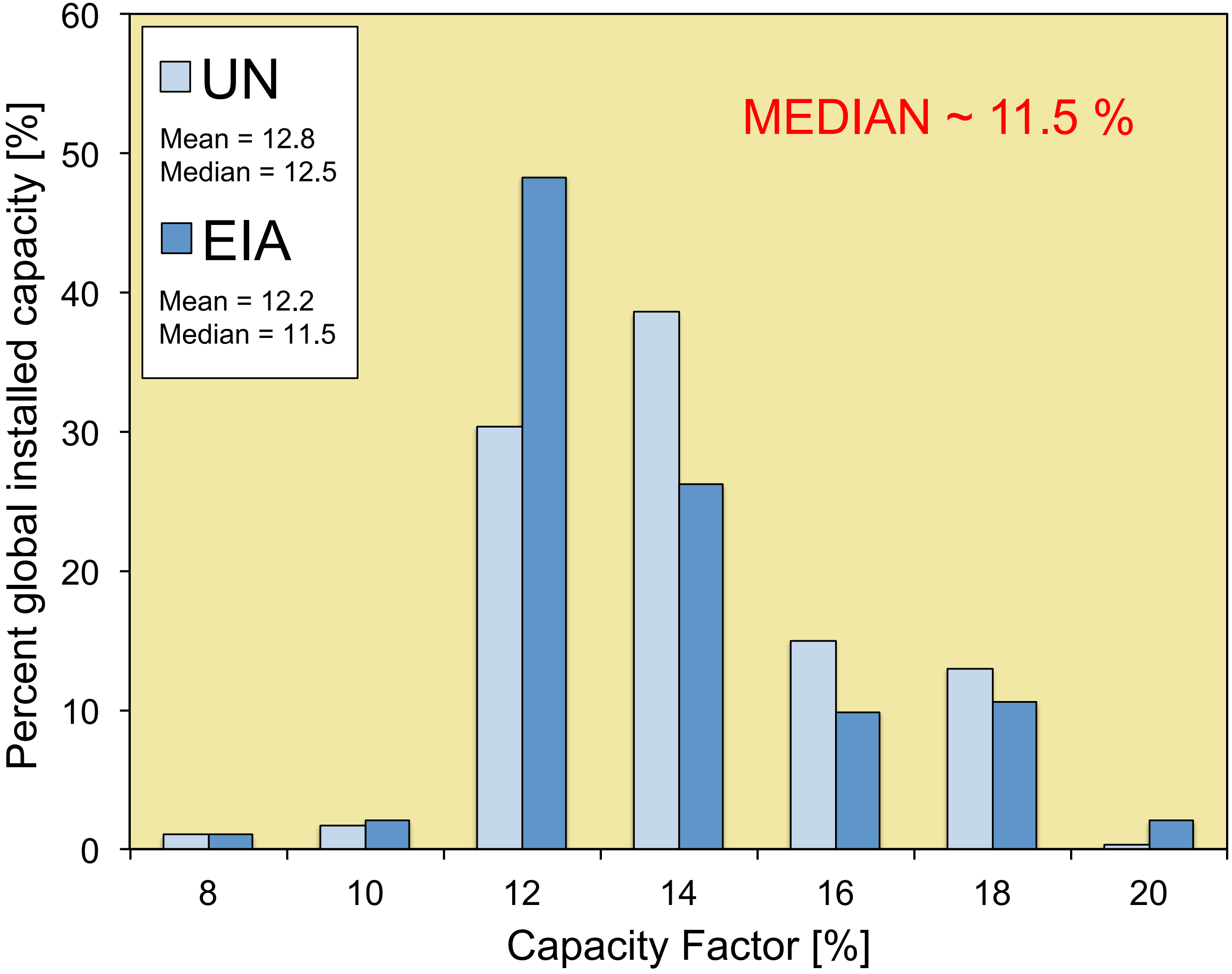
PV industry is growing rapidly



Average growth 2000-2010 40% per year

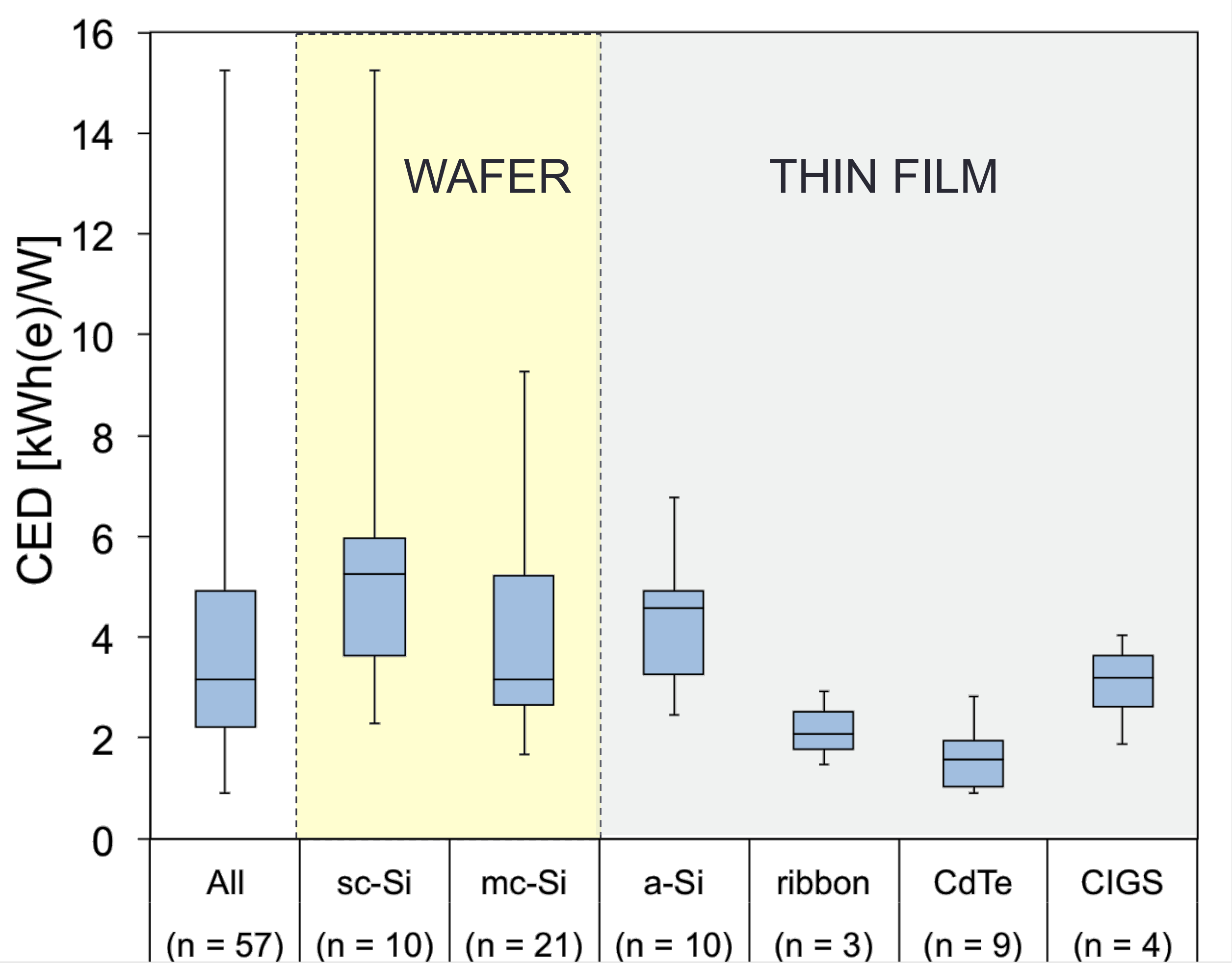
Dale & Benson (2013) using data from DOE (2008), EPIA (2011), EIA (2012), UN (2012)

Global PV capacity factor



Dale & Benson (2013) using data from UN (2011), EIA (2012)

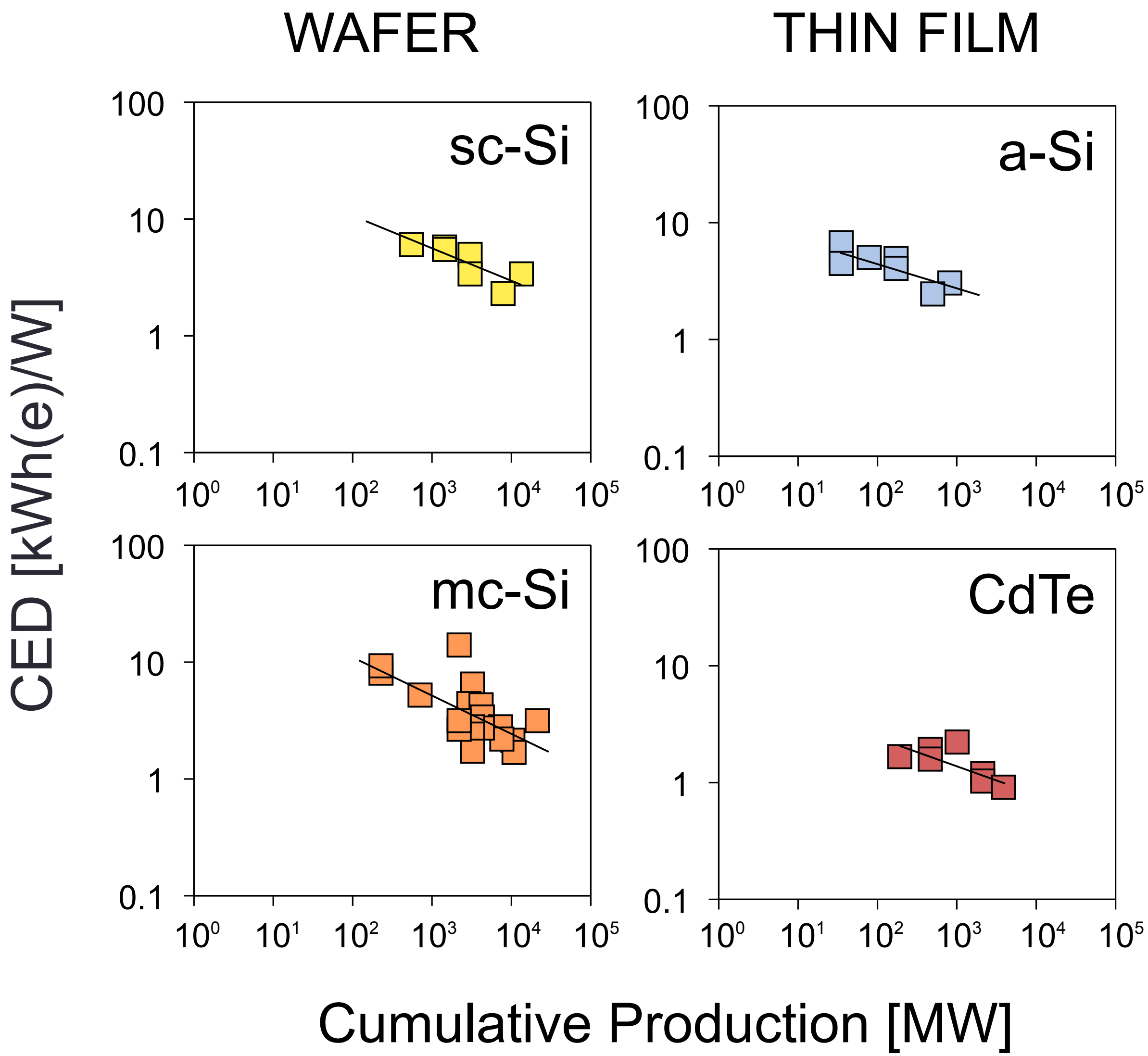
CED – ‘energetic cost’ for PV: meta-analysis



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)

Dale & Benson (2013)

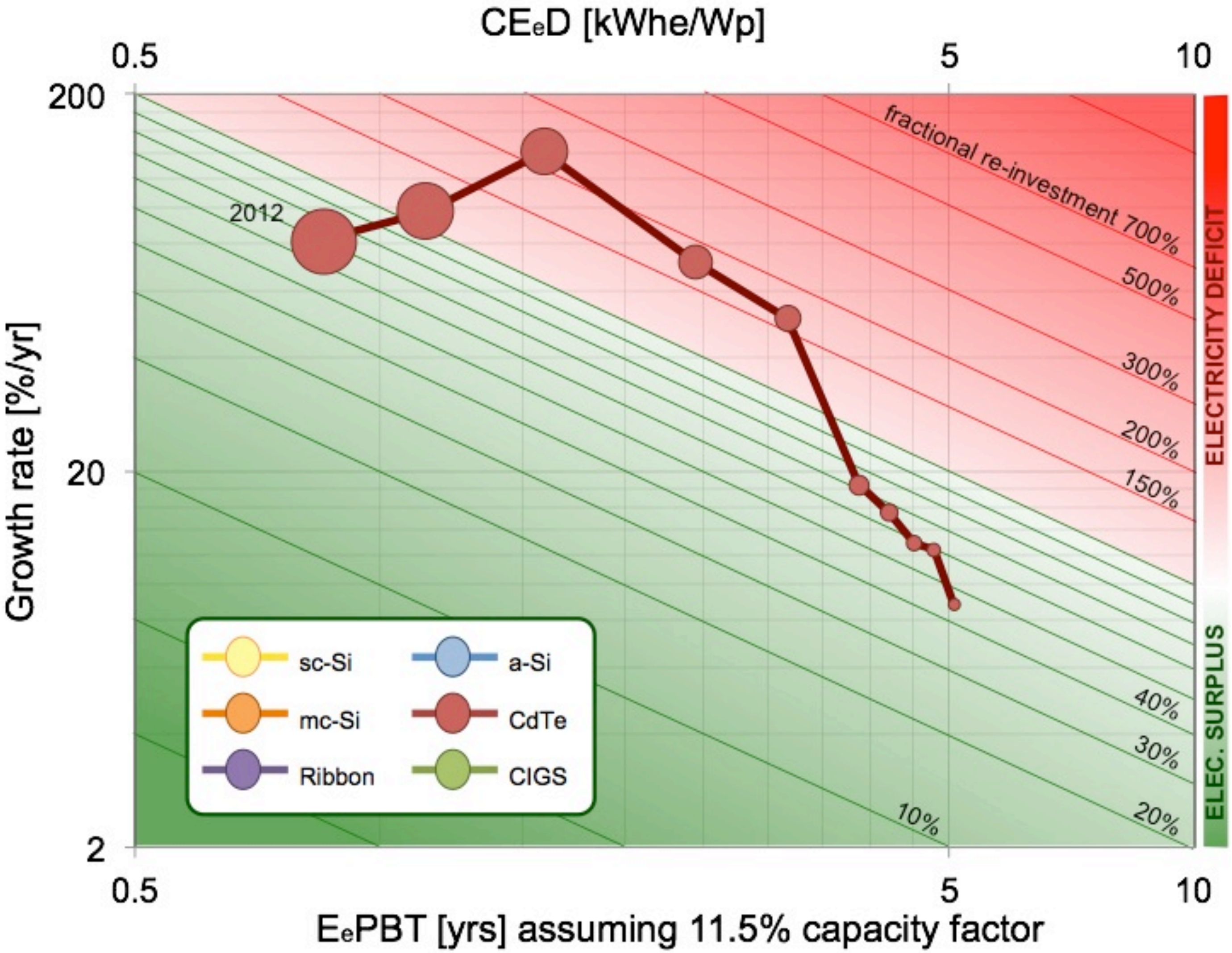
Energy inputs to PV – energy learning curves



Learning is reducing the energetic cost of PV deployment

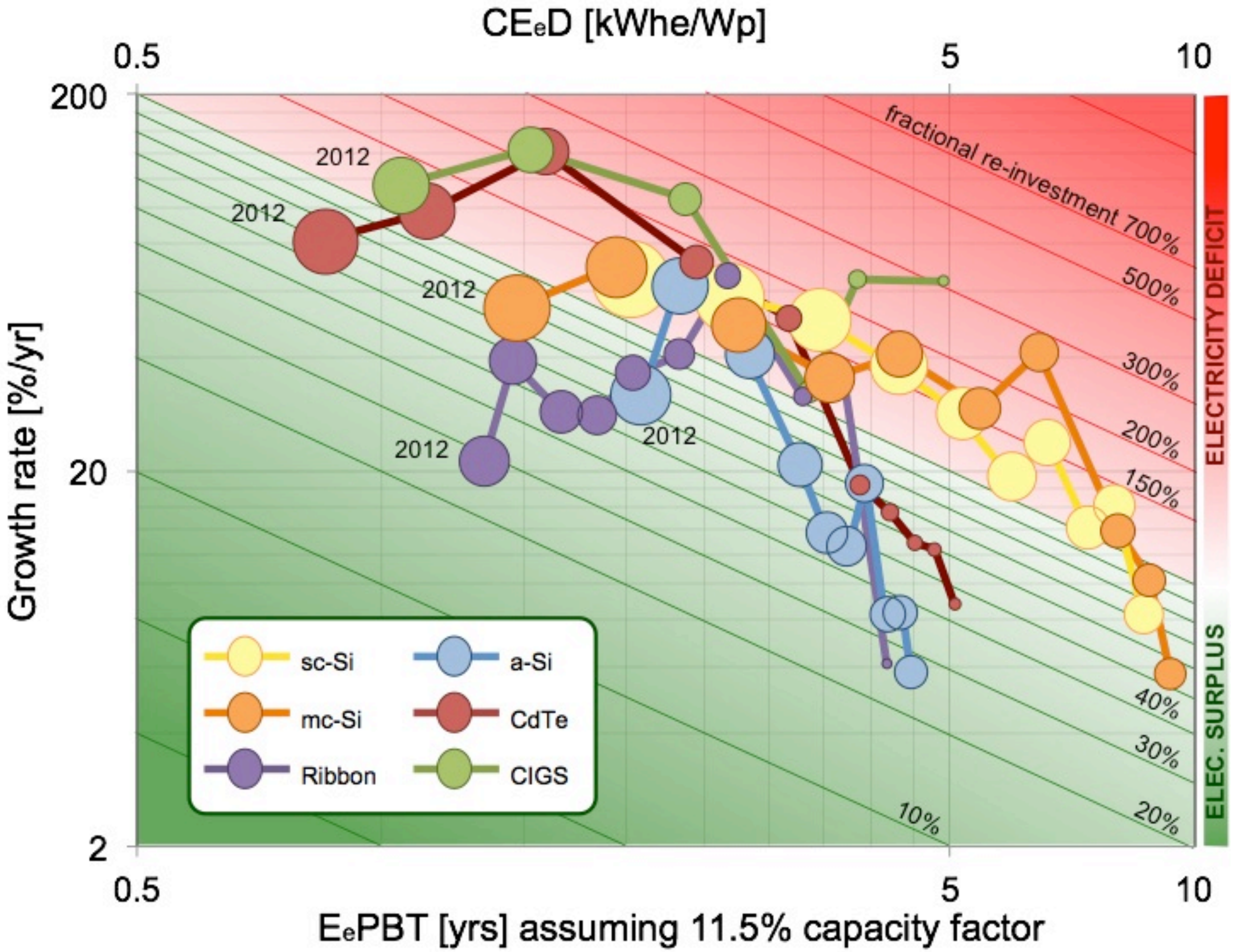
Dale & Benson (2013)

Net Energy Trajectories for CdTe PV



Dale, Barnhart & Benson (2014)

Net Energy Trajectories for all PV technologies



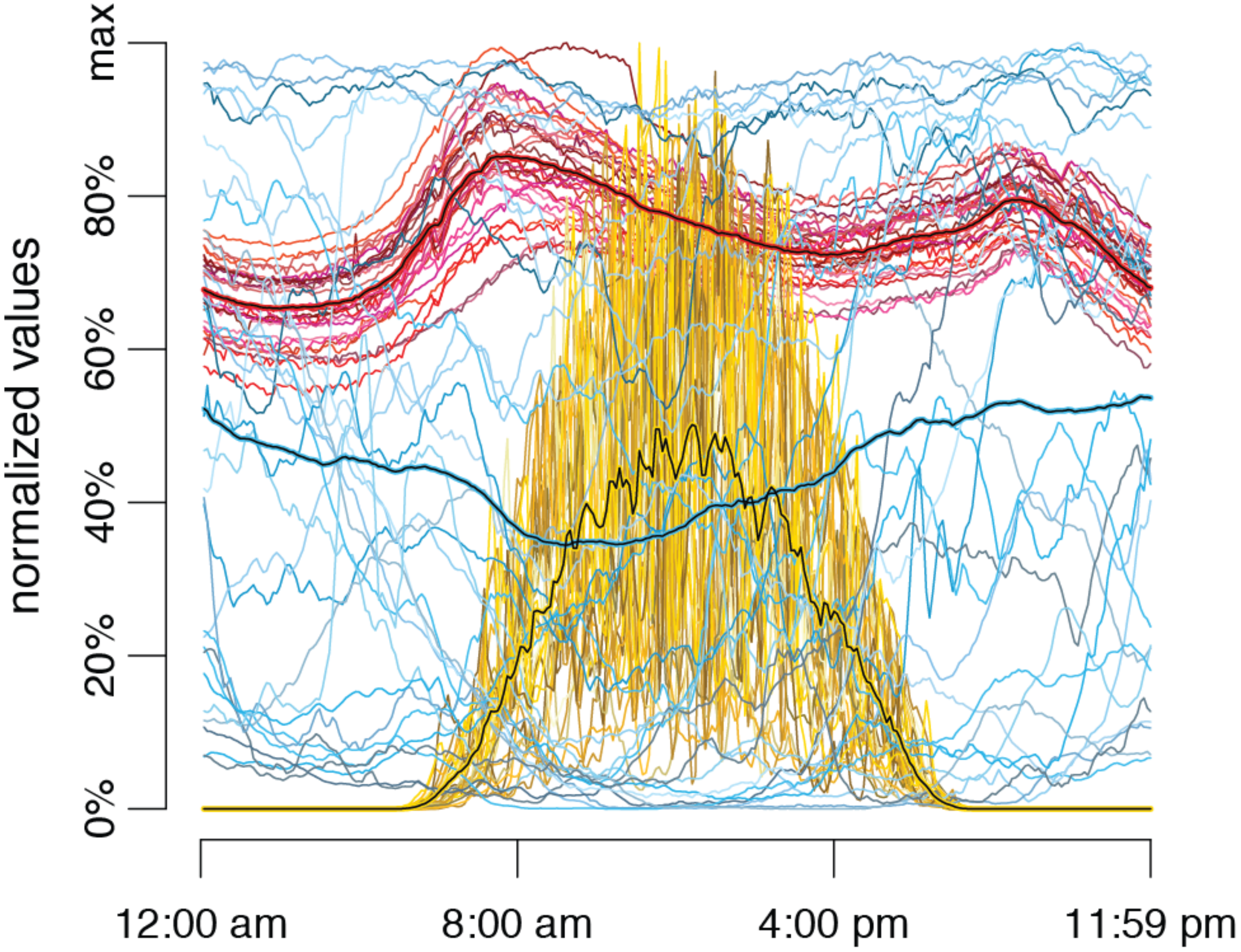
Dale, Barnhart & Benson (2014)

Lower CED technology can grow at a faster rate

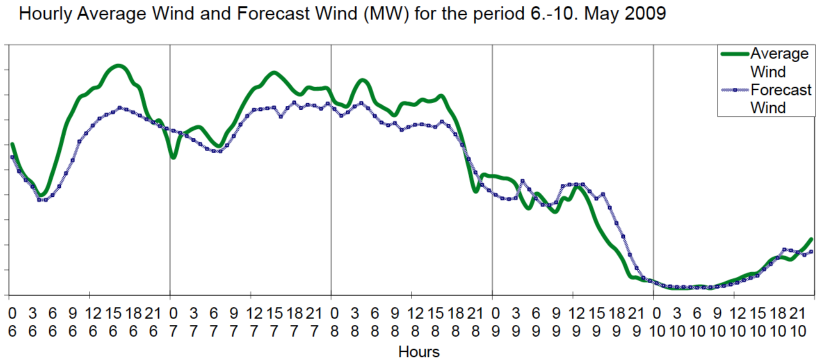
The Power Grid

CAISO Operations (Whittaker, NYT 10/25/11)

Wind Turbines and Solar PV generate variable and intermittent power



Increasing Flexibility in Power Supply and Delivery



Improved Forecasting

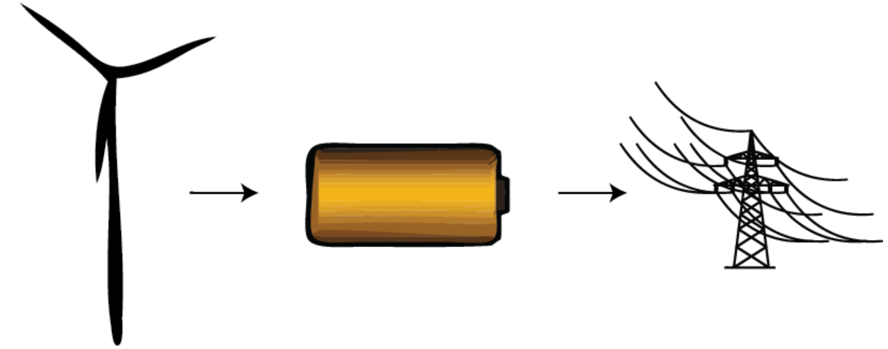
Wider Area Aggregation (Transmission)

Flexible Dispatchable Generation (Natural Gas Plants)

Energy Storage

Flexible Generation Pathways

Stored
Renewables

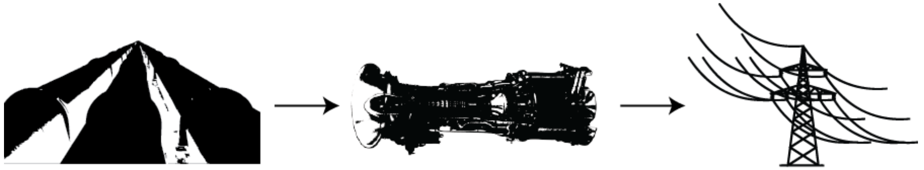


ELECTRICITY GENERATION → STORAGE → ELECTRICAL POWER GRID

Grid
Storage

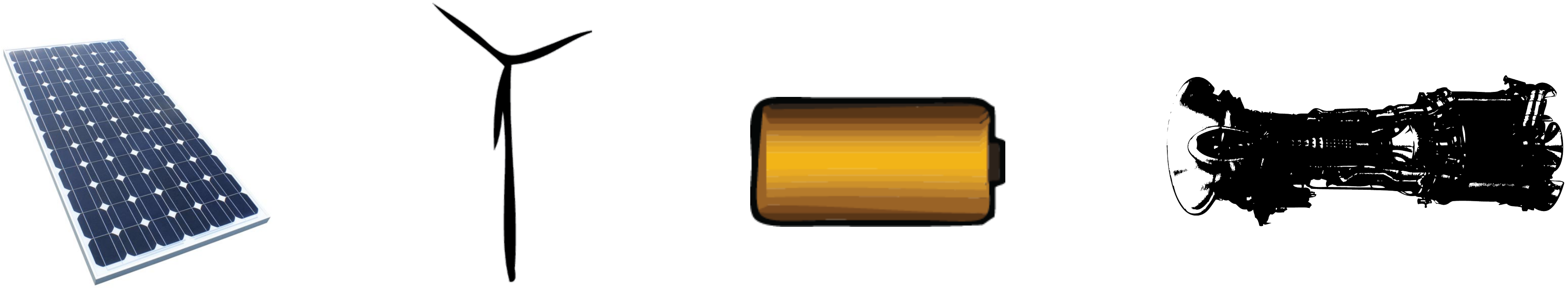
ELECTRICAL POWER GRID → STORAGE → ELECTRICAL POWER GRID

Responsive
Gas
Generation



NATURAL GAS SUPPLY → GAS COMBUSTION → ELECTRICAL POWER GRID

How does the energetic performance of stored renewables compare with energetic performance of natural gas generation?



Should We…

- store wind or curtail it?
- store solar or curtail?
- store wind or employ NGCT peaker plants?
- store solar or employ NGCT peaker plants?

- what about from a carbon emissions perspective?
- what about economic, human welfare, environmental and social justice perspectives?

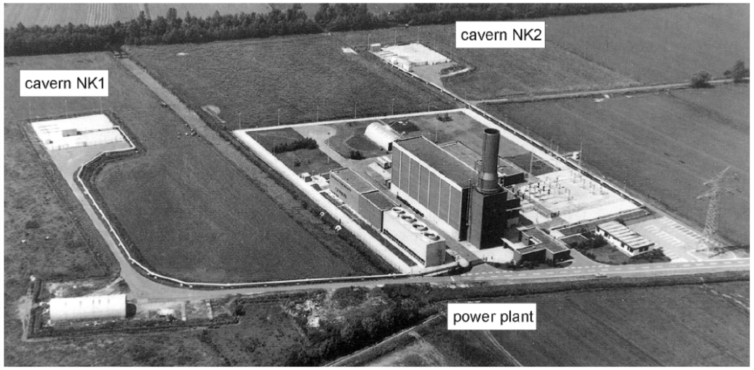
Methodology

- Developed a theoretical framework to combine the energetic costs and carbon intensities of electricity generation resources and electrical energy storage technologies.
  - Track energy expenditures and flows as well as carbon emissions for energy resources and storage technologies.
- Data were obtained from
  - Energy storage and energy generation life cycle assessment studies.
  - Data were divided into 'cradle-to-gate' and operational components. Energy expenditures and carbon emissions associated with decommissioning and recycling were not considered.
  - Data are harmonized to Cradle-to-Gate when possible but are uncertain.
- This work focused on building the theoretical framework.

Grid-Scale Storage Technologies

- safe
- inexpensive
- made from abundant materials
- high cycle-life
- high round-trip efficiency

- Lead Acid (PbA)
- Sodium Sulfur (NaS)
- Flow (ZnBr, VRB)
- Compressed air energy storage (CAES)
- Pumped hydroelectric storage (PHS)



Energy Stored on Invested

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

where

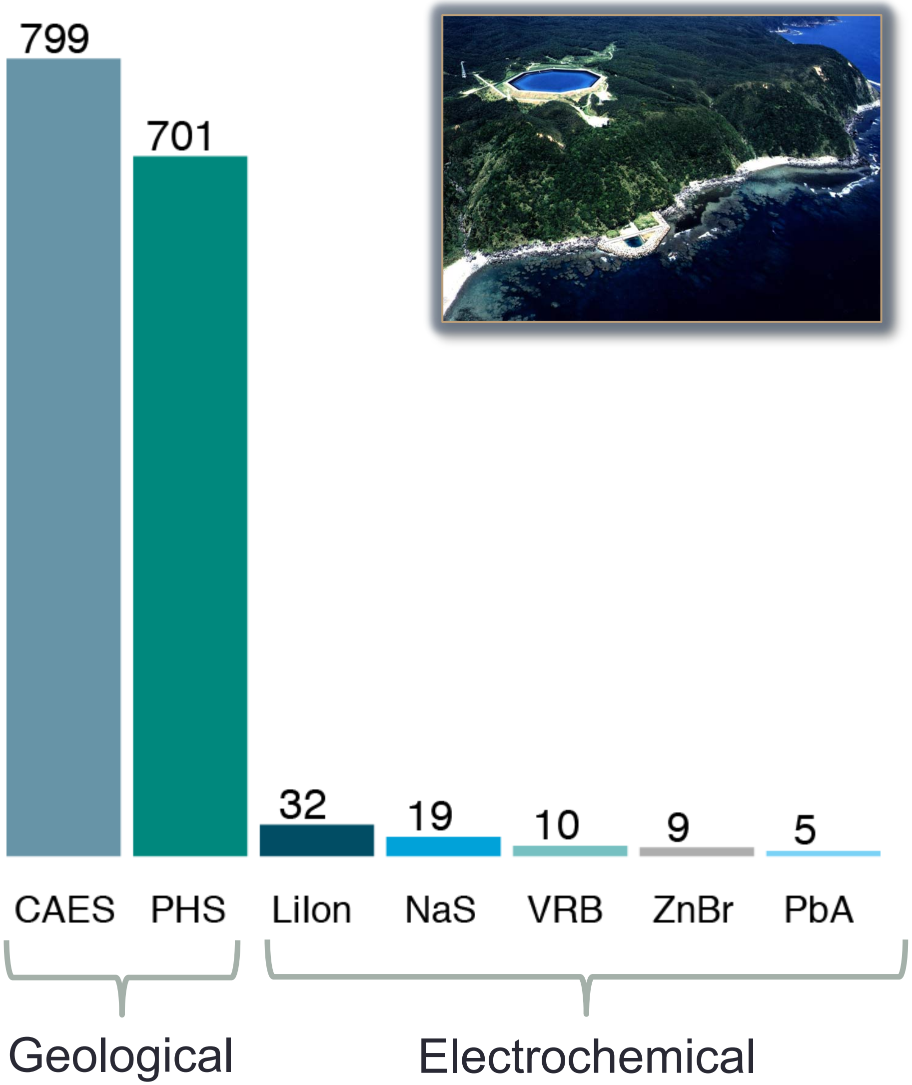
$\eta = efficiency$

$D = depth\ of\ discharge$

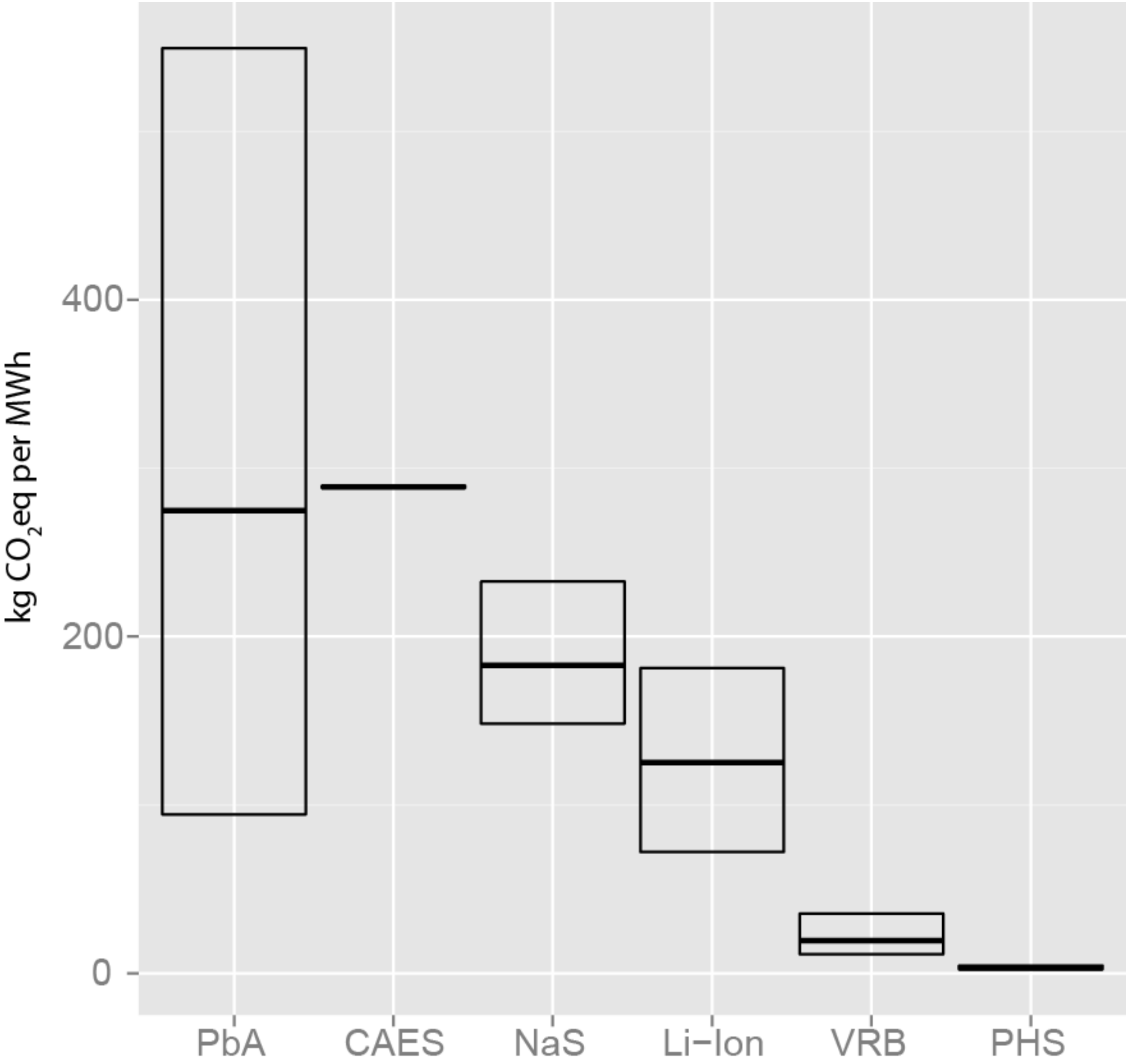
$\lambda = cycle\ life$

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

Barnhart and Benson, 2013



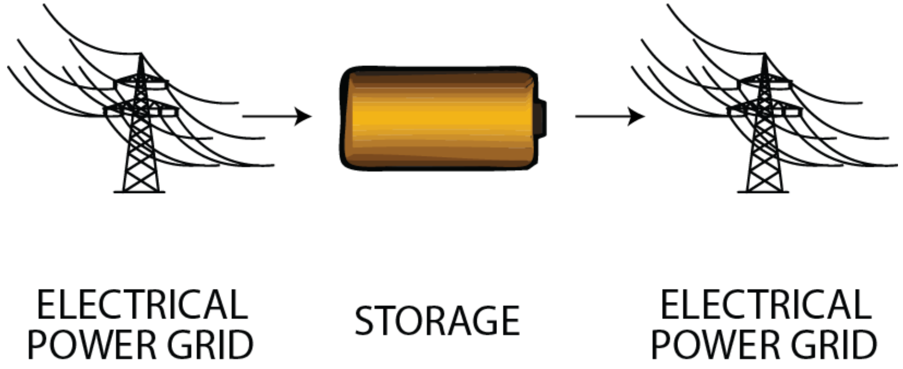
Life Cycle Storage CO_2eq Emissions



Sources:
Sullivan and Gaines, 2000
Denholm and Kulcinski, 2004
eGRID, EPA, 2009

Source Carbon Multiplier

Storage Tech	AC-AC efficiency	Source Carbon Multiplier
PbA	0.9	1.11
Li-Ion	0.9	1.11
NaS	0.75	1.33
CAES	*1.36*	0.74
PHS	0.85	1.18
VRB	0.75	1.33

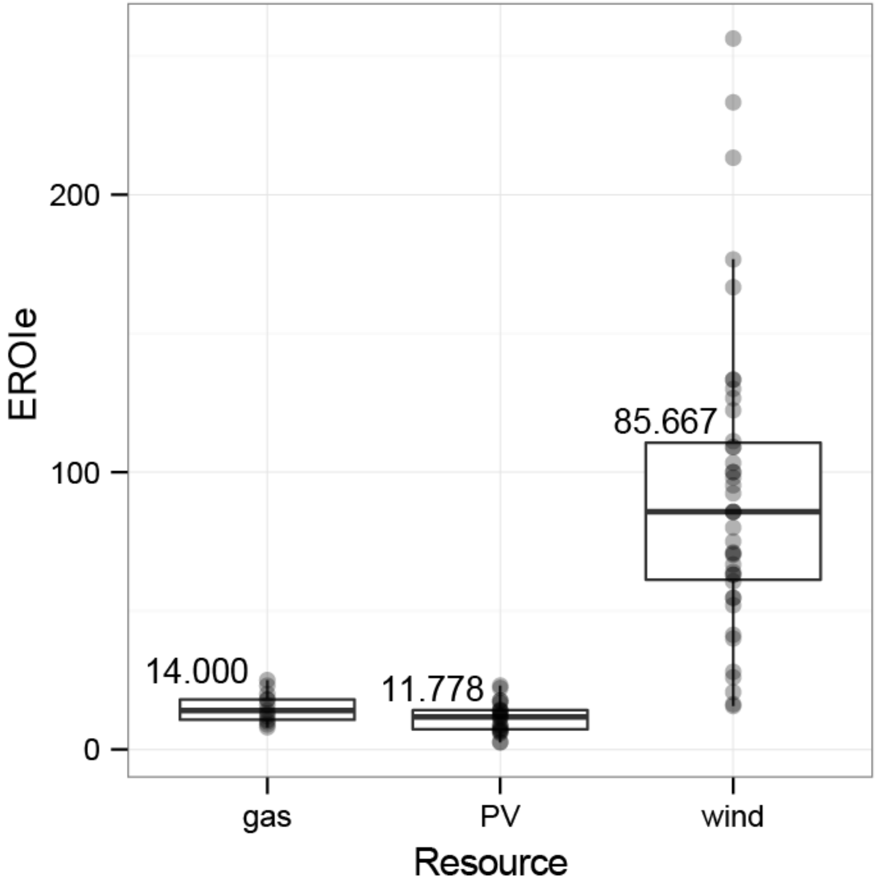


ELECTRICAL POWER GRID

STORAGE

ELECTRICAL POWER GRID

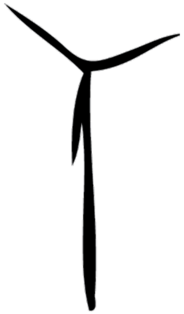
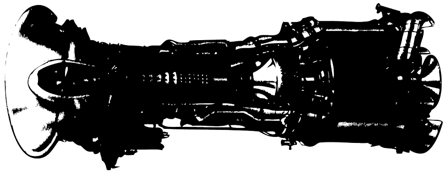
The Generation Resource Footprint
Energy return on investment (electrical)



EROIe data were obtained from numerous sources. Only post-2000 values were considered. EROI data were converted to EROIe values by energy quality correction value of 0.3 were appropriate.

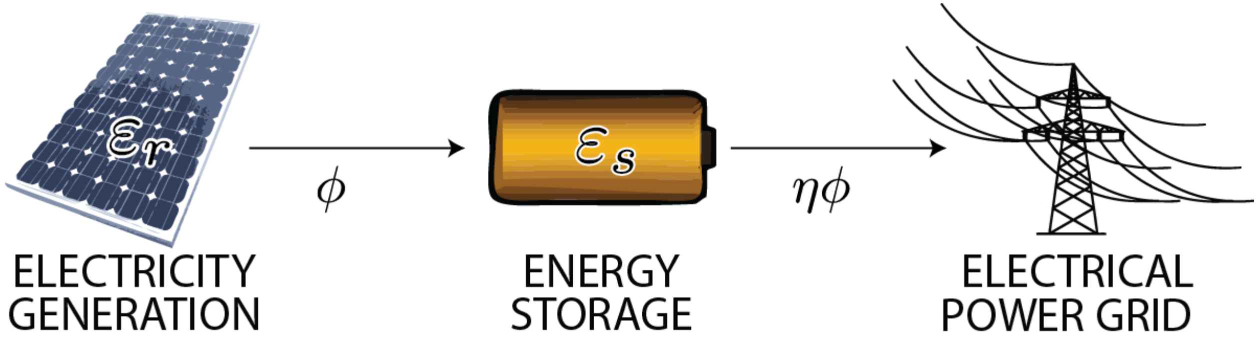
Gas: n=14 from 5 sources
PV: n=24 from 27 sources
Wind: n=42 from 4 sources
(Kubiszewski et al., 2009 was in itself a meta-analysis considering 119 turbines)

Carbon Life Cycle Assessment (CO$_2$eq)

kg CO$_2$eq/MWh	Upstream	Operational	Downstream
 39 to 49 Hsu et al., 2012	~60% - 70% • Raw Materials Extraction • Materials Production • Module/System/Plant Component Manufacture • Installation	~21% - 26% • Power Generation • System/Plant Operation • System Maintenance	~5% - 20% • Decommissioning • Disposal
 3 to 45 Dolan and Heath, 2012	86% • Raw Materials Extraction • Materials Production • Parts Manufacture • Wind/Turbine/Farm Construction	9% • Power Generation • System/Plant Operation • System Maintenance	5% • Decommissioning • Disposal
 420 to 670 O'Donoughue et al., 2014	0.1% • Raw Materials Extraction • Materials Production • System/Plant Component Manufacture	99.8% • Fuel Cycle (13%) • Combustion (87%)	0.1% • Decommissioning • Disposal

NREL LCA Harmonization Studies (2012-2014)

Flexible Electrical Energy Systems

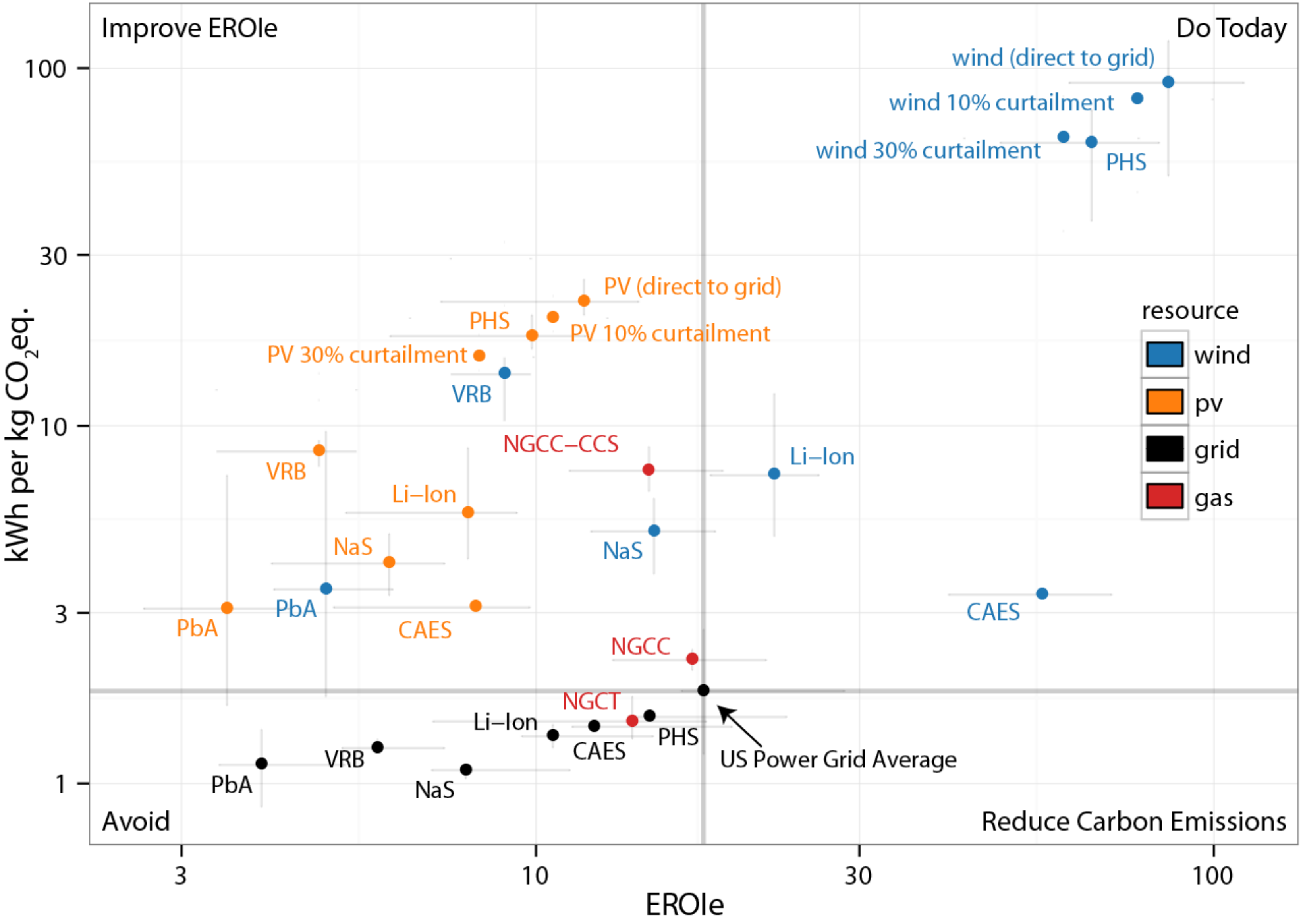


$$\text{Energy Return} = \eta\phi$$

$$\text{Energy Investment} = \varepsilon_{\text{resource}} + \varepsilon_{\text{storage}}$$

$$\text{EROI}_{\text{e}} = \frac{\eta\phi}{\varepsilon_{\text{resource}} + \varepsilon_{\text{storage}}}$$

$$GHG = \frac{GHG_{s,cap}}{\lambda D} + GHG_{s,op} + \frac{GHG_r}{\eta_s}$$


Improve EROIe
Do Today
Avoid
Reduce Carbon Emissions
kWh per kg CO₂eq.
EROIe
100
30
10
3
1
3
10
30
100
wind (direct to grid)
wind 10% curtailment
wind 30% curtailment
PHS
PV (direct to grid)
PHS
PV 10% curtailment
PV 30% curtailment
VRB
VRB
NGCC–CCS
Li–Ion
Li–Ion
NaS
NaS
PbA
PbA
CAES
CAES
NGCC
NGCT
Li–Ion
PHS
CAES
VRB
PbA
NaS
US Power Grid Average
resource
wind
pv
grid
gas

Big Ideas from NEA for grid flexibility

- Flexible power grid energy resources and technologies affect the carbon and energy intensity of the power grid in which they are deployed.
- The flexible technology cannot be considered alone. The energy resource predominates energy and carbon intensities
- Technological solutions not only need to be affordable, they need to be aligned with the principles of environmental stewardship that guided policy makers to spur the use of renewable energy resources.

Implications from NEA for grid flexibility

- With today's flexible grid technologies we should…
  - Store wind power with Li-Ion and PHS
  - Use efficient high power capacity gas turbines
  - Promote swing capabilities of NGCC-CCS
  - Avoid storing grid power
  - Avoid older inefficient low capacity gas turbines
  - Avoid conventional PbA Storage
- R&D focus for tomorrow's technologies should…
  - Focus on improving battery cycle life and efficiency
  - NGCC-CCS is a low carbon high efficiency technology, technology for storage, capture and variable generation is needed.

Net Energy Analysis and Energy Policy

COMMENTARY:

A better currency for investing in a sustainable future

Michael Carbajales-Dale, Charles J. Barnhart, Adam R. Brandt and Sally M. Benson

Net energy analysis should be a critical energy policy tool. We identify five critical themes for realizing a low-carbon, sustainable energy future and highlight the key perspective that net energy analysis provides.

Most energy planning efforts consider primary energy production by countries, industries, companies or projects. This focus on gross production of primary energy does not reflect the reality that some fraction of this gross production must be invested in sustaining and growing the energy system itself, as well as in processing and transforming energy to provide the useful energy services we desire. Put simply, we need to 'spend' energy to 'make' energy. If the fraction of energy used by the energy system is constant, tracking and forecasting the evolution of the energy system without considering the energy reinvestment may be adequate. However, new energy resources, new energy conversion and storage devices, and new global supply chains will affect the fraction of energy reinvestment required to support societal energy demands. Given the large changes required in coming

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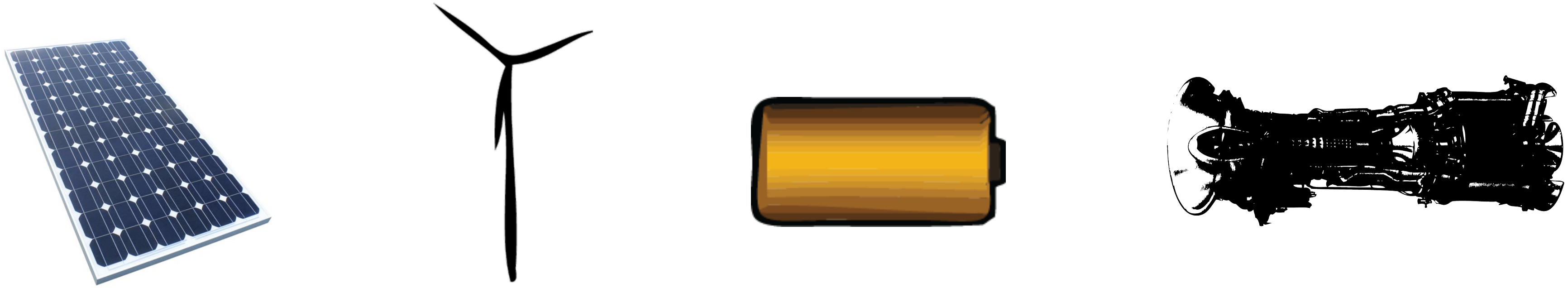
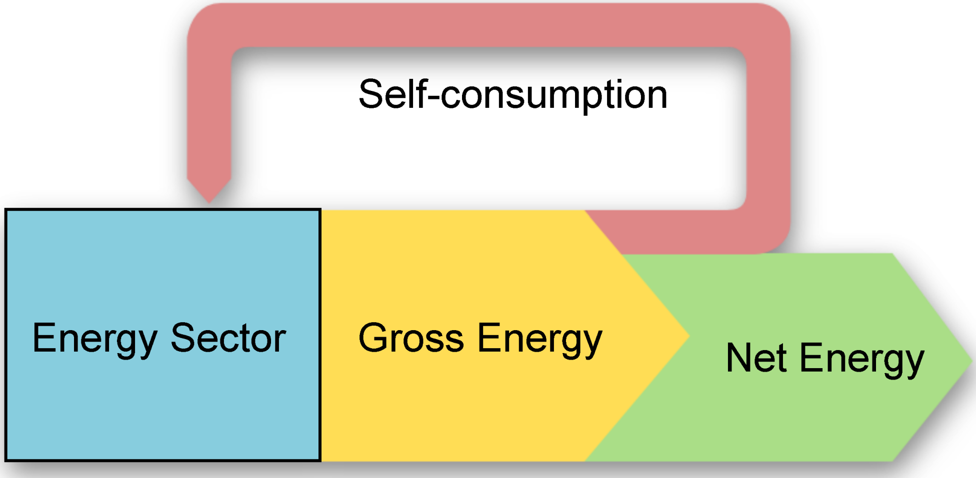
1) Valuing Energy Resources



2) Net Energy Fuels the Economy

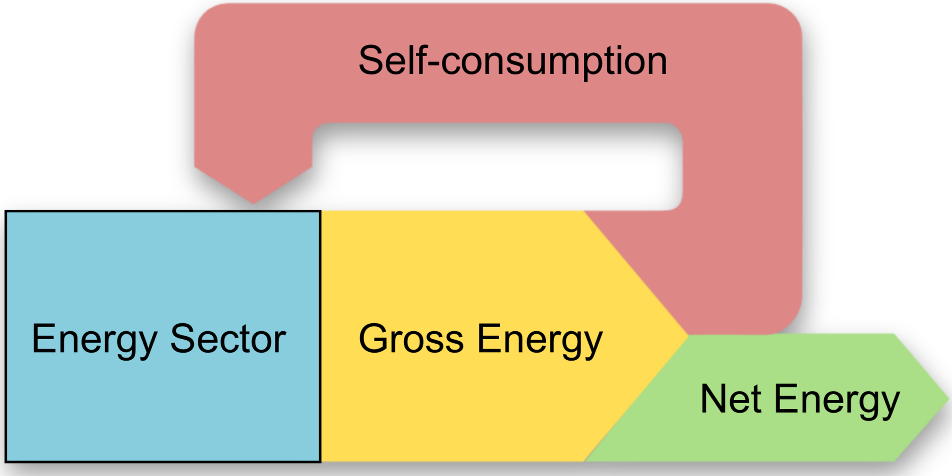


Self-consumption

Energy Sector

Gross Energy

Net Energy



Self-consumption

Energy Sector

Gross Energy

Net Energy

3) Assessing Environmental Impacts

NER, EROI = 5.25 GJ/GJ

Brandt A.R., J. Englander and S. Bharadwaj (2013). The energy efficiency of oil sands extraction: Energy return ratios from 1970 to 2010. *Energy*

4) Early Technology Appraisal

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

where

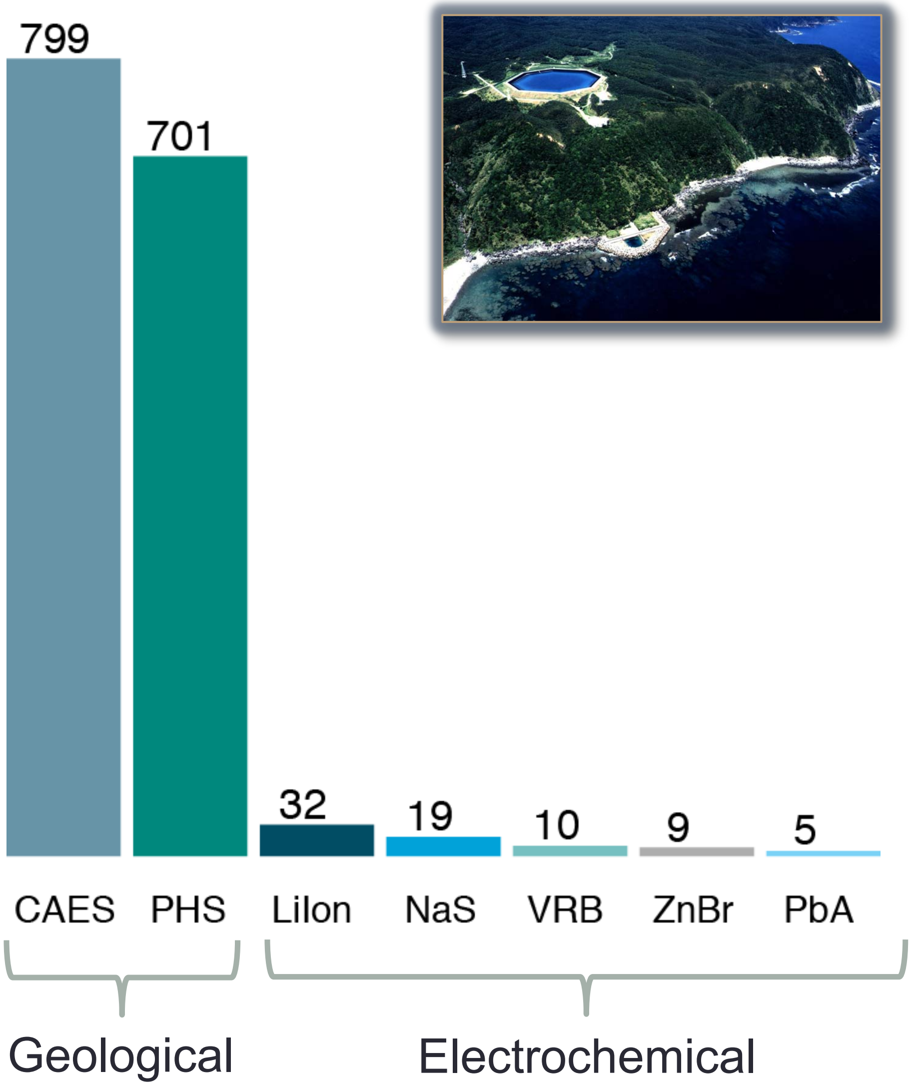
η = efficiency

D = depth of discharge

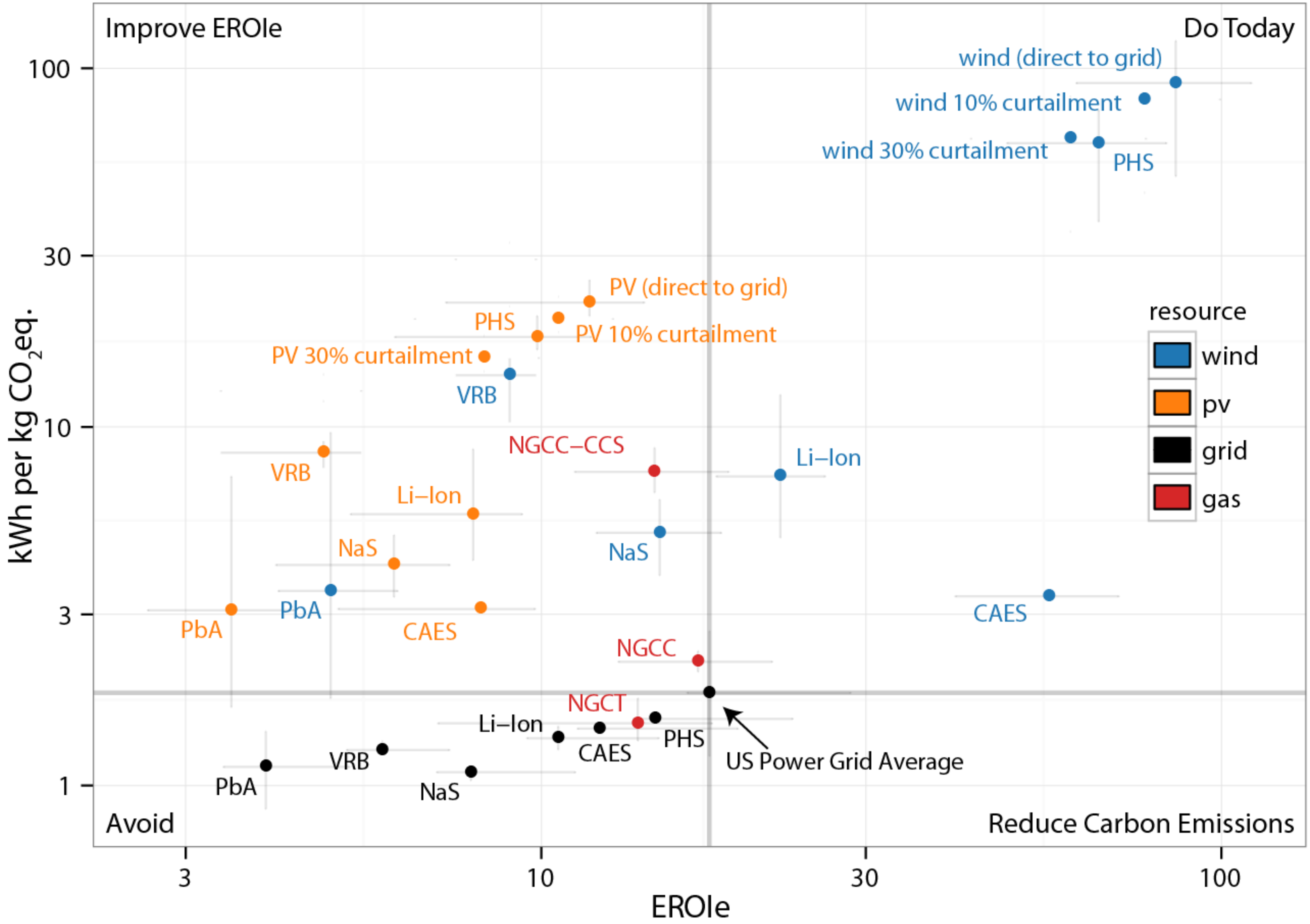
λ = cycle life

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

Barnhart and Benson, 2013



5) Managing the energy transition



Why is net NEA Important?

Photo: Karim Nafatni

End of Tutorial

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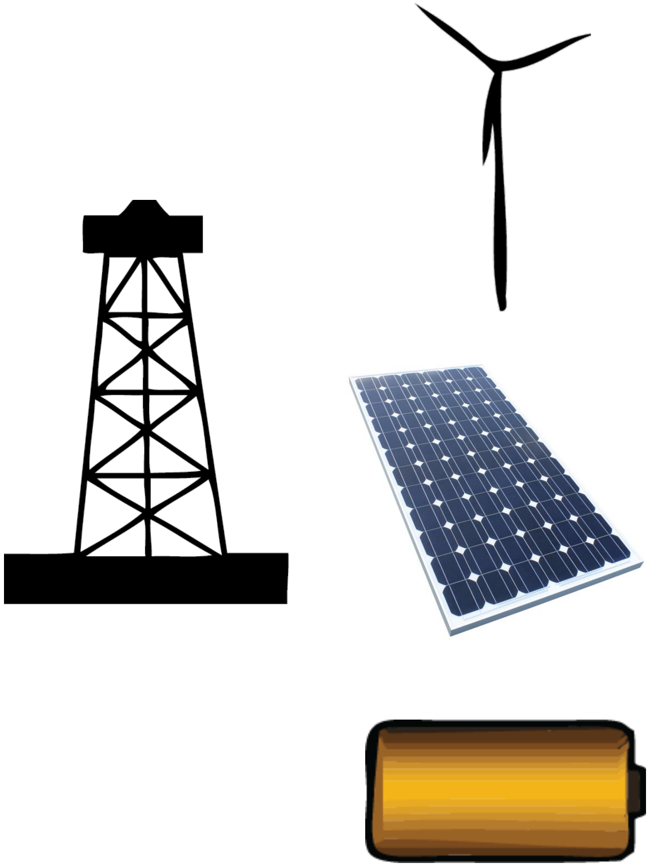
Challenges Facing an Energy Transition

- 1) Scalability and Timing
- 2) Commercialization
- 3) Substitutability
- 4) Material Input Requirements
- 5) Intermittency
- 6) Energy Density
- 7) Water
- 8) Economics
- 9) Energetic Input Requirements



Nine Challenges of Alternative Energy, David Fridley, 2010 PCI