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 Paleo diet
Think, Pair, Share ---Then **Poll**

On average, who ‘consumes’ more energy per day?

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**)

\[
\frac{\text{energy}}{\text{day}} = \frac{\text{distance}}{\text{day}} \times \frac{\text{energy}}{\text{fuel}}
\]

\[
\frac{\text{energy}}{\text{day}} = \frac{44 \, \text{km}}{\text{day}} \times \frac{10 \, \text{kWh}}{4.7 \, \text{km per liter}} = 94 \, \text{kWh per day}
\]
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 (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

Net Energy Flow [J/yr]

INPUTS

Construction

Net Energy Production

Operation & Maintenance (O&M)

Decommission

OUTPUTS

$t_0$ $t_1$ $t_2$ $t_3$ $t$ (yrs)

Energy Production

$E_c$

$E_{op}$

$E_d$

$E_g$
Energy Return on Investment (EROI)

\[
EROI = E_c + E_{op} + E_{d} + E_g
\]
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

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

Data from White & Kulcinski (2000).

\[ E_c = 147 \text{ TJ} \quad E_{op} = 83 \text{ PJ} \quad E_d = 20 \text{ TJ} \]
Example 1: Coal

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

\[ E_c = 147 \, \text{TJ} \quad E_{op} = 83 \, \text{PJ} \quad E_d = 20 \, \text{TJ} \]

Data from White & Kulcinski (2000).
Example 1: Coal

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.

E_C = 147 TJ  E_op = 83 PJ  E_d = 20 TJ

EROI = 11  EPBT = 3.5 yrs

Data from White & Kulcinski (2000).
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

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**

- Polysilicon: 12%
- Ingot: 6%
- Wafer: 9%
- Solar cell: 14%
- Solar panel: 25%
- System: 34%

**ENERGY COST**

- Polysilicon: 21%
- Ingot & Wafer: 36%
- Solar cell: 11%
- Solar panel: 19%
- System: 13%

---

Energy flows industry growing at 100% per year

EPBT = 2 yrs
Energy flows industry growing at 100% per year

EPBT = 2 yrs
Energy flows industry growing at 100% per year

$\text{EPBT} = 2$ yrs

GCEP Symposium 2014 -- Net Energy Analysis Tutorial -- charles.barnhart@wwu.edu
Energy flows industry growing at 100% per year

EPBT = 2 yrs
Energy flows industry growing at 100% per year

EPBT = 2 yrs

YEAR 5
Energy flows industry growing at 100% per year

EPBT = 2 yrs

Industry operates at energy ‘deficit’
Growing industry requires 'start-up capital'.
Net energy yield, growth and energy cost

Energy Cost \([\text{kWh}_e/\text{W}_p]\]

- **BREAKEVEN THRESHOLD**
- **ENERGY SURPLUS**
- **ENERGY DEFICIT**

- **NEGATIVE NET ENERGY YIELD**
- Fractional re-investment 20%
- Net energy yield, growth and energy cost

**GCEP Symposium 2014 -- Net Energy Analysis Tutorial --**
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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

Global PV capacity factor

UN
Mean = 12.8
Median = 12.5

EIA
Mean = 12.2
Median = 11.5

MEDIAN ~ 11.5 %

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

CED [kWh(e)/W]

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

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

Flexible Dispatchable Generation (Natural Gas Plants)

Energy Storage

Wider Area Aggregation (Transmission)
Flexible Generation Pathways

Stored Renewables

Grid Storage

Responsive Gas Generation
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
\[ \eta = \text{efficiency} \]
\[ D = \text{depth of discharge} \]
\[ \lambda = \text{cycle life} \]

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

Barnhart and Benson, 2013
Life Cycle Storage CO₂eq Emissions

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

<table>
<thead>
<tr>
<th>Storage Tech</th>
<th>AC-AC efficiency</th>
<th>Source Carbon Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbA</td>
<td>0.9</td>
<td>1.11</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>0.9</td>
<td>1.11</td>
</tr>
<tr>
<td>NaS</td>
<td>0.75</td>
<td>1.33</td>
</tr>
<tr>
<td>CAES</td>
<td>1.36</td>
<td>0.74</td>
</tr>
<tr>
<td>PHS</td>
<td>0.85</td>
<td>1.18</td>
</tr>
<tr>
<td>VRB</td>
<td>0.75</td>
<td>1.33</td>
</tr>
</tbody>
</table>
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\textsubscript{2}eq)

<table>
<thead>
<tr>
<th>Stage</th>
<th>CO\textsubscript{2}eq/MWh</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td>~60% - 70%</td>
<td>Raw Materials Extraction, Materials Production, Module/System/Plant Component Manufacture, Installation</td>
</tr>
<tr>
<td>Operational</td>
<td>~21% - 26%</td>
<td>Power Generation, System/Plant Operation, System Maintenance</td>
</tr>
<tr>
<td>Downstream</td>
<td>~5% - 20%</td>
<td>Decommissioning, Disposal</td>
</tr>
</tbody>
</table>

- **Upstream CO\textsubscript{2}eq**: 39 to 49 kg/MWh (Hsu et al., 2012)
- **Operational CO\textsubscript{2}eq**: 86% (Dolan and Heath, 2012)
- **Downstream CO\textsubscript{2}eq**: 0.1% (O’Donoughue et al., 2014)

NREL LCA Harmonization Studies (2012-2014)

- **Total CO\textsubscript{2}eq**: 420 to 670 kg/MWh (O’Donoughue et al., 2014)
- **Power Generation CO\textsubscript{2}eq**: 99.8% (NREL LCA Harmonization Studies)
- **Decommissioning CO\textsubscript{2}eq**: 0.1% (NREL LCA Harmonization Studies)
Flexible Electrical Energy Systems

Energy Return = $\eta \phi$

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

$EROI_e = \frac{\eta \phi}{\varepsilon_{\text{resource}} + \varepsilon_{\text{storage}}}$

$GHG = \frac{G\text{HG}_{s,\text{cap}}}{\lambda D} + G\text{HG}_{s,\text{op}} + \frac{G\text{HG}_r}{\eta_s}$
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...
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

4) Early Technology Appraisal

\[ ESOI = \frac{\eta D \lambda}{CTG} \]

where
\( \eta = \text{efficiency} \)
\( D = \text{depth of discharge} \)
\( \lambda = \text{cycle life} \)

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

Barnhart and Benson, 2013
5) Managing the energy transition

![Graph showing various energy resources and their impact on EROI and carbon emissions.](image)
Why is net NEA Important?

Photo: Karim Nafatni
End of Tutorial

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- abrandt@stanford.edu (Adam Brandt)
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