Energy Systems Analysis 101

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...and many others!

GCEP Research Symposium

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Some things we’ll discuss...

Which produces more emissions, combustion of traditional biomass or fossil fuels?

How much energy do we spend to get a kWh of coal-fired vs. photovoltaic electricity?

Which are better for the environment, battery vehicles or fuel cell vehicles?
What is Energy Systems Analysis?

*There are different “flavors” of energy systems analysis.*
What is Energy Systems Analysis?

- Compiles information about energy infrastructure
- Compares different technology alternatives that provide the same energy services
- Evaluates the impact of specific technical advances on a larger energy infrastructure
Who does Energy Systems Analysis?
Outline: Types of Energy Systems Analysis

- Compiles information about energy stocks and flows
Toolbox

• Statistical data
U.S. energy use

Estimated U.S. Energy Use in 2014: ~98.3 Quads

Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant “heat rate.” The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527
IEA flow charts

http://www.iea.org/sankey/
National energy statistics: India
National energy statistics: U.S.
GCEP flow charts: Exergy ("useful energy")

What is exergy?

• The useful part of energy

• The maximum amount of work that can be extracted from a system containing a resource which is out of equilibrium with an environment
GCEP flow charts: Exergy ("useful energy")

Hermann, W., Energy, 2006, 31, 1349
GCEP flow charts: Exergy ("useful energy")

Sassoon, R. et al., MRS Symposium Proceedings, 2009, 1170, 29
Hermann, W., Energy, 2006, 31, 1349
Carbon flows (U.S.)

About 40% of U.S. carbon emissions come from the electricity sector.
Carbon flows (Global)

Worldwide, almost as much carbon emissions come from agriculture and forestry as from fossil fuels

Sassoon, R. et al., MRS Symposium Proceedings, 2009, 1170, 29
Hermann, W., Energy, 2006, 31, 1349
Carbon flows (Global)

Sassoon, R. et al., MRS Symposium Proceedings, 2009, 1170, 29
Hermann, W., Energy, 2006, 31, 1349
Outline: Types of Energy Systems Analysis

- Compiles information about energy stocks and flows
- Compares different technology alternatives that provide the same energy services
Toolbox

- Statistical data
- Net energy analysis
Net energy analysis: Tracking energy flows

Energy costs of energy services: A familiar example
Energy costs of energy services: Society as a whole
The net energy analysis concept

Net energy analysis seeks to quantify the direct and indirect energy required to produce a unit of energy.

- **Direct energy**: Fuel or electricity used directly in the extraction or generation of a unit of energy.

- **Indirect energy**: Energy used elsewhere in the economy to produce goods and services used in energy extraction and production.

Energy Return on Investment

\[ \text{EROI} = \frac{\sum E_{\text{dispatched}}}{E_{\text{embodied}}} \]
Processing stage analysis: Oil refining

US average oil refinery

Crude quality: 30.44 API, 1.41% sulfur
Crude energy density: 6.21 GJ/bbl
Total crude inputs = 37.2 EJ, outputs = 35.2 EJ

EROI of hydrocarbon fuels

Processing stage analysis: Conc. PV generation

PV electricity has a moderate EROI (~4)

EROI of renewable generation

**Energy Returned On Investment**
relative to the breakeven value of 1

- without energy storage
- with energy storage
- *economically-viable threshold*

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Weissbach *et al.*, Energy, 2013, **52**, 210
EROI of renewable generation

EROI of renewable generation

- Wind has higher EROI than solar
- Wide variation in EROI estimates

Energy flows in a growing industry

Growing industry requires ‘start-up capital’

PV industry is growing rapidly

Average growth 2000-2010
40% per year

~ 90% crystalline silicon

Net energy yield, growth and energy cost

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**Figure Description**

The figure illustrates the relationship between energy cost, growth rate, and energy payback time (EPBT) for various net energy yield scenarios. The axes represent:

- **Energy Cost** [kWh_e/W_p]
- **Growth Rate** [%/yr]
- **EPBT** [yrs]

The graph visually distinguishes between different yield scenarios:

- **Energy Surplus**
- **Energy Deficit**
- **Energy Cost Deficit**

Key indicators include:

- **Fractional Re-investment** (20%)
- **Break-even Threshold**
- **Negative Net Energy Yield**
- **Positive Net Energy Yield**

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**References**

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]
Net Energy Trajectories for CdTe PV

Lower CED technology can grow at a faster rate.

*PV industry is now a net energy producer*

Energy Return on Investment

\[ \text{EROI} = \frac{\sum E_{\text{dispatched}}}{E_{\text{embodied}}} \]
Energy Return on Investment

\[ \text{EROI} = \frac{\sum E_{\text{dispatched}}}{E_{\text{embodied}}} \]

\[ \text{ESOI}_{e} = \frac{\sum E_{\text{dispatched}}}{E_{\text{embodied}}} \]

Brandt et al., Energy, 2013, 62, 235-247
Pellow et al., Energy Environ. Sci., 2015, 8, 1938
Barnhart and Benson, Energy Environ. Sci., 2013, 6, 2804-2810
Net energy analysis of energy storage technologies

Pellow et al., Energy Environ. Sci., 2015, 8, 1938
Options for storage to firm renewables

**Diagram:**
- Generation
  - [EROI]_{gen}
  - \(1 - \phi\)
- Storage
  - [EROI]_{grid}
  - [EROI]_{curt}
  - \(\phi\)
  - ESOL, \(\eta_{st}\)
- Curtailment

**Equation:**
\[
\text{Generation [EROI]}_{gen} = 1 - \phi
\]
\[
\text{Storage [EROI]}_{grid} = \phi
\]

**Graph:**
- Wind (\(\text{[EROI]}_{gen} = 86\))
- Fossil energy

**References:**
Options for storage to firm renewables

A storage technology with low efficiency but high ESOI may be a good choice

Pellow et al., *Energy Environ. Sci.*, 2015, 8, 1938
Toolbox

- Statistical data
- Net energy analysis
- Life cycle assessment
LCA encompasses all life-cycle stages
A standardized protocol

“compilation and evaluation of the

• inputs,
• outputs, and
• potential environmental impacts

of a product system through its life cycle.”

(ISO 14040)
LCA: Valuable but imperfect

- Different LCA studies of the same topic may have **different system boundaries**

- **Results vary**: Similarly scoped LCA studies may arrive at different results

- Be a critical consumer: Compare **apples to apples**
Battery vs. fuel cell cars: What’s cleaner?
BEVs vs. ICVs: Global warming potential

BEV’s have slightly lower emissions than ICV’s – with non-coal electricity

Hawkins et al., J. Industrial Ecology, 2013, 17, 53
BEVs vs. ICVs: Human toxicity

BEV’s have significantly higher health impacts

Hawkins et al., J. Industrial Ecology, 2013, 17, 53
Battery vs. fuel cell cars: What’s cleaner?
Hydrogen-powered vehicles may have higher emissions than fossil-fueled – depending on the hydrogen source

Bauer et al., Applied Energy, 2015 (10.1016/j.apenergy.2015.01.019)
What about network benefits of BEVs/FCVs?
Integrated emissions-economic model

• Inputs include:
  • Real-world energy demands
  • Real-world solar resource
  • Consensus technology cost forecasts
  • Forecast prices for electricity, natural gas

• Linear optimization routine

• Model selects the cost-optimal mix of energy infrastructure to meet community’s energy demand

Felgenhauer, Pellow et al., 2015 (submitted)
Cost and emissions projections for vehicle scenarios

Felgenhauer, Pellow et al., 2015 (submitted)
Implied emissions abatement cost for vehicle scenarios

Felgenhauer, Pellow et al., 2015 (submitted)
BEVs reduce emissions more cost-effectively than FCVs in this scenario

Felgenhauer, Pellow et al., 2015 (submitted)
Outline: Types of Energy Systems Analysis

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Solar fuels energy analysis
Solar hydrogen: A prototype device

Zhai et al., Energy Environ. Sci., 2013, 6, 2380
Solar hydrogen: Requirements for energy payback

Zhai et al., Energy Environ. Sci., 2013, 6, 2380
Solar hydrogen: Requirements for energy payback

If this solar hydrogen generator is 5% efficient, it must last for 5 years in order to repay its energy cost.

Zhai et al., Energy Environ. Sci., 2013, 6, 2380
Recycling CO$_2$ to fuels
Catalyst requirements for emissions benefit

\[
\frac{\text{Energy intensity of CO}_2 \text{ capture}}{\text{Faradaic efficiency}} - \frac{\text{deCO}_2\text{rr}}{\text{conv}} \quad \frac{\text{[CO}_2\text{-eq]}_{\text{FU}_{\text{deCO}_2\text{rr}}} - \text{[CO}_2\text{-eq]}_{\text{FU}_{\text{conv}}}}
\]
Catalyst requirements for emissions benefit

- **Emissions-favorable CO$_2$-to-methanol may be achievable**
- **Requires advances in both CO$_2$ capture and conversion**
Conclusion
Summary: Toolkit

- **Statistical compilations** illustrate the significance of an individual energy service in a national/global context.

- **Net energy analysis** evaluates a technology’s useful output to the economy (excluding self-consumption).

- **Life cycle assessment** includes all life cycle stages in evaluating a product’s impact.
Summary: Examples of insights

Worldwide, fossil fuels contribute slightly more emissions than biomass

*Wind power* has a higher EROI than photovoltaic power

Battery vehicles have slightly lower life-cycle emissions than gasoline, with non-coal electricity

Fuel cell vehicles have no emissions advantage over gasoline when using hydrogen from methane

Current solar-to-hydrogen prototypes must have a ten-year lifetime to achieve energy payback
Thank you!

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