Lifecycle assessment and net energy analysis: birds of a feather or uneasy bedfellows?

…or Apples to apples: why net energy analysts community needs to adopt the LCA framework

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Abstract

Lifecycle assessment (LCA) and net energy analysis (NEA) are complementary approaches with a common historical basis but different underlying motivations and methodologies. As LCA practitioners move more and more beyond the bounds of attributional to consequential LCA the methodological concerns of NEA become more and more appropriate. As such, it is important to understand the large overlaps in method, but also the important distinctions between the two frameworks.

The hope is that NEA practitioners will appreciate more of the common elements between NEA and LCA adopt more of the methodological rigor of LCA and that practitioners of LCA will understand more of the underlying differences between the two frameworks and see insights and opportunities for developing consequential LCA.
Overview

• Historical development
• Goal (motivation and aim)
• Scope (system boundary & assumptions)
  – Functional unit
  – Project vs. industry scale
• NEA to-do list
1960
Smith
New Zealand Journal of Agricultural Research, 3(5), 745-763

1969
Coca-cola
Analysis of energy required for aluminum, glass and plastic packaging

1970
Hunt & Cross
Resource and Environmental Profile Analysis (REPA) of Plastics and Competitive Materials

1972
Herendeen
Energy IO matrix for the US

1974
Public Law 93.577
Requires NEA for all prospective energy technologies

1974
CERI Report

1975
NSF/Stanford Workshop

1974
IFIAS Workshop

1978
Bullard et al.
Handbook for combining process and input-output (IO) methods

1984
Cleveland et al.
Energy and the US economy, Science, 225(4665), 890-897

1986
Hall et al.
Energy and resource quality: the ecology of the economic process

1984
Coca-cola
Analysis of energy required for aluminum, glass and plastic packaging

1991
Fava et al.
A Technical Framework for Life-Cycle Assessments, SETAC Workshop Report

1993
Consoli et al.
Guidelines for life-cycle assessment, SETAC-Europe

1995
Lave
Using IO analysis to estimate economy-wide discharges, ES&T, 29(9), 420A-426A

1997-1998
ISO 14040, 14042, & 14043
Environmental management – life cycle assessment

1999
Suh
Input-output and hybrid LCA
International Journal of LCA, 8(5), 257-257.

2000
2001
2002
Heijungs & Suh
The computational structure of life cycle assessment, Springer

2006
ISO 14040 & 14044
Environmental management – life cycle assessment – requirements and guidelines

2006
Farrell et al.
Net energy of ethanol
Science, 311(5760), 506-508

2009
Consoli et al.
Guidelines for life cycle assessment, SETAC-Europe

2011
Murphy et al.
A preliminary protocol for determining the EROI of fuels, Sustainability, 3(10), 1888-1907
Overall steps in LCA

Life cycle assessment framework

- Goal and scope definition
- Inventory analysis (LCI)
- Impact assessment (LCIA)
- Interpretation

- Based on ISO 14044: Standards for life cycle assessment
Overall steps in LCA

According to ISO, goal definition shall “unambiguously state the intended application, the reason for carrying out the study and the intended audience”

Scope definition defines LCA purpose expected product, boundary conditions, functional unit and assumptions

- Based on ISO 14044: Standards for life cycle assessment

**Life cycle assessment framework**

- **Goal and scope definition**
- **Inventory analysis (LCI)**
- **Impact assessment (LCIA)**
- **Interpretation**
# Target audience and goal - LCA

<table>
<thead>
<tr>
<th>Type: LCA</th>
<th>Producer and User</th>
<th>Life cycle thinking</th>
<th>Stand-alone (descriptive)</th>
<th>Accounting (comparative &amp; retrospective)</th>
<th>Change-oriented (comparative &amp; prospective)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy makers</td>
<td>•Development of policies</td>
<td>•Producer take back schemes</td>
<td>•Procurement •Eco-labeling criteria</td>
<td>•Development of policies</td>
<td></td>
</tr>
<tr>
<td>Industry</td>
<td>•Supply chain management •Product development •Buildings</td>
<td>•Find “hot spots” •Product declarations</td>
<td>•Purchasing •Market communication •Methodological standards</td>
<td>•Product development •Buildings •Process choices &amp; optimization</td>
<td></td>
</tr>
<tr>
<td>NGOs</td>
<td>•Campaign ideas</td>
<td>•Evaluation of strategies</td>
<td>•Eco-labeling criteria</td>
<td>•Evaluation of strategies</td>
<td></td>
</tr>
<tr>
<td>Consumers</td>
<td>•Life style choices</td>
<td></td>
<td></td>
<td>•Product choices</td>
<td></td>
</tr>
</tbody>
</table>
Goals for NEA

A. descriptive assessment of the viability of a particular technology (e.g., solar satellite);
B. comparative assessment of alternative energy technologies;
C. calculation of the (minimum) EROI to support an industrial society, or alternatively assessing the feasibility of some technology to (single-handedly) support an industrial society

AND
D. calculation of net energy metrics for industry (e.g. oil and gas) and/or whole economy

How can this issue play out

- Weiβbach et al. (2013)
  - claimed goal: comparing EROI for “typical” power plants [p. 210]
  - solar and wind technologies require ten days of storage(!!) – far from “typical”

Overall steps in LCA

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According to ISO, goal definition shall “unambiguously state the intended application, the reason for carrying out the study and the intended audience”

Scope definition defines LCA purpose expected product, boundary conditions, functional unit and assumptions

- Based on ISO 14044: Standards for life cycle assessment
Scope definition

Scope definition must answer following:

- What materials, processes, or products are to be considered?
- What is their function? What is the functional unit?
- What will be addressed?
- Who is performing LCA? Where are data from (industry or literature?)
- What are limitations of this LCA?
- What are the system boundaries?
- What stages are included?
Functional unit

The functional unit (FU) provides a reference flow to which inventory data are normalized.

Foam vs. ceramic cups

Inkjet vs. laser printer
What the functional unit!

A financial interlude

• **Cost-benefit ratio**
  – ratio of present value of benefits ($) to present value of costs ($) for project

• **Efficiency ratio**
  – ratio of the expenditures ($/yr) to revenues ($/yr) in a given year
Power vs. energy return on investment

Gross Energy, \( E_g = \int P_g \, dt \)

Operation, \( E_{op} = \int P_{op} \, dt \)

Construction, \( E_c = \int P_c \, dt \)

Decommission,
Power vs. energy return on investment

EROI

- defined at project level (e.g. oil well)
- defined over project lifetime (e.g. 5 years)

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

- Units \( \left[ \frac{J}{J} \right] \)

PROI

- defined at industry/economy scale
- defined over arbitrary timescale (e.g. 1 year)

\[ PROI = \frac{P_g}{P_c + P_{op} + P_d} \]

- Units \( \left[ \frac{J}{yr} \right] \)

- Units
Gross Energy, \( E_g = \int P_g \, dt \)

Operation, \( E_{op} = \int P_{op} \, dt \)

Construction, \( E_c = \int P_c \, dt \)

Decommission, \( E_c = \int P_c \, dt \)
Power vs. energy return on investment

Energy flows for an industry growing at 100% per year
EROI = 15
Power vs. energy return on investment

Energy flows for an industry growing at 100% per year

EROI = 15
Power vs. energy return on investment

Energy flows for an industry growing at 100% per year

EROI = 15
Power vs. energy return on investment

Energy flows for an industry growing at 100% per year

EROI = 15

YEAR 3
Power vs. energy return on investment

Energy flows for an industry growing at 100% per year

EROI = 15
Power vs. energy return on investment

Energy flows for an industry growing at 100% per year

EROI = 15

Net Power [GJ/yr] vs. Energy Return on Investment (EROI)
Power vs. energy return on investment

Energy flows for an industry growing at 100% per year
EROI = 15 → PROI = 0.5

Industry operates at energy ‘deficit’
Zooming out to longer time-scale

Gross Output

NET POWER [GJ/yr]

OUTPUTS

INPUTS

Gross Input

NET POWER [GJ/yr]

OUTPUTS

INPUTS

Gross Output

time (decades)
Zooming out to longer time-scale

- A fraction of gross output is re-invested for industry growth

PROI < 1

PROI > 1
How can this play out?

• Prieto & Hall (2013)
  – “We employ five general methods in analyzing the energy contained/embodied or spent on the equipment, goods and services related to the solar PV plants in Spain… What follows is our estimate of each of the above five categories of energy inputs for Spain for the year 2009” [p.62]

• Clearly this is a PROI but is often compared directly with project-level estimates of EROI of PV.

Net energy trajectories for all PV technologies

Technologies with lower CED can grow at a faster rate

Net energy analysis to-do list:

1. **Write a proper goal statement**, including the following information:
   a. Intended application, i.e. is this a comparison study?
   b. Reasons for the research
   c. For whom the work is intended, i.e. the audience

2. **Define the product system using a diagram** with flows labeled
   a. Use the product flow diagram as a map when listing equations within the paper so that the reader is clear about which inputs are included and which are not
   b. Use this product flow diagram and labels when listing equations, so that the reader can clearly link calculations to the diagram and the boundaries used in the analysis

3. **Clearly identify the functional unit** of the analysis and make sure that this unit is the same as other units in the literature if the research is intended to be used comparatively.

4. **Utilize process-level data** when available and input-output level data as a backup/supplement
   a. Utilize EcoInvent (or other) major LCI database as a primary loci for data
   b. Supplement these databases with other data (e.g. EIO-LCA) when needed, but only after these datasets have been utilized

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Thanks for listening…
What about Ferroni & Hopkins

• Large storage requirement
  – again a ten-day storage is required
• Methodological flaws
  – The way in which labor and capital costs are included leads to double counting
• Non-standard parameters
  – Capacity factor of 7.5% because statistics not adjusted for growth - actual figure is closer to 10.5% (close to value for Germany of ~12%)
• Cherry-picking estimates for embodied energy in panels
• Harmonizing their values leads to an EROI of 12
Overview of LCA and TEA

Inputs:
- Raw materials
- Energy
- Water

Outputs:
- Emissions
  - To air
  - To water
  - To soil

ECONOMY

PRODUCT SYSTEM

Product inputs

Product

TEA

LC

NATURAL ENVIRONMENT
Attributional vs. consequential LCA

• Attributional LCA
  – calculates or compares environmental impacts at the product scale, e.g. GWP of corn-based ethanol

• Consequential LCA
  – calculates potential impacts of product change on larger system (industry or economy), e.g. climate impact of shift to 10% increase in corn-based ethanol
Scope NEA
Structure of LCA – Heijungs & Suh (2002)

• Determine bill of materials (direct inputs) over full lifecycle of product/service, $f$
Structure of LCA – Heijungs & Suh (2002)

- Determine bill of materials (direct inputs) over full lifecycle of product/service, $f$

\[
A \cdot s = f \quad \text{demand}
\]

\[
B \cdot s = g \quad \text{impact}
\]
Structure of LCA – Heijungs & Suh (2002)

\[ \text{product } 1 \times \text{process } 1 \times \text{scaling} = f \text{ demand} \]

\[ \text{product } n \times \text{process } n \times \text{scaling} = g \text{ impact} \]
Structure of NEA

• *Process-based*, ‘bottom-up’ methods based on engineering-type models

• *Input-output*, ‘top-down’ methods based on economic (national accounts) methods
Process-based method

Dynamic analysis possible because *timing* of flows is known

Gross Energy, $E_g$

Construction, $E_c$

Operation, $E_{op}$

Decommission, $E_d$
Input-output method

- Uses environmentally-extended economic input-output models
- Financial flows (e.g. $/yr) used as a proxy for energy and material flows
- Resolution limited to scale of sector
- Steady-state assumption (no accumulation within sectors) inherent within national accounts
Common methodological issues

• Truncation issue (missing data)
• Co-product allocation
• Hybridization
• Aggregation
• Labor and services
• Indirect impacts (e.g. land-use change)
• Marginal vs. absolute impacts
• Linear model
• Inclusion of non-physical (e.g. social) impacts
Uncommon methodological issues

NEA:
• Production vs. investment
• Energy return ratios poorly defined
• Aggregation of different energy types

LCA:
• Weighting and aggregation of impact metrics
• Collapse of time dimension
Hybrid approaches

• Avoid truncation issue by combining process and input-output methods
  – process method is *transfer-based*
  – Input-output method is *flow-based*

• Must assume either
  – all input-output expenditures occur *within a single year* or
  – that the economy is *not changing* (steady-state)
Product scale vs. industry scale

• Product scale
  – *transfer-based* assessment of impacts over full lifecycle which is well defined

• Industry scale
  – lifetime poorly (if at all) defined, often arbitrary
  – dynamic assessment necessary
  – *flow-based* analysis
Caveat emptor - whose lifetime?
Caveat scrutator - whose lifecycle?

Flows of mass and energy in and out of system need not balance in arbitrary time period

\[ \dot{m}_{in} \quad \frac{dm}{dt} \neq 0 \quad \dot{m}_{out} \]

\[ \dot{e}_{in} \quad \frac{de}{dt} = 0 \quad \dot{e}_{out} \]
**Caveat scrutator - whose lifecycle?**

Flows of mass and energy in and out of system need not balance in arbitrary time period.

Transfers of mass and energy in and out of system must balance over full lifecycle.
What do we mean by a ‘cycle’?

Otto cycle, e.g. internal combustion engine

![Diagram of the Otto cycle](image)
What do we mean by a ‘cycle’?

Otto cycle, e.g. internal combustion engine

Pressure

Volume

\[ Q_{in} \]

1

2

3

4
What do we mean by a ‘cycle’?

Otto cycle, e.g. internal combustion engine
What do we mean by a ‘cycle’?

Otto cycle, e.g. internal combustion engine

We end up ‘back where we started’
Do LCI processes ‘end up where they started’?
Do LCI processes ‘end up where they started’?
Do LCI processes ‘end up where they started’?

\[ \sum_{i} \text{product}_i + \sum_{j} \text{interaction}_j = 0 \]
Conclusions

• LCA and NEA share many common methodological similarities
  – NEA practitioners would benefit from the LCA framework (goal & scope, LCI, etc.)

• *Caveat scrutator*
  – Care must be taken when calculating NEA metrics from LCA data
  – LCA as is, not well suited to dynamic consequential analyses
## Structure of LCA

### Industrial processes

<table>
<thead>
<tr>
<th>Steel prod.</th>
<th>Elec.</th>
<th>Car man.</th>
<th>…</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>…</td>
</tr>
</tbody>
</table>

### Steel

<table>
<thead>
<tr>
<th>Electricity</th>
<th>Car</th>
<th>…</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>+1</td>
<td>-1</td>
</tr>
</tbody>
</table>

### Raw materials

<table>
<thead>
<tr>
<th>Raw materials</th>
<th>Emissions</th>
<th>…</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

### Environmental transfers

- within economy
- environmental transfers