A Scale-up Framework for Life Cycle Assessment (LCA) of Emerging Technologies

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Introduction

- Environmental and health issues play a key role in the development of new products, processes and technology.

- It is important to make decisions, even if based on only preliminary or extrapolated data at early stages of design because of high risk involved.
When to consider environmental issues?

- Most of the environmental issues with a product or process are determined at the design phase.*

- Early assessment provides greater flexibility for environmental considerations to guide the innovation process.

(Adapted from Graedel and Allenby, 2011)

(*Tischner, Masselter, & Hirschl, 2000)
Technology Readiness Level (TRL)

- Technology Readiness Level (TRL) indicates the maturity of a given technology
  - pioneered by National Aeronautics and Space Administration (NASA) in the 1960s
  - TRL scale ranges from 1 through 9

<table>
<thead>
<tr>
<th>TRL</th>
<th>Definition</th>
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<tbody>
<tr>
<td>1</td>
<td>Basic principle observed</td>
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<tr>
<td>2</td>
<td>Formulation of concept</td>
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<tr>
<td>3</td>
<td>Proof of concept</td>
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<tr>
<td>4</td>
<td>Validation of laboratory</td>
</tr>
<tr>
<td>5</td>
<td>Component testing in simulated environment</td>
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<tr>
<td>6</td>
<td>Prototype in representative environment</td>
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<tr>
<td>7</td>
<td>Prototype in operation environment</td>
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<tr>
<td>8</td>
<td>System qualification</td>
</tr>
<tr>
<td>9</td>
<td>Technology ready</td>
</tr>
</tbody>
</table>
TRL and LCA

- **Concepts**
  - Lab scale
  - TRL 1
  - Lab scale
  - TRL 2
  - Bench scale
  - TRL 3
  - Engineering scale
  - TRL 4
  - TRL 5
  - Full scale
  - TRL 6
  - TRL 7
  - TRL 8
  - TRL 9

- **Extended domain of LCA**
- **Traditional LCA**
Scale up issues in LCA

- LCA study typically does not consider TRL of the technology.
- Depending on TRL there can be significant differences in LCA result.
- Difference in level of complexity and efficiency of equipment
- Scale up in process can change process yield, material and energy efficiency and environmental burdens
- Data availability, data quality and uncertainty
- Changes in technology, availability of raw materials, prices etc.
Effect of scale-up on LCA

- Scale-up of chemical processes
- Pilot plant to Commercial scale plant
- This method requires an LCA of pilot process

- Change in process yield and energy efficiency in unit processes
- Change in environmental burdens
- Change in background technology
- Material and energy provision
- Synergy effects among processes

(M. Shibasaki et al. 2007)
Other approaches...

- Quantitative scaling factor or scaling laws based on empirical data

\[ key \ properties \ i = a_i \times capacity^{b_i} \]

- Dimensional analysis

(Caduff et al. 2014)
Scale-up procedure for Chemical processes

Overview of Scale-up procedure of chemical processes

1. Laboratory protocol
2. Plant flow chart with scale and reactor sizes
3. Separate scale-up of each process step
4. Linkage of process steps
5. Perform LCA

(Piccinno et al. 2016)
Specific objective

- To develop a general scale-up framework to perform LCA of emerging technologies.
Scale-Up Framework

Lab Scale → Pilot Scale → Commercial Scale
1. Select relevant life cycle phase
2. Update/substitute unit process
3. Add additional process required for pilot plant

Process unit: reactor, pump, harvesting etc.

1. Process flow diagram with detail Specifications
2. Mass and Energy specifications

1. Scale up using theoretical formula/empirical methods/vendors data/expert
2. Update based on mass, energy and technology efficiency
3. Consider plant synergy (e.g. recycle materials, process heat)
4. Scenario analysis

1. Fully developed process flow diagram with recycle streams
2. Adjusted Mass and Energy specifications e.g. catalyst, toxic chemicals
3. Inclusion of impacts of capital equipment

LAB SCALE LCA RESULTS
PILOT SCALE LCA RESULTS
Commercial Scale LCA RESULTS
Case study: perovskite PV panel (lab to fab)

<table>
<thead>
<tr>
<th>Layer (process unit)</th>
<th>Lab Scale</th>
<th>Commercial Scale</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top contact layer</td>
<td>Fluorine doped tin oxide (FTO)/Indium tin oxide (ITO)</td>
<td>FTO</td>
<td>Low in cost and widely used in industry. Indium has been designated as “critical metal” with high supply risk.</td>
</tr>
<tr>
<td>Electron transport layer</td>
<td>TiO2, ZnO, Al2O3, SnO2</td>
<td>SnO2</td>
<td>Low-temperature process used for deposition</td>
</tr>
<tr>
<td>Back contact layer</td>
<td>Gold, Silver, Al</td>
<td>MoOx/Al</td>
<td>Gold and silver are expensive and not suitable for mass production</td>
</tr>
</tbody>
</table>

- Spray deposition and co-evaporation under vacuum is used as manufacturing method during commercialization rather than spin coating.

I. Celik et al. (2016)
Big picture…

User's Input/System Inputs

Materials
- Common element lists
- Recycled amount (User input/Built-in value)
- Raw material sources
- Environmental releases

Energy
- Energy mix
  - Non-renewables
  - Renewables
  - Process heat or electricity

Process
- Process Flow diagram
- Major units

Technology
- Technology Readiness Level
- Technology growth rate
- Change in efficiency
- Major functions

LCA Model
- Stakeholder's inputs
- Data availability and data quality
- Proxy technology?
- Simplification options?

Scale up model
- Lab Scale
- Pilot Scale
- Commercial Scale

Uncertainty model
- Uncertainty analysis
- Uncertainty communications

Output
- Range Data
- Scenario analysis
Thank you for your attention!