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

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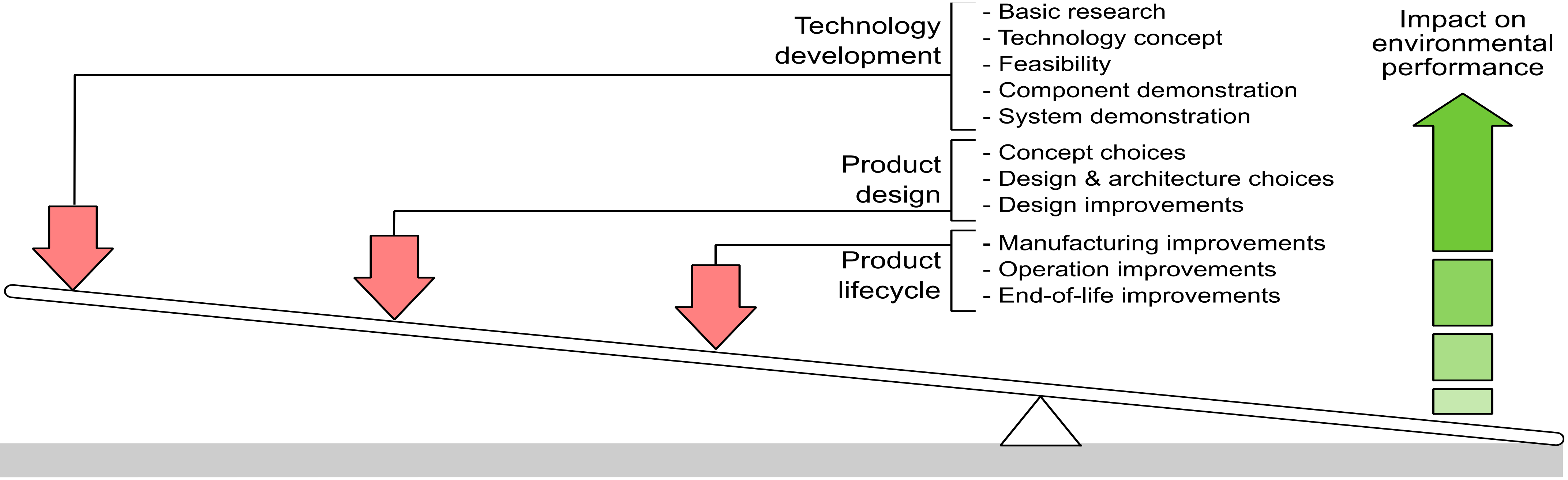
Introduction

- 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 design phase.*
- Early assessment provide greater flexibility for environmental considerations to guide innovation process



(Adapted from Graedel and Allenby, 2011)

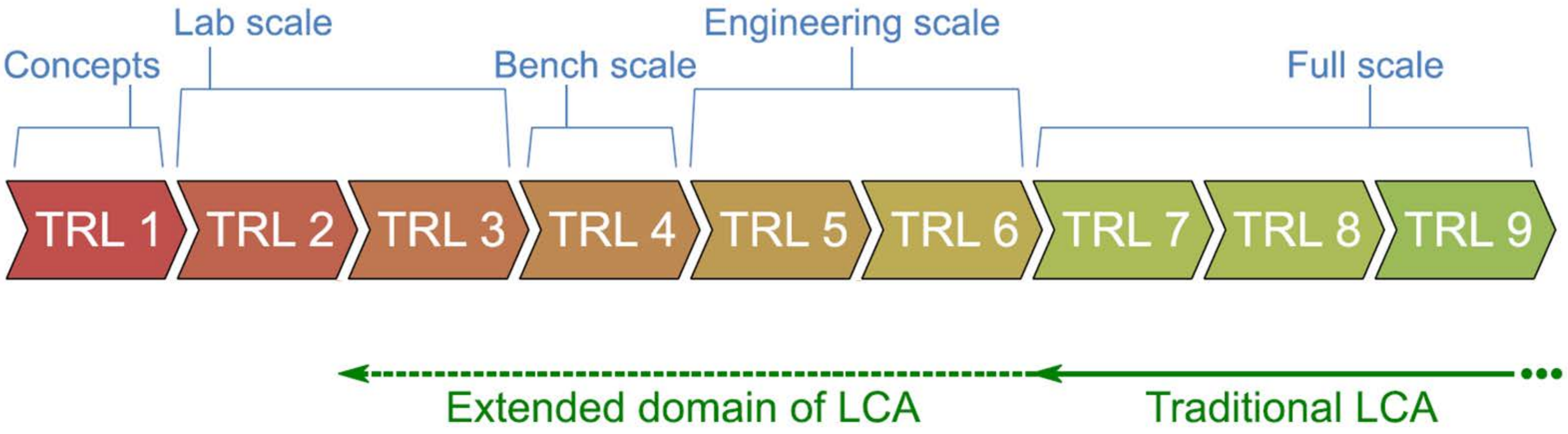
(*Tischner, Masselter, & Hirschl, 2000)

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

TRL	Definition
1	Basic principle observed
2	Formulation of concept
3	Proof of concept
4	Validation of laboratory
5	Component testing in simulated environment
6	Prototype in representative environment
7	Prototype in operation environment
8	System qualification
9	Technology ready

TRL and LCA


Lab scale
Engineering scale
Concepts
Bench scale
Full scale
TRL 1
TRL 2
TRL 3
TRL 4
TRL 5
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

Process as system

- Change in background technology
- Material and energy provision

Process line as system

- Synergy effects among processes

Plant complex as system

(M. Shibasaki et al. 2007)

Other approaches…

- Quantitative scaling factor or scaling laws based on empirical data

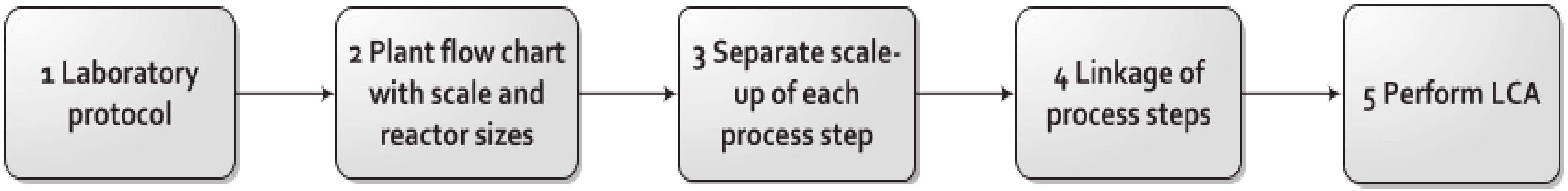
$$key\ properties\ i = a_i * capacity^{b_i}$$

- Dimensional analysis

(Caduff et al. 2014)

Scale-up procedure for Chemical processes

- Overview of Scale-up procedure of chemical processes

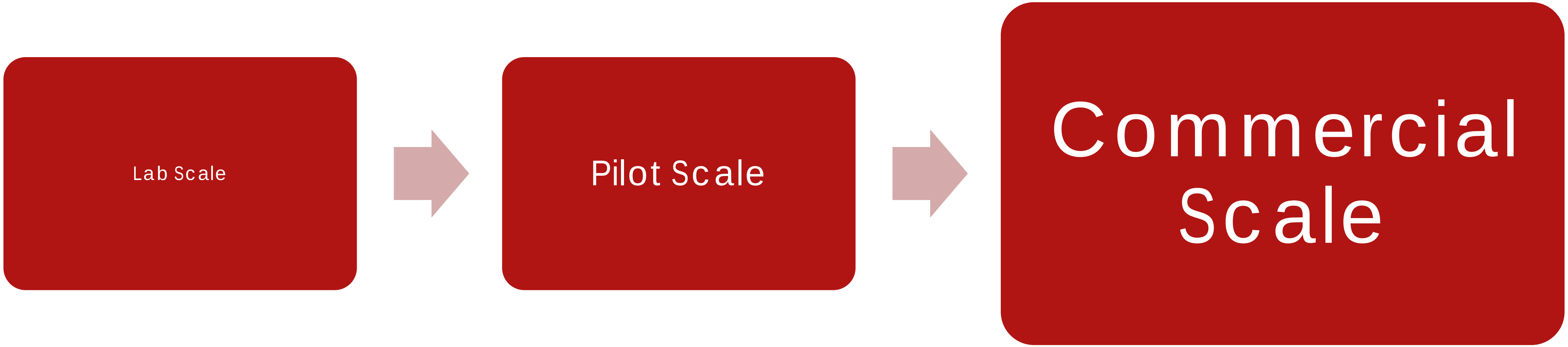


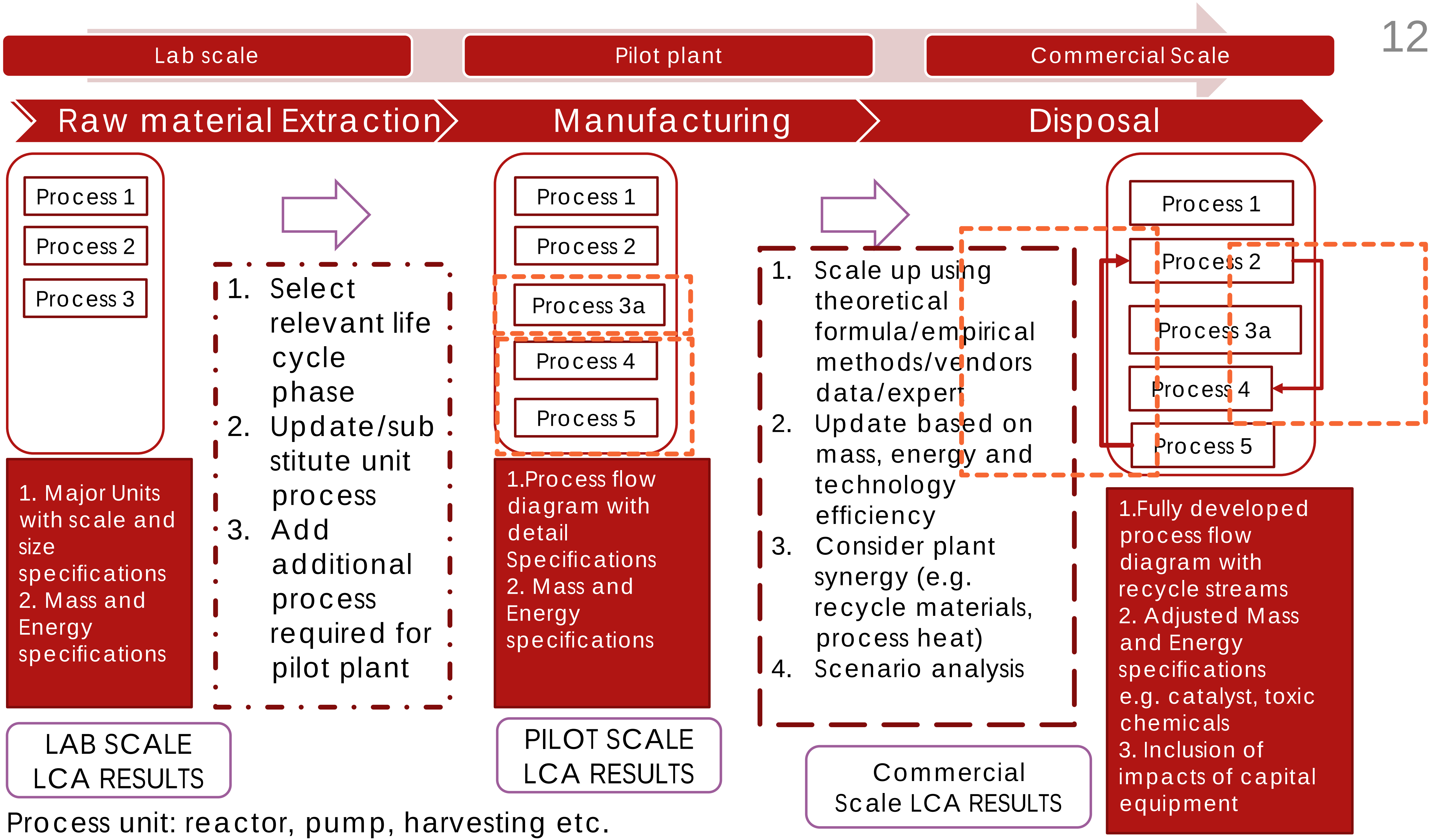
(Piccinno et al. 2016)

Specific objective

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

Scale-Up Framework




Lab scale
Pilot plant
Commercial Scale
Raw material Extraction
Manufacturing
Disposal
Process 1
Process 2
Process 3
1. Major Units with scale and size specifications
2. Mass and Energy specifications
LAB SCALE LCA RESULTS
1. Select relevant life cycle phase
2. Update/substitute unit process
3. Add additional process required for pilot plant
Process 1
Process 2
Process 3a
Process 4
Process 5
1.Process flow diagram with detail Specifications
2. Mass and Energy specifications
PILOT SCALE LCA RESULTS
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
Commercial Scale LCA RESULTS
Process 1
Process 2
Process 3a
Process 4
Process 5
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
Process unit: reactor, pump, harvesting etc.

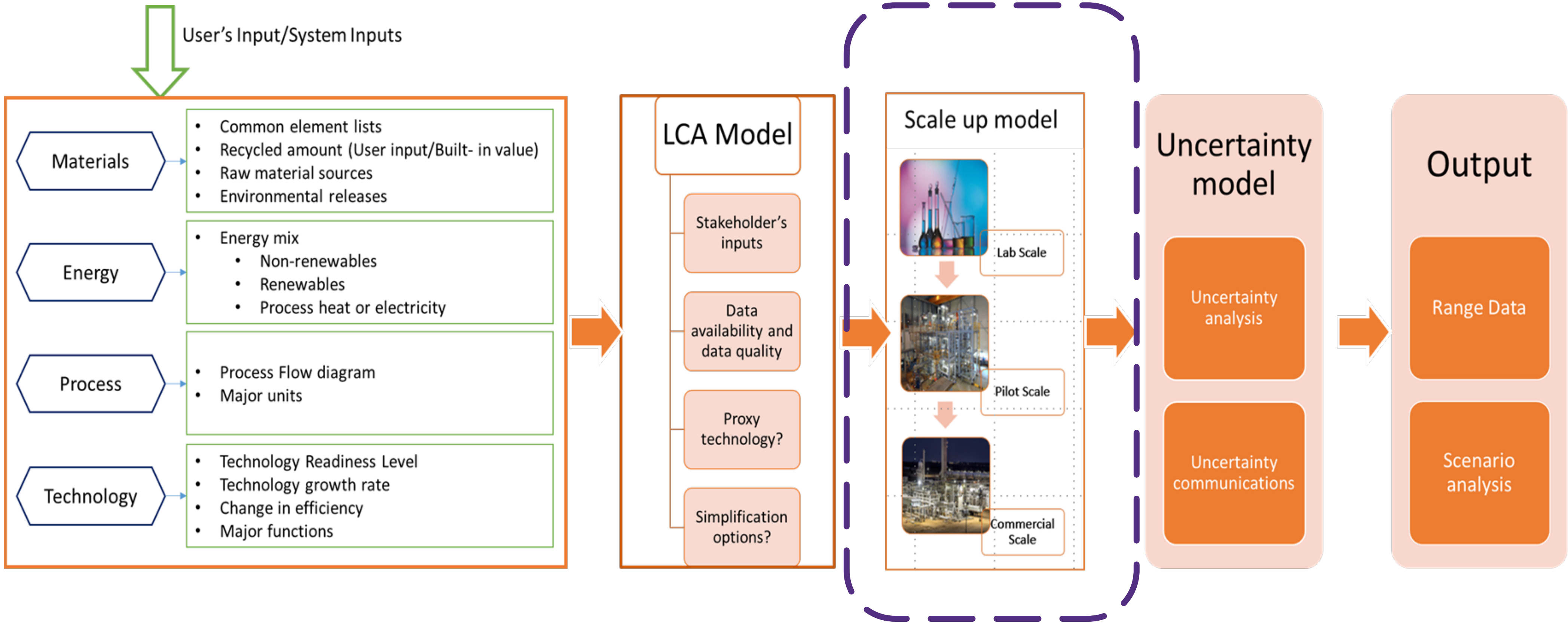
Case study: perovskite PV panel (lab to fab)

Layer (process unit)	Lab Scale	Commercial Scale	Comments
Top contact layer	Fluorine doped tin oxide (FTO)/Indium tin oxide (ITO)	FTO	Low in cost and widely used in industry Indium has been designated as "critical metal" with high supply risk.
Electron transport layer	TiO_2, ZnO, Al_2O_3, SnO_2	SnO_2	Low-temperature process used for deposition
Back contact layer	Gold, Silver, Al	MoO_x/Al	Gold and silver are expensive and not suitable for mass production

- 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!