A systematic approach to assess emerging technologies

Mitchell K. van der Hulst

Radboud University
Department of Environmental Science
Heyendaalseweg 135
Nijmegen, the Netherlands
m.vanderhulst@science.ru.nl

TNO
Department of Climate, Air and Sustainability
Princetonlaan 6
Utrecht, the Netherlands
mitchell.vanderhulst@tno.nl

Environmental Assessment of Emerging Technologies

Recommendations for Prospective LCA

Rickard Arvidsson, Anne-Marie Tillman, Björn A. Sandén, Matty Janssen, Anders Nordelöf, Duncan Kushnir, and Sverker Molander

Environmental Systems Analysis, Chalmers University of Technology, Gothenburg, Sweden

sustainability

MDPI

Review

How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance

Nils Thonemann *, Anna Schulte and Daniel Maga

Department of Sustainability and Resources Management, Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, 46047 Oberhausen, Germany; anna.schulte@umsicht.fraunhofer.de (A.S.); daniel.maga@umsicht.fraunhofer.de (D.M.)

* Correspondence: nils.thonemann@umsicht.fraunhofer.de

sustainability

MDPI

Review

The Future of Ex-Ante LCA? Lessons Learned and Practical Recommendations

Matthias Buyle [1,2,*], Amaryllis Audenaert [1], Pieter Billen [3], Katrien Boonen [2] and Steven Van Passel [4]

1 Energy and Materials in Infrastructure and Buildings (EMIB), University of Antwerp, 2020 Antwerp, Belgium
2 Unit Sustainable Materials Management, Flemish Institute for Technological Research (VITO), 2400 Mol, Belgium
3 Biochemical Green Engineering & Materials (BioGEM), University of Antwerp, 2020 Antwerp, Belgium
4 Department of Engineering Management, University of Antwerp, 2000 Antwerp, Belgium
* Correspondence: matthias.buyle@uantwerpen.be

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

ELSEVIER

A critical view on the current application of LCA for new technologies and recommendations for improved practice

Coen van der Giesen [a, *], Stefano Cucurachi [a], Jeroen Guinée [a], Gert Jan Kramer [b], Arnold Tukker [a]

[a] Institute of Environmental Sciences (CML), Leiden University, Einsteinweg 2, 2333 CC, Leiden, the Netherlands
[b] Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 CB, Utrecht, the Netherlands

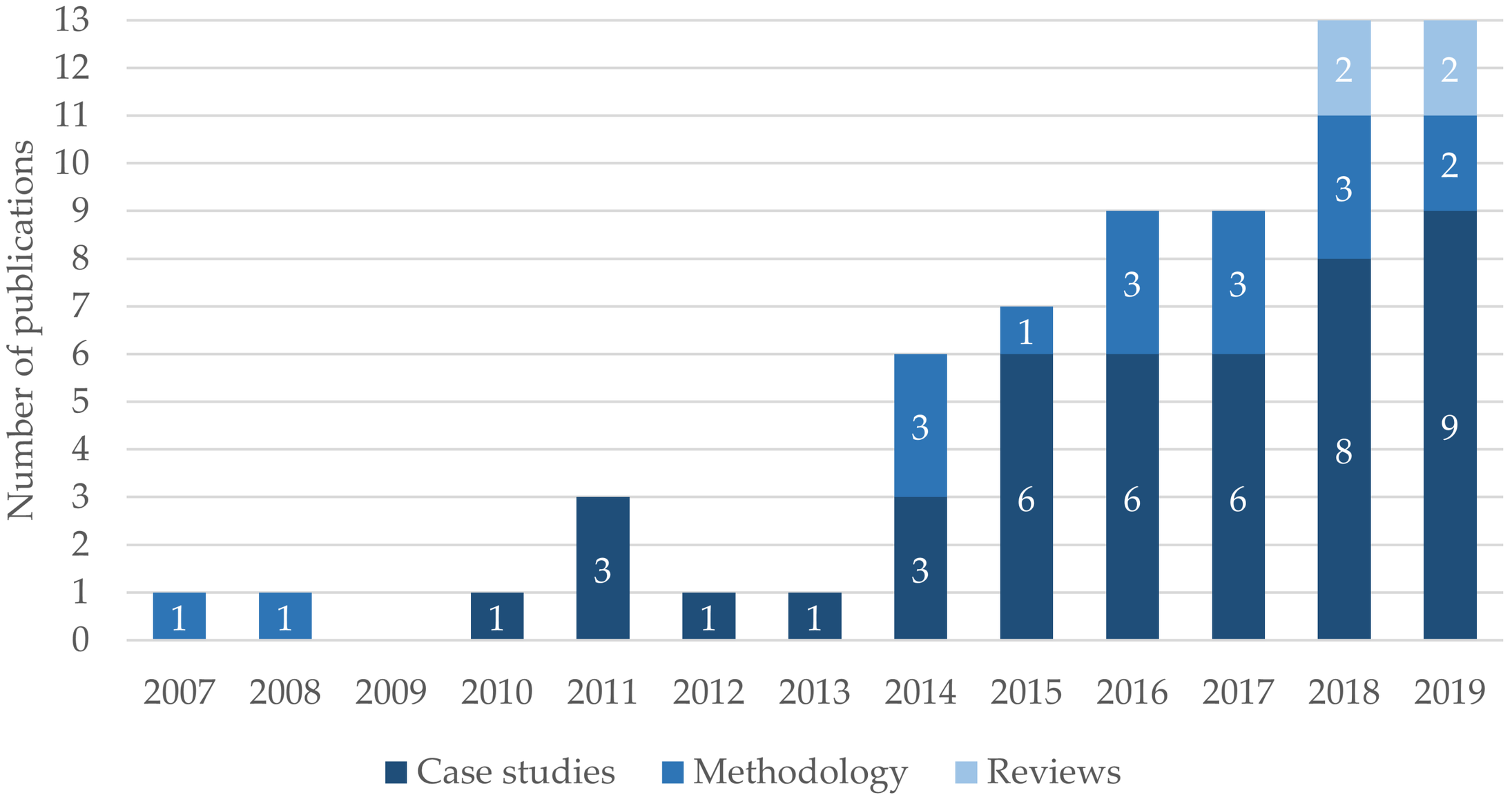


Figure 2 from: Thonemann et al. **2020** *How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance.* Sustainability, *12*, 1192. DOI: 10.3390/su12031192

PERCEIVED PROBLEMS

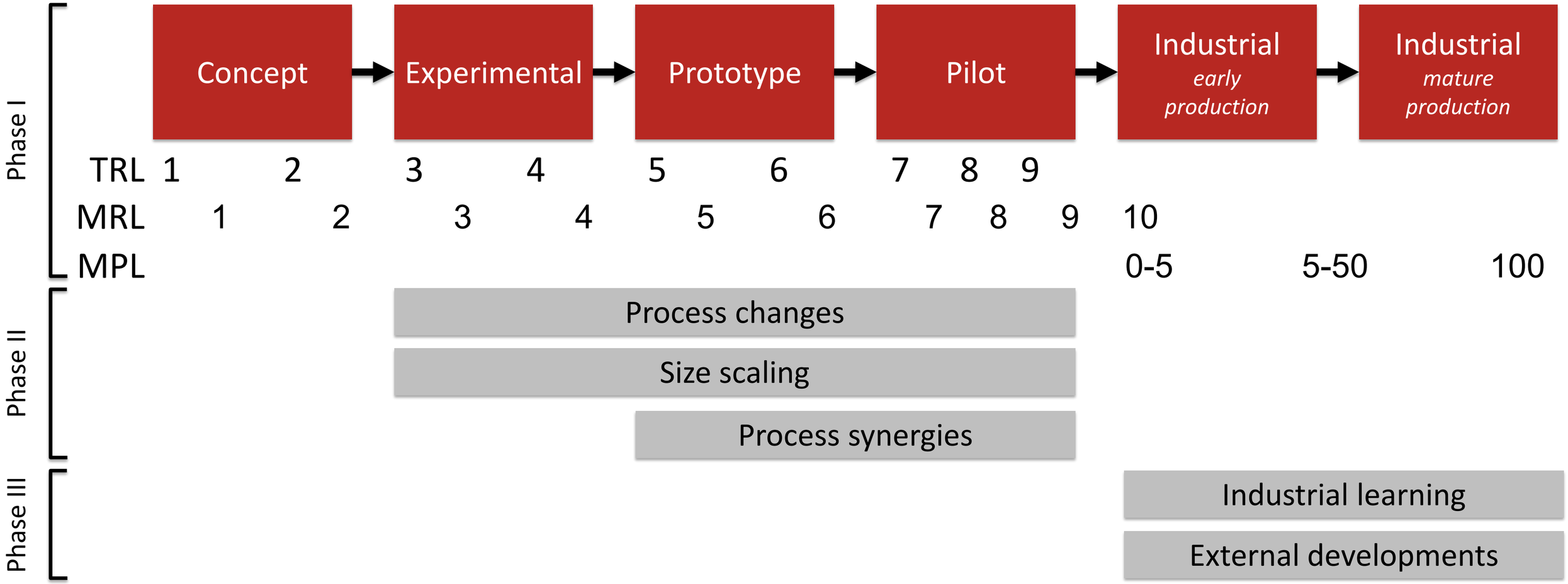
Plurality of approaches
could lead to
different outcomes

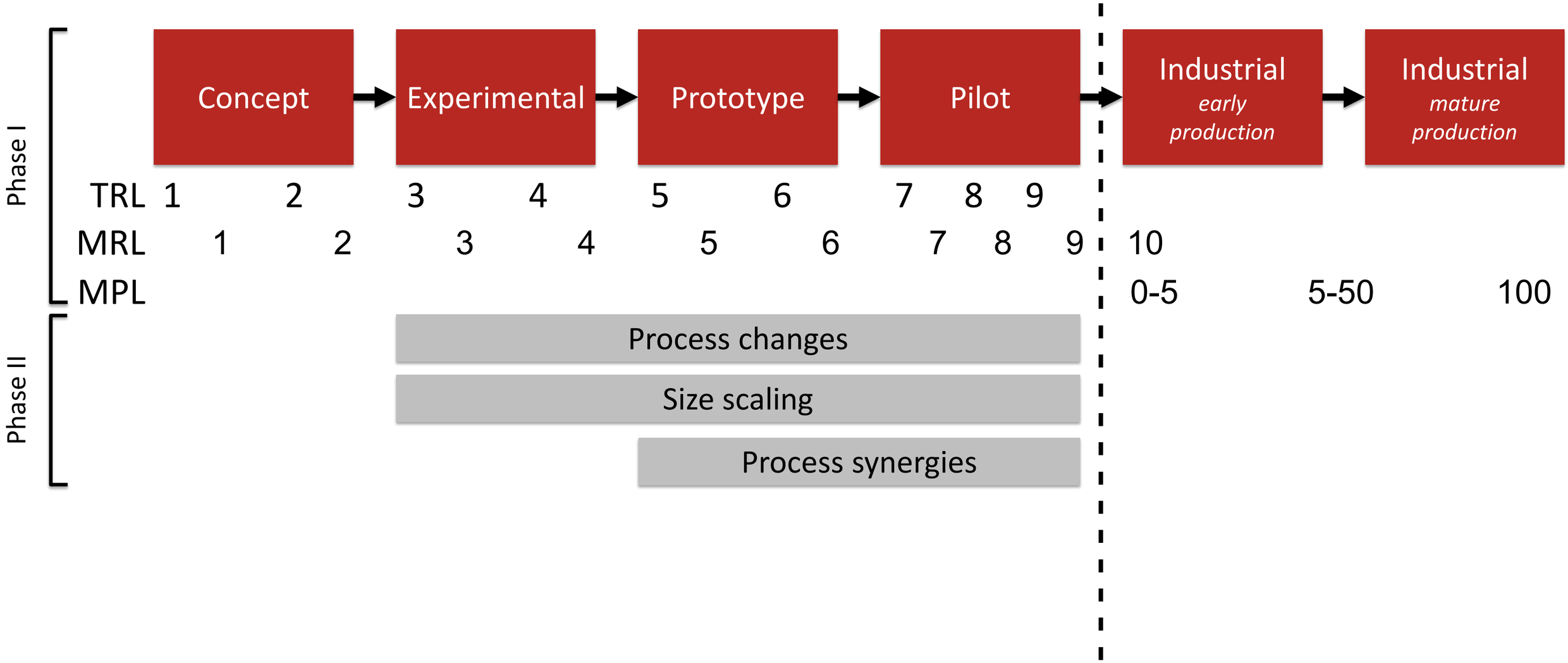
Absence of an explicit, overarching protocol
for assessing emerging technologies

AIM OF OUR STUDY

Combine recommendations for prospective LCA in a
systematic approach

Showcase applicability and utility
in a
case study
for a thin-film PV technology


Phase I
Concept
Experimental
Prototype
Pilot
Industrial
early
production
Industrial
mature
production
TRL 1 2 3 4 5 6 7 8 9
MRL 1 2 3 4 5 6 7 8 9 10
MPL
0-5
5-50
100
Phase II
Process changes
Size scaling
Process synergies
Phase III
Industrial learning
External developments


Phase I
Concept
Experimental
Prototype
Pilot
Industrial
early
production
Industrial
mature
production
TRL 1 2 3 4 5 6 7 8 9
MRL 1 2 3 4 5 6 7 8 9 10
MPL
0-5
5-50
100
Phase II
Process changes
Size scaling
Process synergies

Process Changes

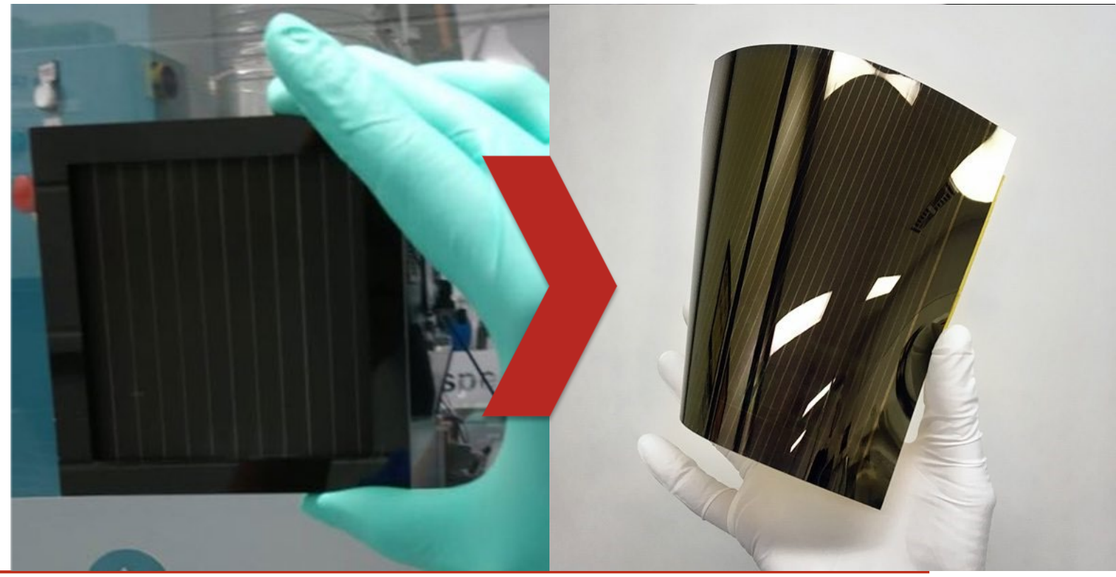
- Physical limitations
- Improve performance
- Cheaper production
- Safer production

Modeling approaches:

- Deduce from existing industrial process with similar function
- Consult technology experts

Case study example

Cheaper roll-to-roll processing with flexible materials leads to changes in bill of materials and energy requirements

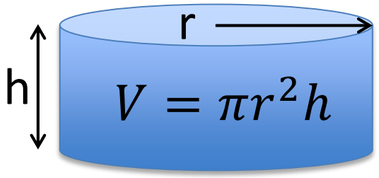


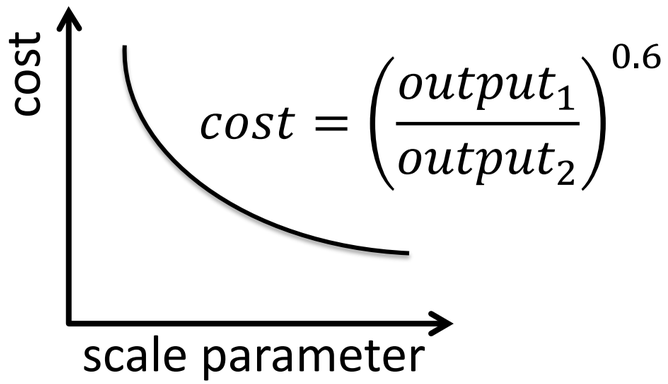
Size Scaling

- Product scaling
- Equipment scaling

Modeling approaches:

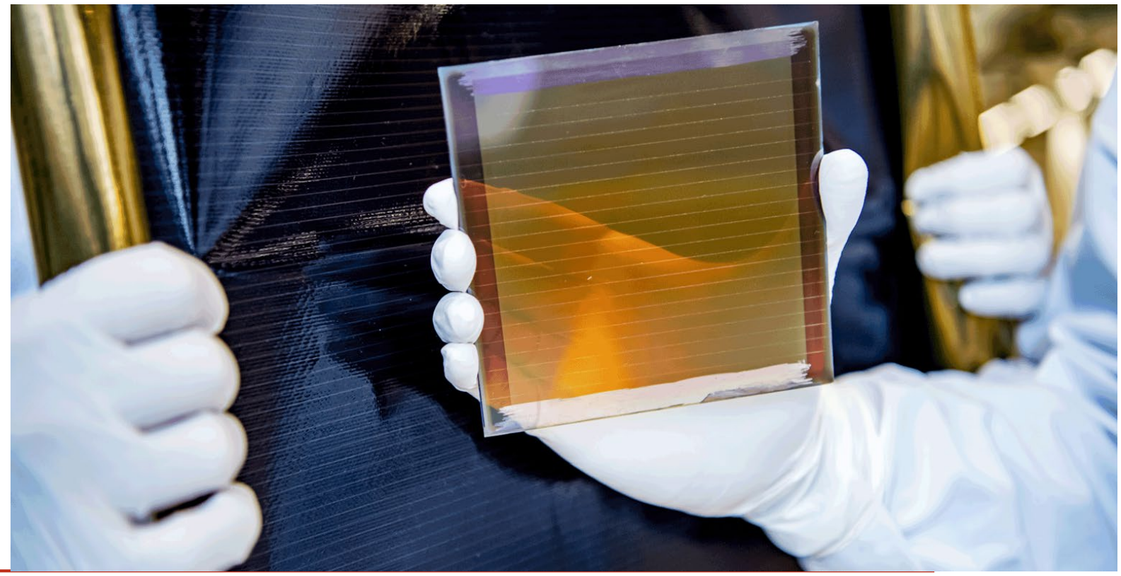
- Scaling curves
- Geometry calculations





Case study example

Scaling curve is applied to upscale electricity demand for processing equipment that can handle wider panels

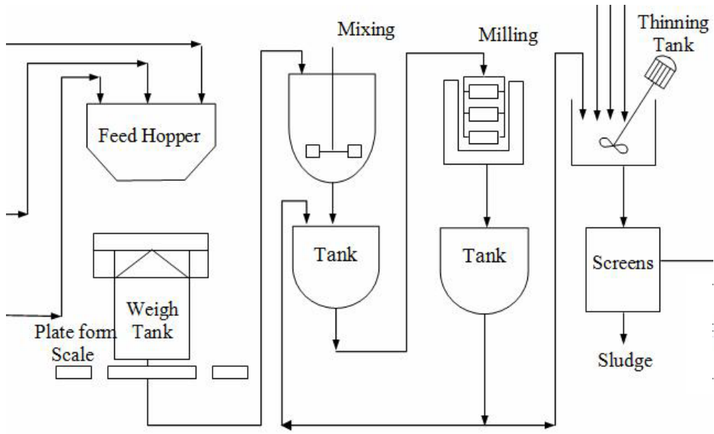


Process Synergies

- Recycling of unutilized inputs
- Waste valorization
- Heat recovery

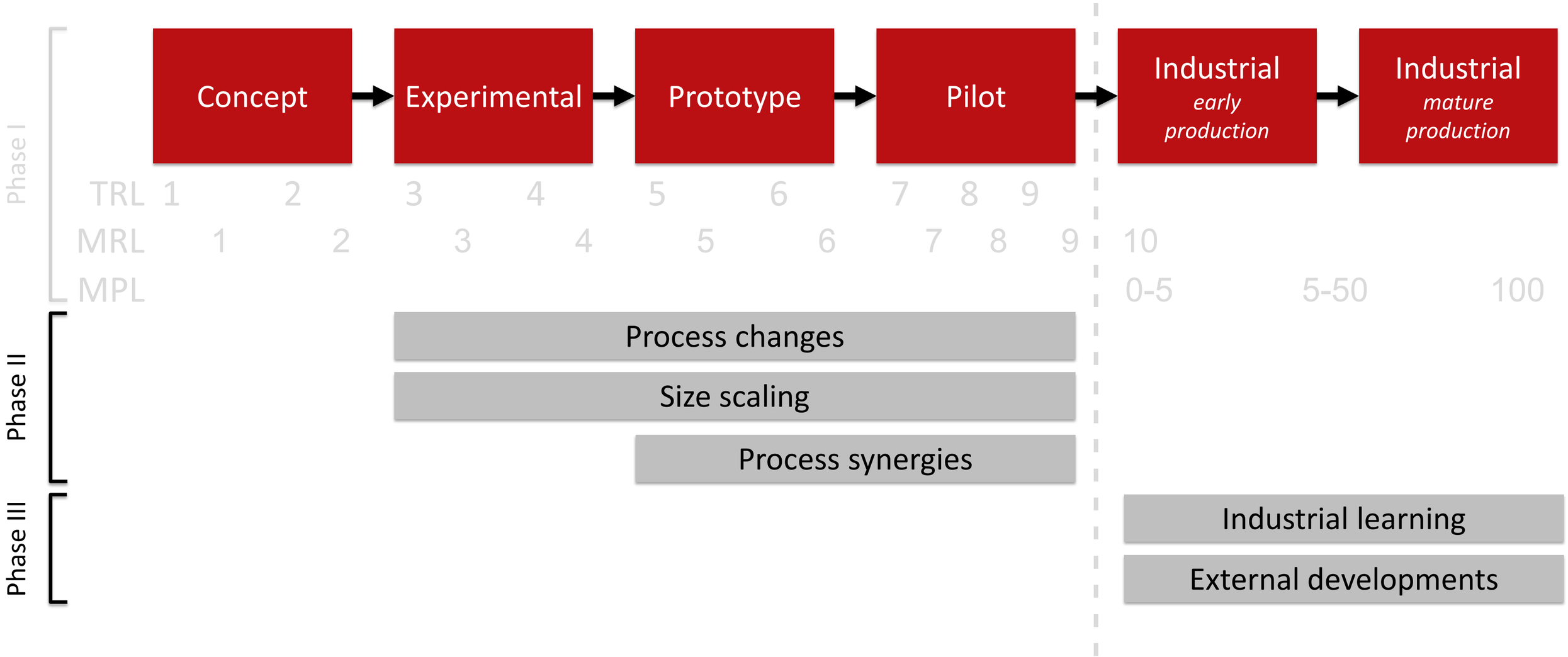
Modeling approaches:

- Deduce from plant flow chart of existing industrial process
- Consult technology expert



Case study

Indium from spent ITO sputtering targets is recycled


Concept
Experimental
Prototype
Pilot
Industrial
early
production
Industrial
mature
production
Phase I
TRL 1 2 3 4 5 6 7 8 9
MRL 1 2 3 4 5 6 7 8 9 10
MPL
0-5
5-50
100
Process changes
Size scaling
Process synergies
Phase II
Phase III
Industrial learning
External developments

Industrial Learning

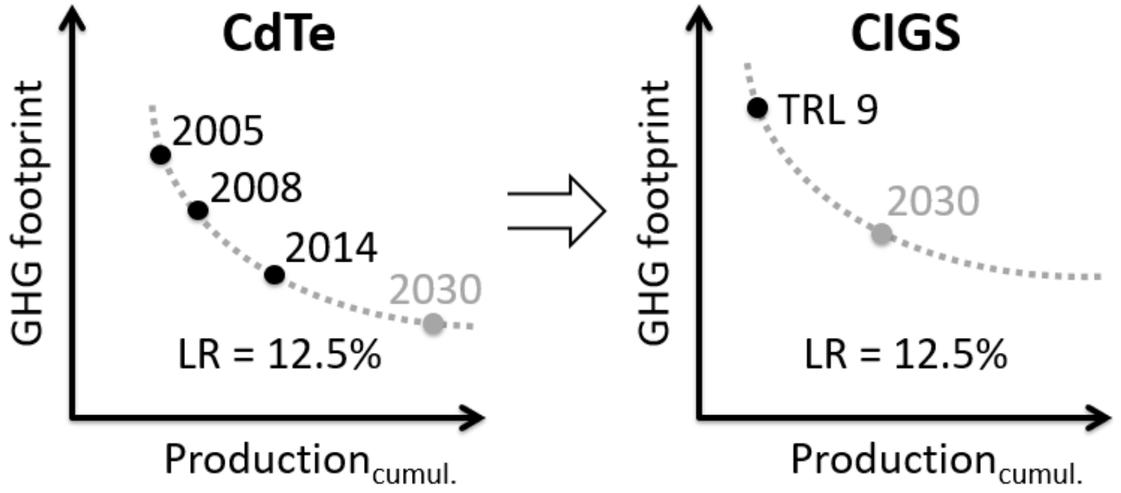
- Learning-by-doing
- Learning-by-(re)searching
- Learning-by-interaction
- *Forgetting*

Modeling approaches:

- Extrapolation of learning curves for similar technologies, using projections for cumulative output

Case study example

The future GHG footprint of CIGS is projected using the learning rate of a comparable thin film PV technology (CdTe) and projections on cumulative production of CIGS



External Developments

- Decarbonization of the energy sector
- Material/energy efficiency improvements
- Land use intensification

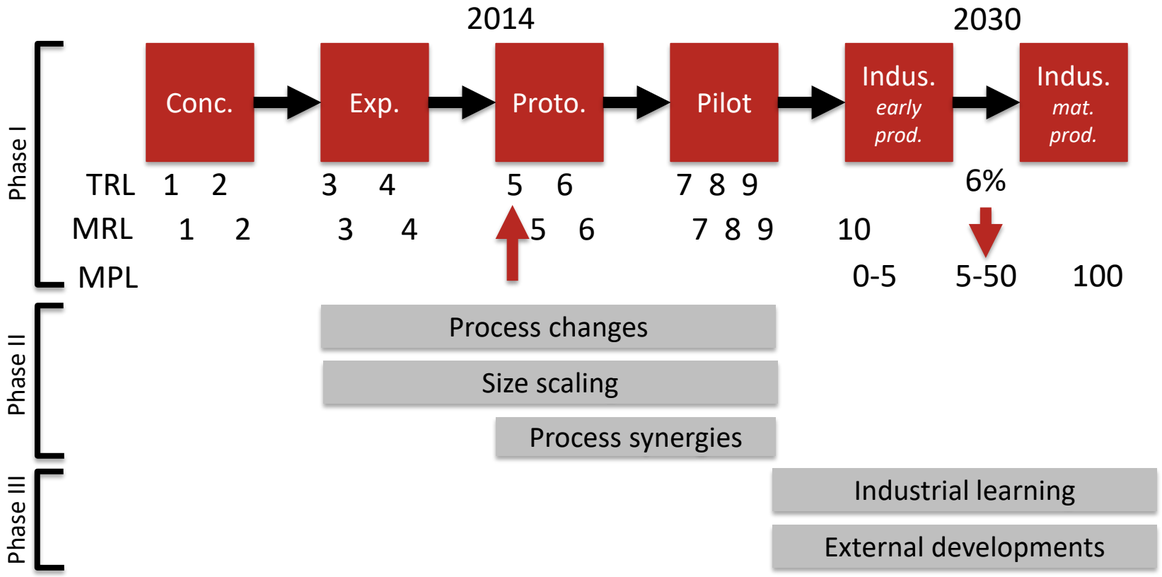
Modeling approaches:

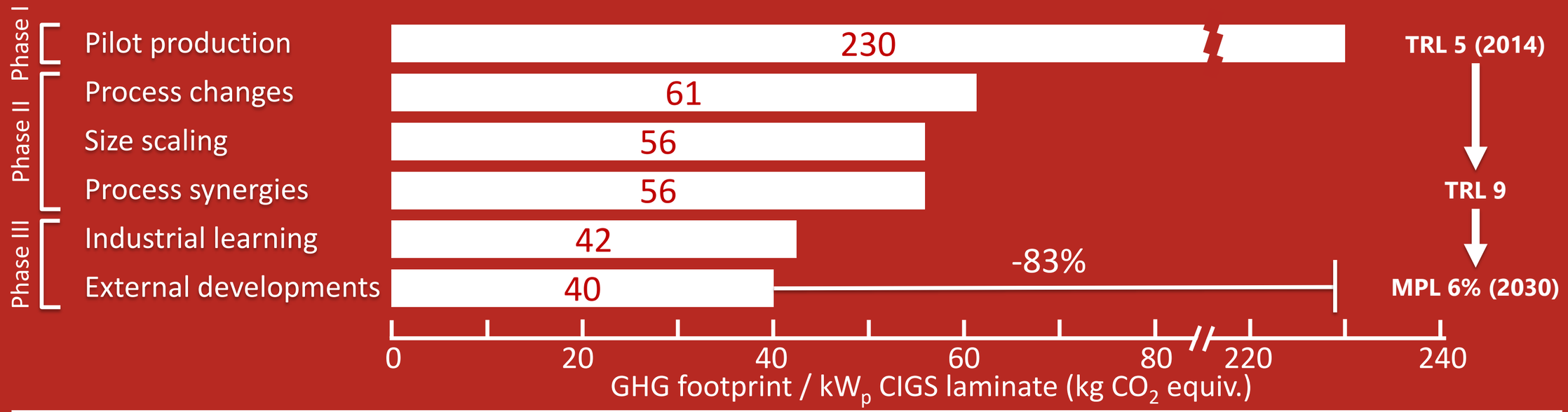
- Adjusting **LCI databases** with projections from **IAMs**

ecoinvent	IMAGE
US LCI	REMIND
⋮	⋮

<u>Case study example</u>

Updated grid mix of the electricity used in the foreground process, based on projections from an IAM


2014
2030
Conc.
Exp.
Proto.
Pilot
Indus. early prod.
Indus. mat. prod.
TRL 1 2 3 4 5 6 7 8 9
MRL 1 2 3 4 5 6 7 8 9 10
MPL 0-5 6% 5-50 100
Phase I
Phase II
Phase III
Process changes
Size scaling
Process synergies
Industrial learning
External developments


Phase I
Phase II
Phase III
Pilot production
Process changes
Size scaling
Process synergies
Industrial learning
External developments
230
61
56
56
42
40
-83%
TRL 5 (2014)
TRL 9
MPL 6% (2030)
0
20
40
60
80
220
240
GHG footprint / kW$_p$ CIGS laminate (kg CO$_2$ equiv.)

DOI: 10.1111/jiec.13027

METHODS, TOOLS, AND SOFTWARE

JOURNAL OF INDUSTRIAL ECOLOGY

A systematic approach to assess the environmental impact of emerging technologies

A case study for the GHG footprint of CIGS solar photovoltaic laminate

Mitchell K. van der Hulst[1,2] | Mark A. J. Huijbregts[1] | Niels van Loon[3] | Mirjam Theelen[3] | Lucinda Kootstra[2] | Joseph D. Bergesen[4] | Mara Hauck[2]

[1]Department of Environmental Science, Institute for Water and Wetland Research, Faculty of Science, Radboud University Nijmegen, Nijmegen, The Netherlands

[2]Department of Climate, Air and Sustainability, TNO, Utrecht, The Netherlands

[3]Solliance/TNO, Eindhoven, The Netherlands

[4]Bren School of Environmental Science & Management, University of California, Santa Barbara, California

Correspondence
Mitchell K. van der Hulst, Department of Environmental Science, Institute for Water and Wetland Research, Faculty of Science, Radboud University Nijmegen, PO Box 9010, 6500 GL Nijmegen, The Netherlands.
Email: m.vanderhulst@science.ru.nl

Abstract

Estimating the environmental impact of emerging technologies at different stages of development is uncertain but necessary to guide investment, research, and development. Here, we propose a systematic procedure to assess the future impacts of emerging technologies. In the technology development stage (technology readiness level < 9), the recommended experience mechanisms to take into account are (a) process changes, (b) size scaling effects, and (c) process synergies. These developments can be based on previous experience with similar technologies or quantified through regression or engineering dimension calculations. In the industrial development phase, (d) industrial learning, based on experience curves or roadmaps, and (e) external developments should be included. External developments, such as changes in the electricity mix can be included with information from integrated assessment models. We show the applicability of our approach with the greenhouse gas (GHG) footprint evaluation for the production of copper indium gallium (di)selenide (CIGS) photovoltaic laminate. We found that the GHG footprint per kilowatt peak of produced CIGS laminate is expected to decrease by 83% going from pilot to mature industrial scale production with the largest decrease being due to expected process changes. The feasibility of

1 Radboud University

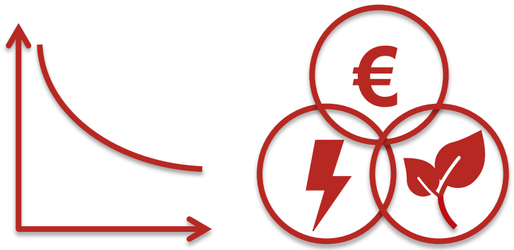
2 TNO innovation for life

3 SOLLIANCE SOLAR RESEARCH

4 Bren School of Environmental Science & Management UNIVERSITY OF CALIFORNIA, SANTA BARBARA

OUTLOOK

The application of our proposed approach in **other case studies** could help to **assess its validity and applicability**



Further research into **size scaling and learning curves** as well as the incorporation of predictions from **integrated assessment models**

The creation of **open-source databases,** containing process-specific information