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Congrès
Management
du Cycle de Vie
2025

LCA and SSbD approaches for more sustainable semiconductor industry

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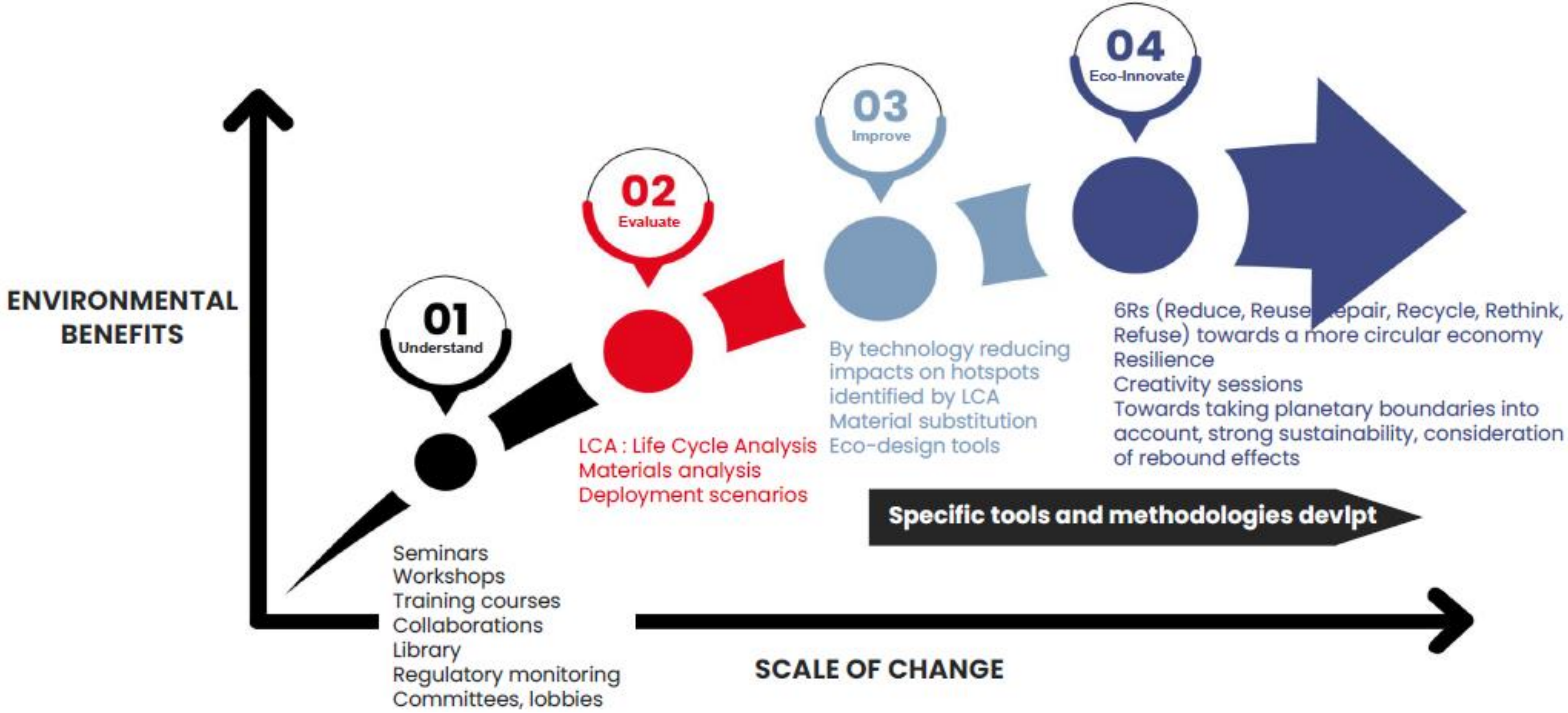
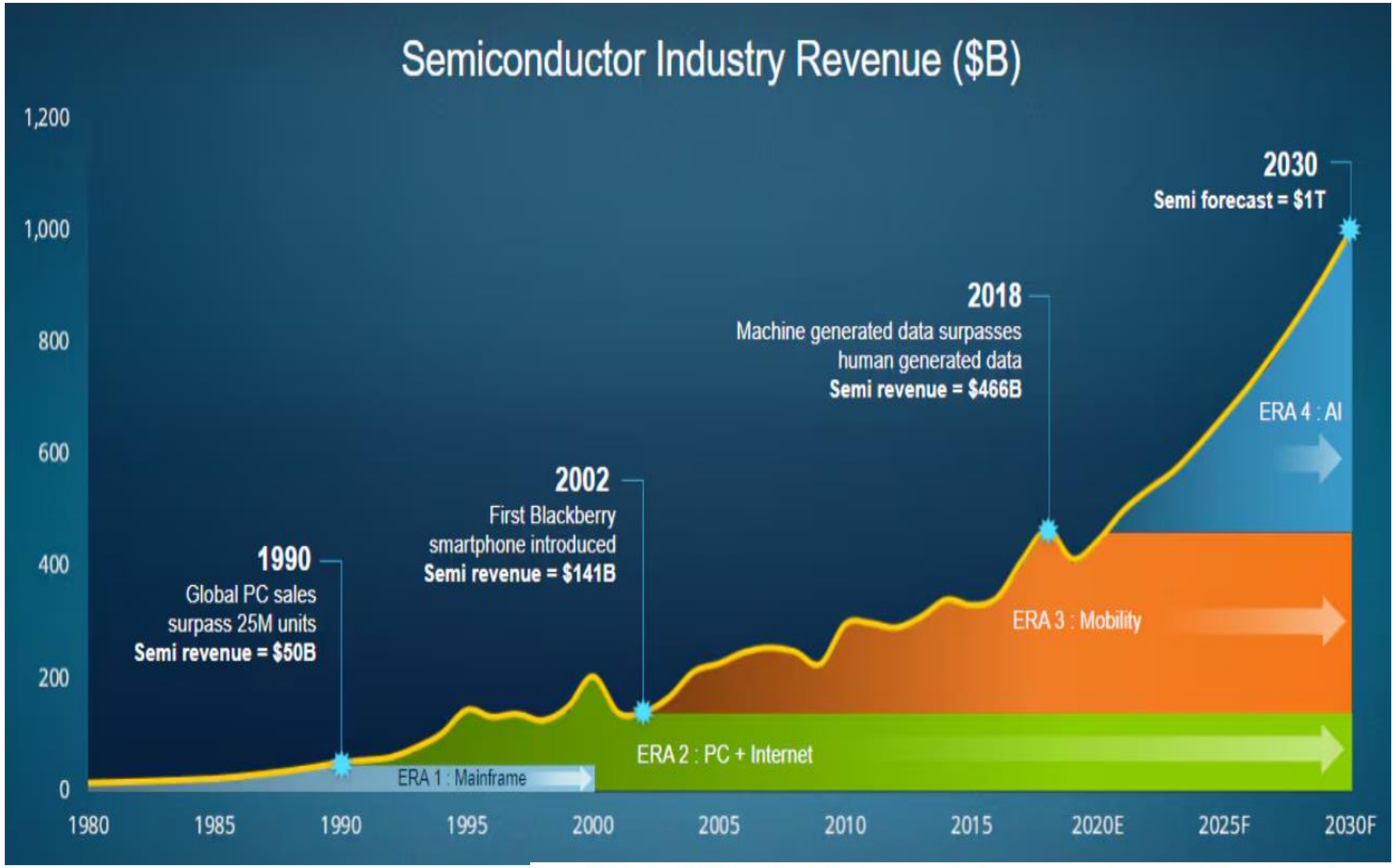
CEA-LETI ECO-INNOVATION APPROACH



→ CEA-LETI SUSTAINABILITY COMMITMENTS WITH 2030 ROADMAP

Semiconducteur market



Source: SEMI, VLSI, Applied Materials

IoT + AI Era is the 4th and Biggest Age of Computing

Carbon footprint of SC

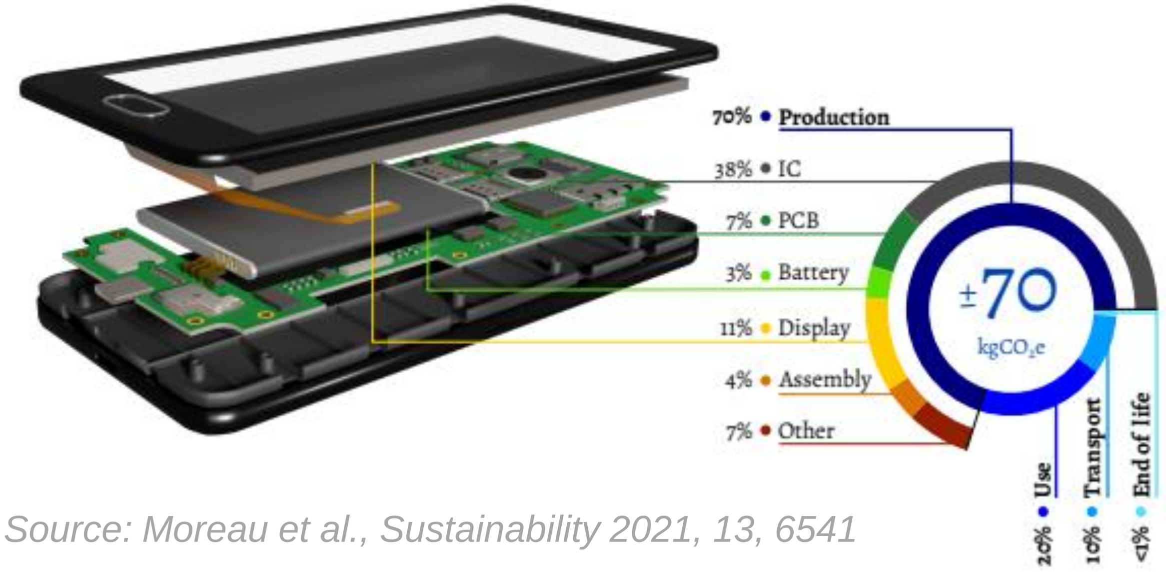
2020		2030
41 Mtons	›	**100 Mtons**

Source: Semi blog 2020

Market growth x2 by 2030

Carbon footprint of a smartphone

Example for a smartphone



Source: Moreau et al., Sustainability 2021, 13, 6541

70% due to production phase with 38% for IC*

GWP emissions

GHG

-55%

Reducing net GHG emissions by 2030

Net-zero carbon neutrality by 2050

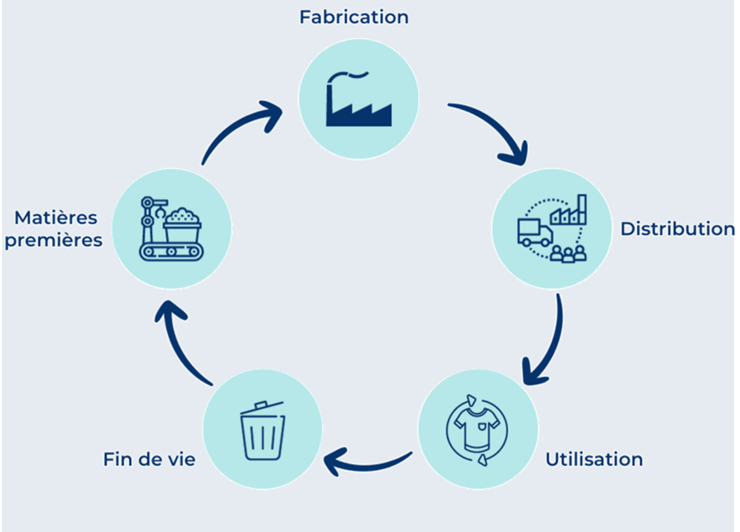
Source: Semi blog 2020

* Integrated Circuit

LCA Life Cycle Analysis

- **LCA** = Quantification of environmental impacts through the entire life cycle of a product or service

Life Cycle



LCA standards

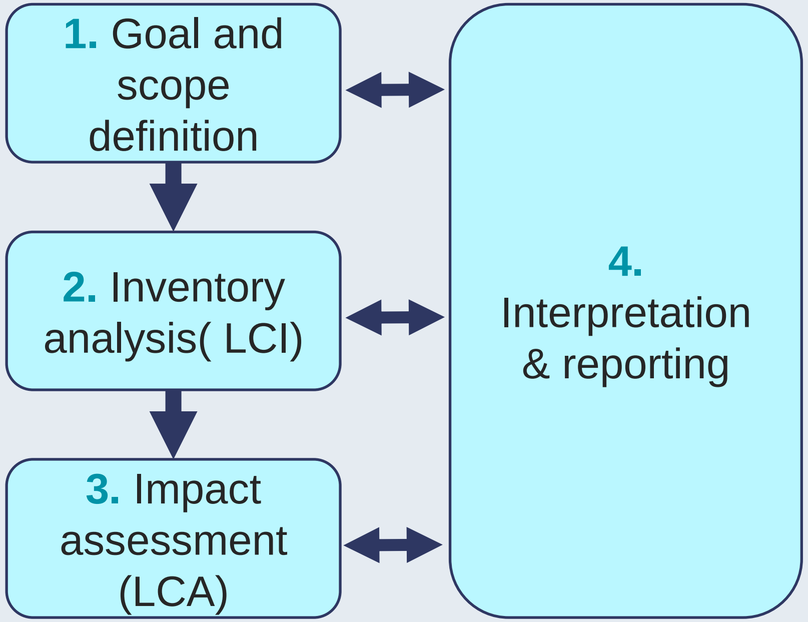
ISO 14 040
and
ISO 14 044
Approved Life Cycle Assessment

Product Environmental Footprint (PEF)

European Commission

PEF **3.1** method

16 impact factors



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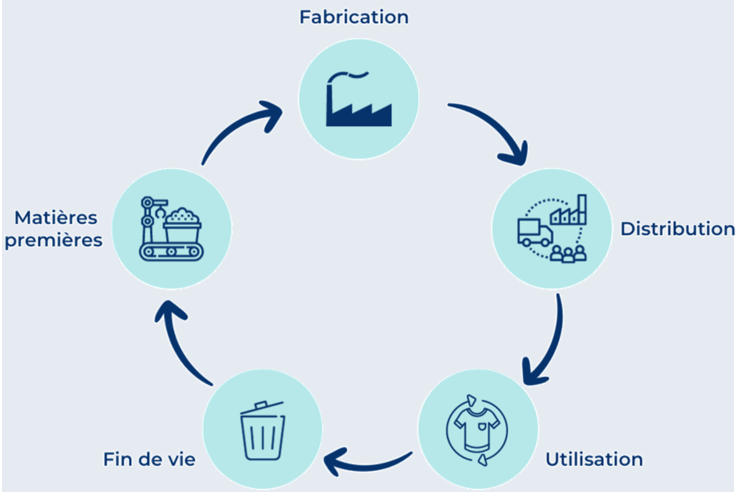

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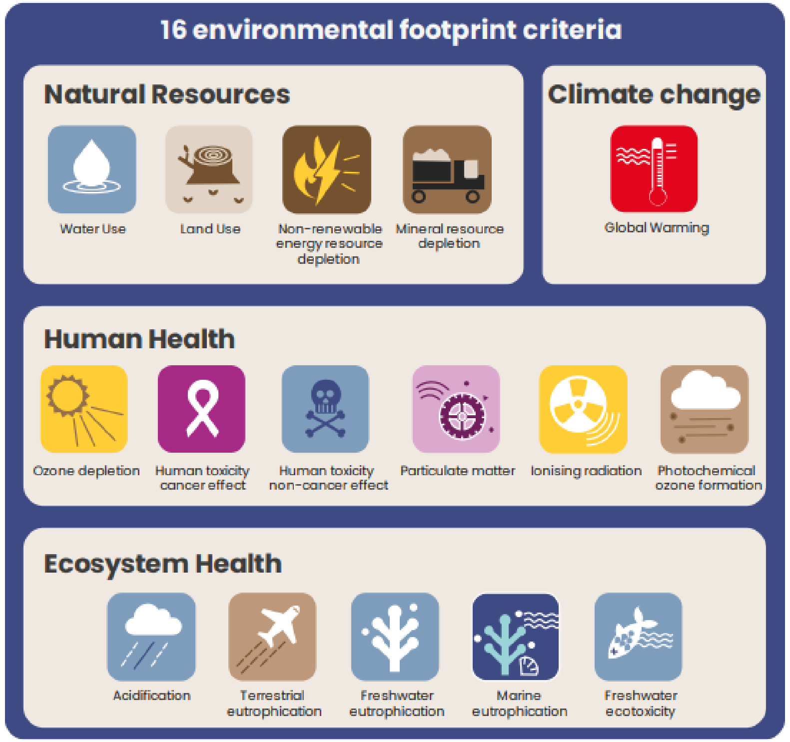
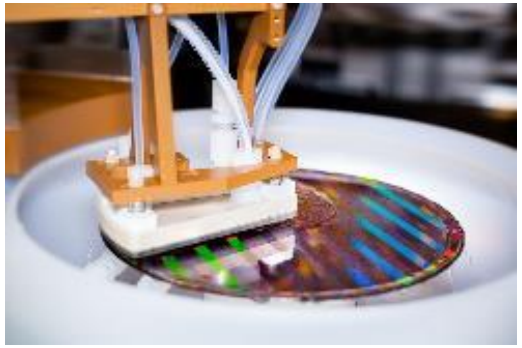


- ✓ Standardized, quantitative, iterative and multi-criteria method
- ✓ Used to identify the “hot spots” (major impacts)

LCA in microelectronics: an adapted methodology

Scope of the study



System boundaries

- ➢ “cradle-to-gate”
- ➢ This study: focus on **chemicals production** for microelectronics

The European Green Deal

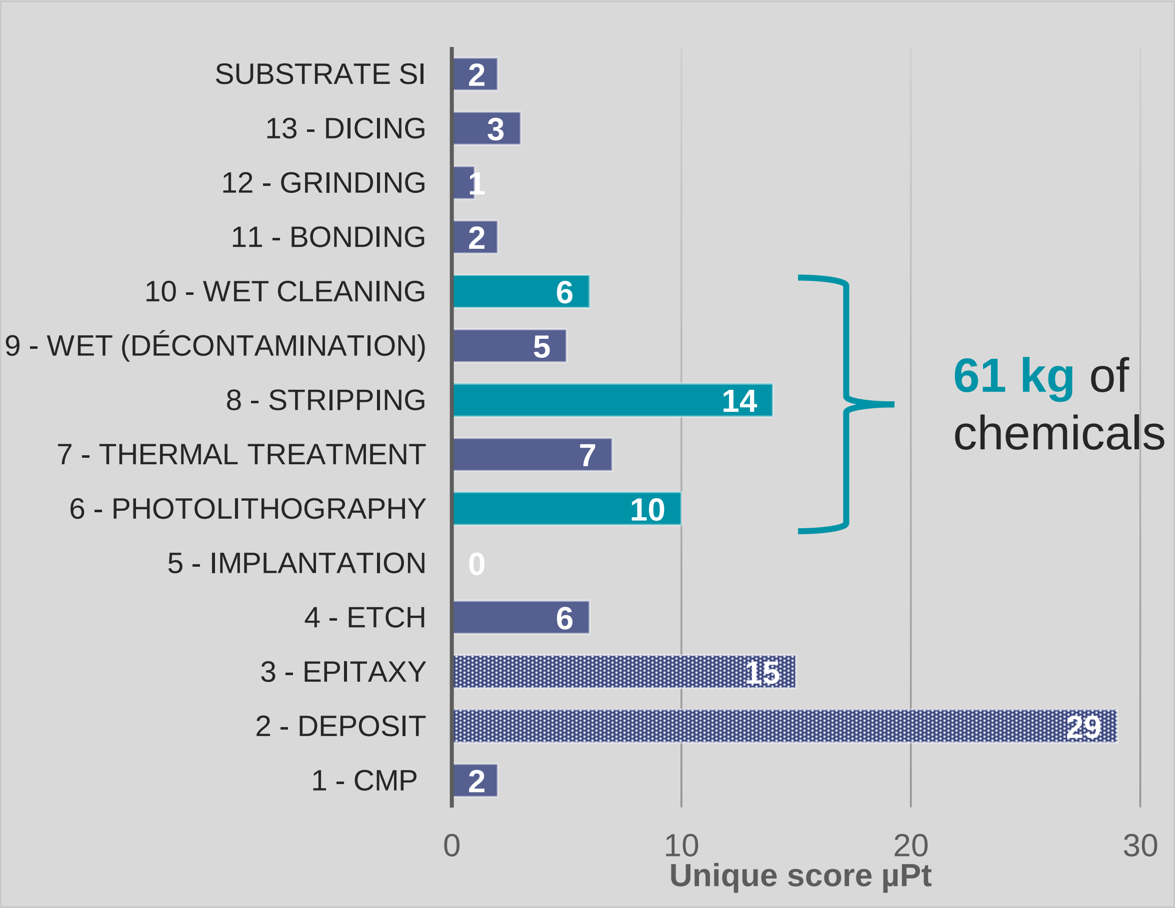
New chemicals strategy towards a **toxic-free environment**

2 examples

Low TRL	High TRL
Bio-sourced photoresists	**Toxic-free chemicals** for
Alternatives for lithography step	**stripping and cleanings steps**

LCA in microelectronics: chemicals impact

Exemple of production of 1 wafer with GaN on Si



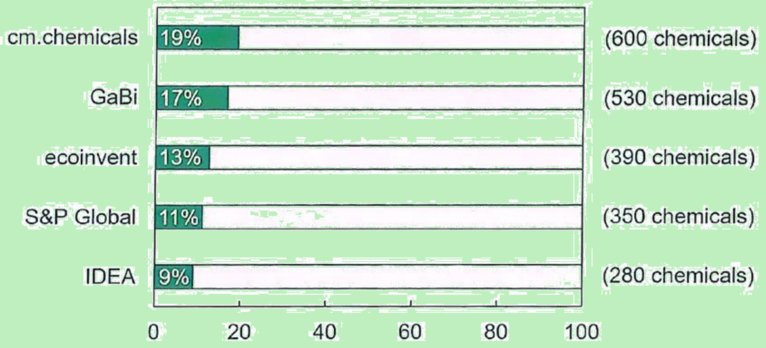
30% due to steps STRIPPING, LITHOGRAPHY & WET using high-volume chemistries

[1] *L. Vauche et al., Sustainability* ***2024****, 16, 901*

Chemicals coverage in database

Among 3,100 chemicals

High-volume production



Christopher Oberschelp, ETH Zurich, LCM conference 2023, Lille (FR)

- ✓ Low coverage by nb of chemicals: **9 à 19 %**
- ✓ BUT much less … for **IC industry**:
  - **Specialities**: Raw Materials mixture & solvent
  - Microelectronics grade– **High-purity**

I. Servin et al., Life Cycle Innovation Conference LCIC Berlin, 2024

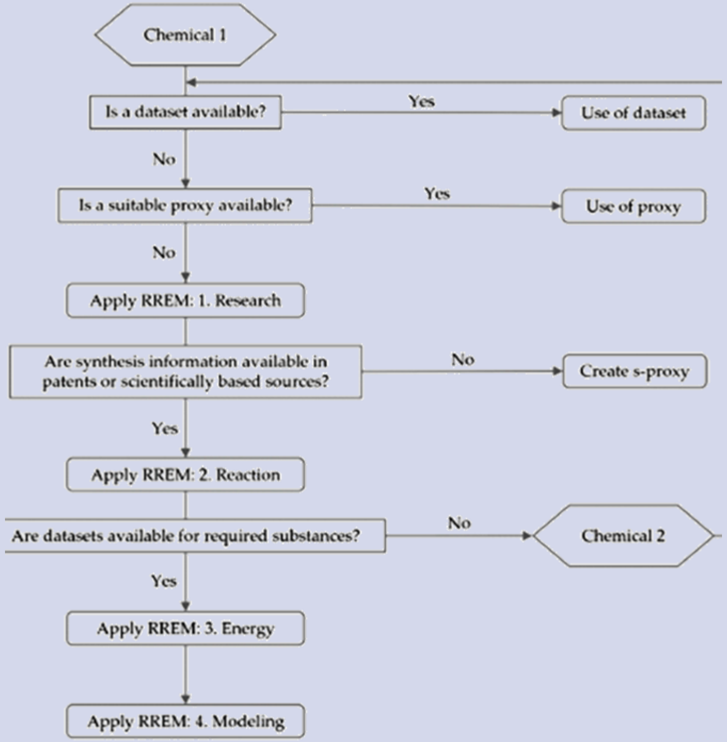
Which strategy for missing data?

Mixture of DB & modeling

DB by default — ecoinvent v3.10

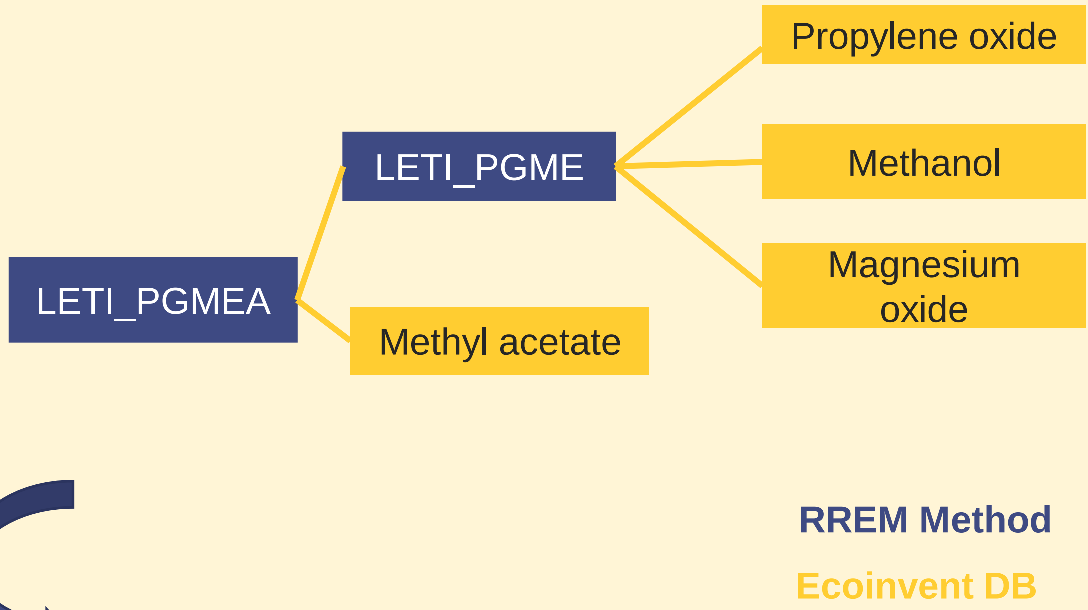
Complementary DB
Data on-demand (paying) — carbonminds, sphera

RREM* method
Modeling with s-proxy



*RREM Research, Reaction, Energy, Modeling

S-proxy model (RREM)



LETI_PGMEA
Hussain et al. 2019 (Hussain *et al.*, 2019)
https://pubs.acs.org/doi/abs/10.1021/acs.iecr.8b04052

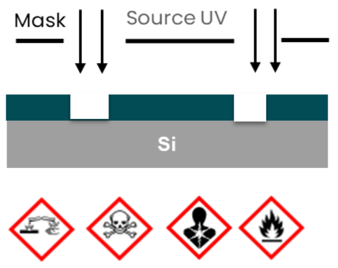
LETI_PGME
By-products not considered
Zeng et al. (Zeng *et al.*, no date)
https://link.springer.com/article/10.1007/s10562-010-0335-y

Huber, E. et al. 'An Approach to Determine Missing Life Cycle Inventory Data for Chemicals (RREM)', Sustainability, 14(6), p. 3161 (2022)
I. Servin et al., Life Cycle Innovation Conference LCIC Berlin, 2024

Environnemental impact of photoresists for optical lithography

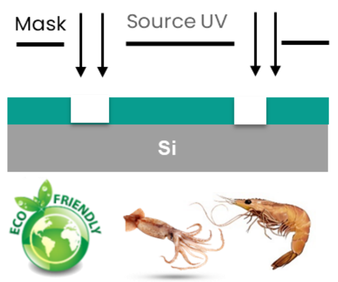
Bio-sourced photoresists

Conventional



Oil-based*
PGMEA
TMAH

Bio-sourced



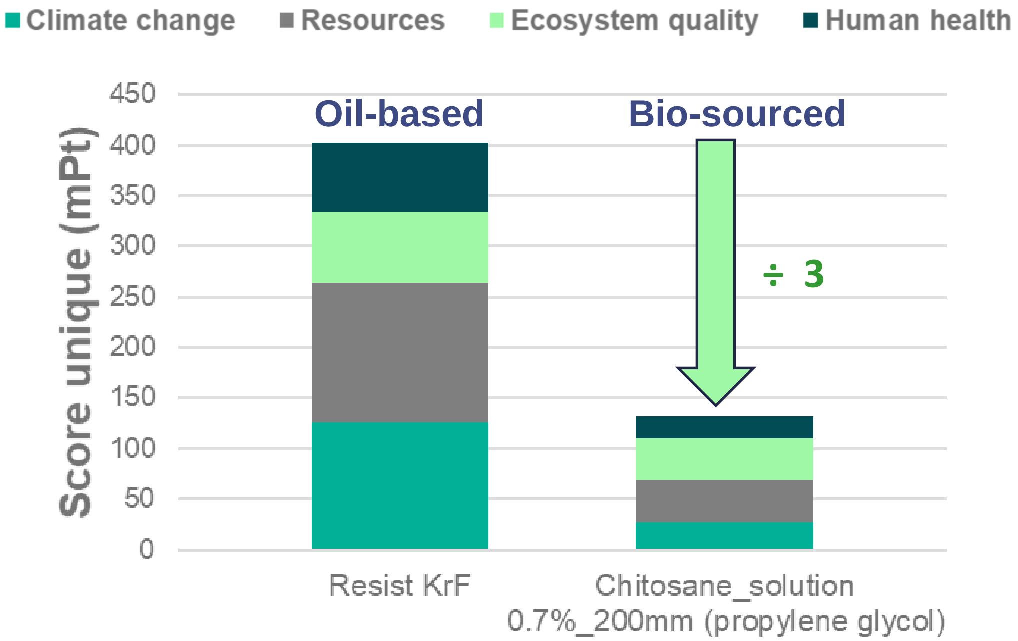
Bio-sourced**
DI Water
DI Water or green solvent

Lithogreen
2020 → Q1 2024

2024 → 2027

I. Servin et al. Micro and Nano Engineering 2023
I. Servin et al., SPIE Advanced Lithography, 2023
O. Sysova et al., Journal of Applied Polymer Science, 2023

Conventional vs bio-sourced for 1ml solution



Bio-sourced resist
3x less impacted vs oil-based resist

LCA of bio-sourced resist

Production modeling 1. to 4.

1. Shrimp fishing [1] → 2. Shrimp shell → 3. Chitine_Mahtani (IN) (2] → 4.Chitosan_Mahtani (IN) [2] →

[1] Farmery, A. *et al.* (2015) *Journal of Cleaner Production*, 87, pp. 96–104. https://doi.org/10.1016/j.jclepro.2014.10.063

[2] Muñoz et al. (2018) The International Journal of Life Cycle Assessment, 23(5), pp. 1151–1160. https://doi.org/10.1007/s11367-017-1290-2.

Data from CNRS 5. & 6.

5. Chitosan_Reacetylation (FR) (CNRS) → 6. Chitosan_solution FR) (CNRS)

Experimental protocol provided by CNRS—IMP (Lyon)

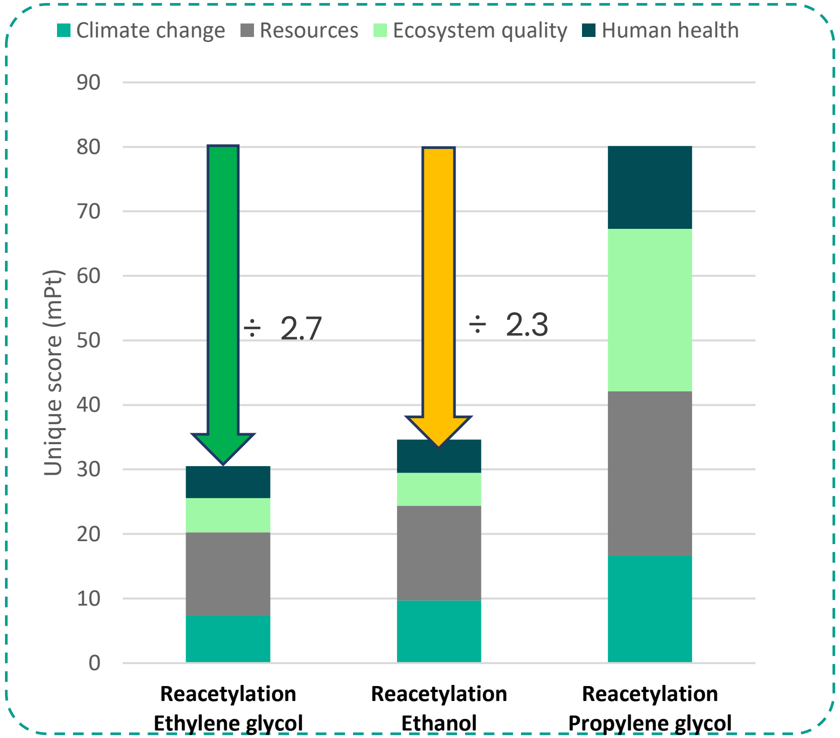
Chitosan solution : major impacts

LETI_chitosan solution 0.7%
100%

- LETI_chitosan reacetylation
  98.8%
  - LETI_chitosan Mahtani (India)
    3%
  - Propylene glycol
    94% 3L for 20 g
- Electricity
  1.03%
- Others

Solvent alternatives

- Ethanol
- Ethylene glycol



Main impact : **Reacetylation step**
With the use of **propylene glycol** as solvent

LCA of bio-sourced resist

Production modeling 1. to 4.

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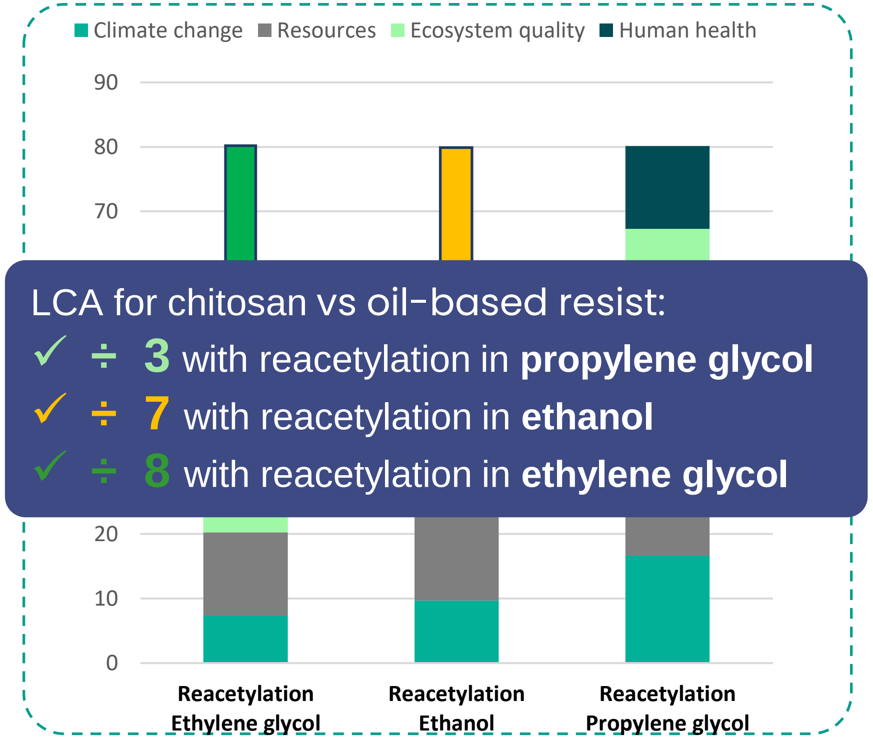
    - Propylene glycol — 94% 3L for 20 g
  - Electricity — 1.03%
  - Others

Solvent alternatives

- Ethanol
- Ethylene glycol



LCA for chitosan vs oil-based resist:

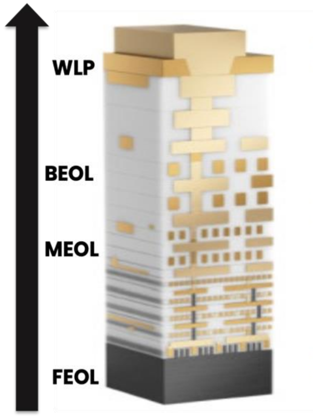
- ✓ ÷ 3 with reacetylation in **propylene glycol**
- ✓ ÷ 7 with reacetylation in **ethanol**
- ✓ ÷ 8 with reacetylation in **ethylene glycol**

Main impact : **Reacetylation step**
With the use of **propylene glycol** as solvent

Environnemental impact of chemicals for post-etch polymer removal

Eco-designed chemistries

Stripping-Etching-Cleaning-Decontamination



- **Quaternary ammonium free** Stripper
  H_3PO_4 free Metal etchant
- **Wet chemistry CMR free** for post-etch cleaning
- **Hot H_3PO_4 free** Si_3N_4 etching
  Aqua regia free for decontamination

Development of eco-designed chemistries

TECHNIC → cea leti → ST

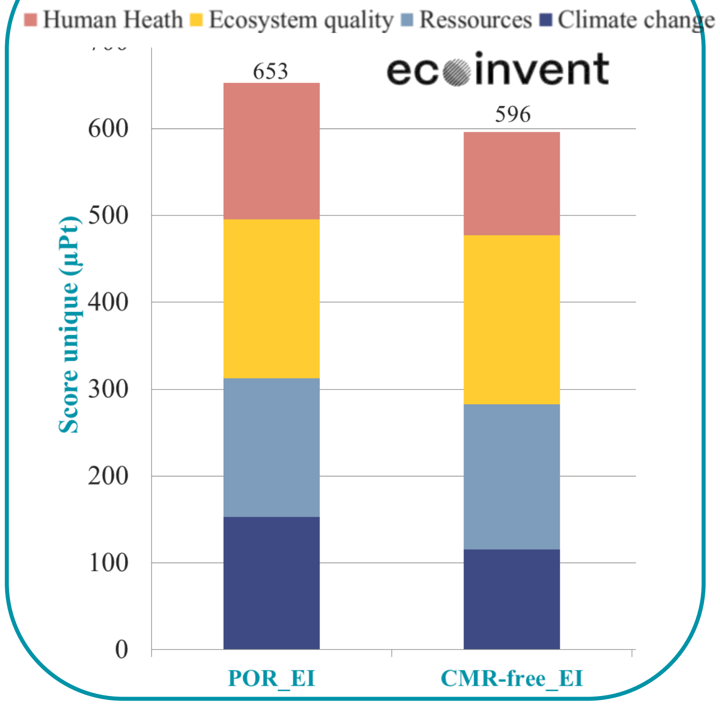
Qualification in pilot line

Industrial transfer

CLEAN bpifrance FRANCE RELANCE

- Local and sustainable raw material
- Health and Safety regulations (Toxic & CMR-free)
- Low impact environmental
- Waste management

LCA for 1kg production PoR vs CMR-free



I.Servin, M.Audouin et al., UCPSS 2025 (Leuven)

Single score (LCA)

PoR ≅ CMR-free

No significant improvement by **removal of CMR**

REASON

Low weight of impact factors

"Human Toxicity" **4%**

& "Eco Toxicity" **1,9%**

SSbD* framework

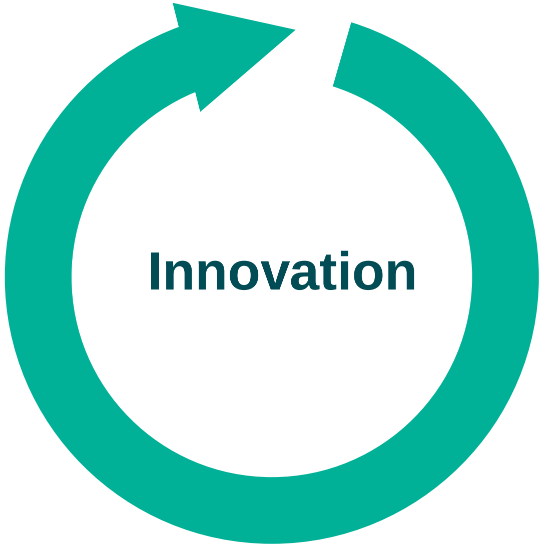
Goals:

- **Manage** and **assess** chemical **risks**
- Prioritize **safety** for both human health and the environment
- Promote **innovation**

Framework

- **Iterative and tiered** approach with increasing TRL

Increasing TRL



Step 4

LCA

ISO 14 040 and ISO 14 044

Approved Life Cycle Assessment

Step 1

Hazard assessment

Priority:
HSE regulations
REACH compliance regulations

Step 2-3

Risk assessment

- Production
- Use

*SSbD Safe and Sustainable by Design

Joint Research Centre (JRC), https://publications.jrc.ec.europa.eu/repository/handle/JRC138035

SSbD Step1 hazard assessment

Step 1

Hazard assessment

Criteria	Hazard categories
H1	Carcinogenicity
	Germ cell mutagenicity
	Reproductive toxicity
	Endocrine disruption
	Respiratory sensitisation
	Immunotoxicity
	Neurotoxicity
	Specific target organ toxicity (repeated exposure)
	(very) Persistent, (very) bioaccumulative and toxic (PBT/vPvB)
	(very) Persistent, mobil and toxic (PMT/vPvM)
H2	Potential carcinogenicity
	Potential mutagenicity
	Potential reproductive toxicity
	Skin sensitisation
	Potential specific target organ toxicity (repeated exposure)
	Specific target organ toxicity (single exposure)
	Potential endocrine disruption
	Hazardous for the ozone layer
	Chronic environmental toxicity
H3	Acute toxicity
	Skin corrosion
	Skin irritation
	Serious eye damage/irritation
	Aspiration hazard
	Potential specific target organ toxicity (single exposure)
	Acute environmental toxicity
	Physical hazard (explosive, flammable, aerosol, self-reactive...)

Example of ***Safety Data Sheet (FDS)***
with Hazard Statements

Label elements

Labelling according Regulation (EC) No 1272/2008

Pictogram

Signal Word Danger

Hazard Statements

H225 Highly flammable liquid and vapor.
H304 May be fatal if swallowed and enters airways.
H315 Causes skin irritation.
H319 Causes serious eye irritation.
H340 May cause genetic defects.
H350 May cause cancer.
H372 Causes damage to organs (Blood) through prolonged or repeated exposure.
H412 Harmful to aquatic life with long lasting effects.

H372 Causes damage to organs

H1 most harmful substances

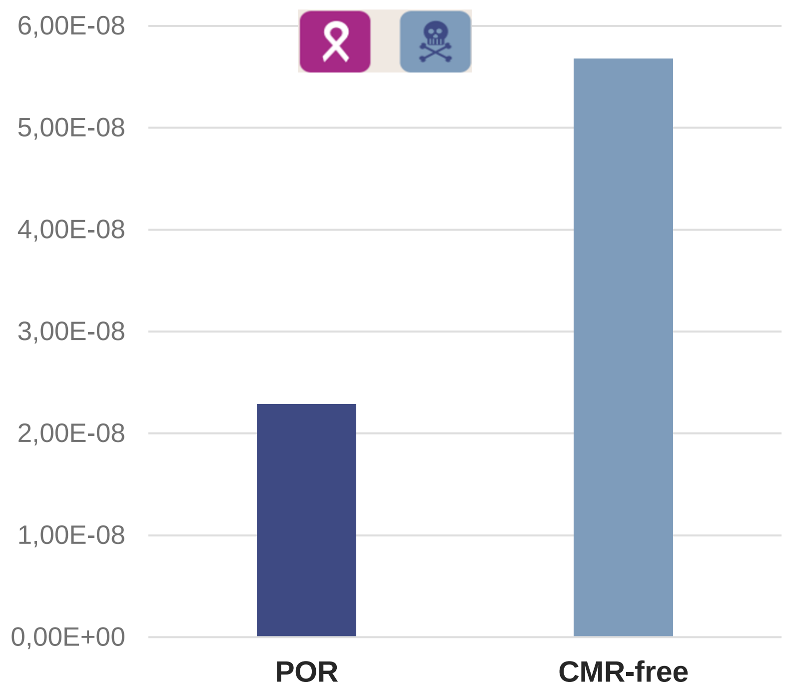
H1 most harmful substances
H2 substances of concern
H3 other classes.

SSbD Hazard asssement of formulation

High TRL

CLEAN

LCA : Human toxicity impact factor (CTUh)

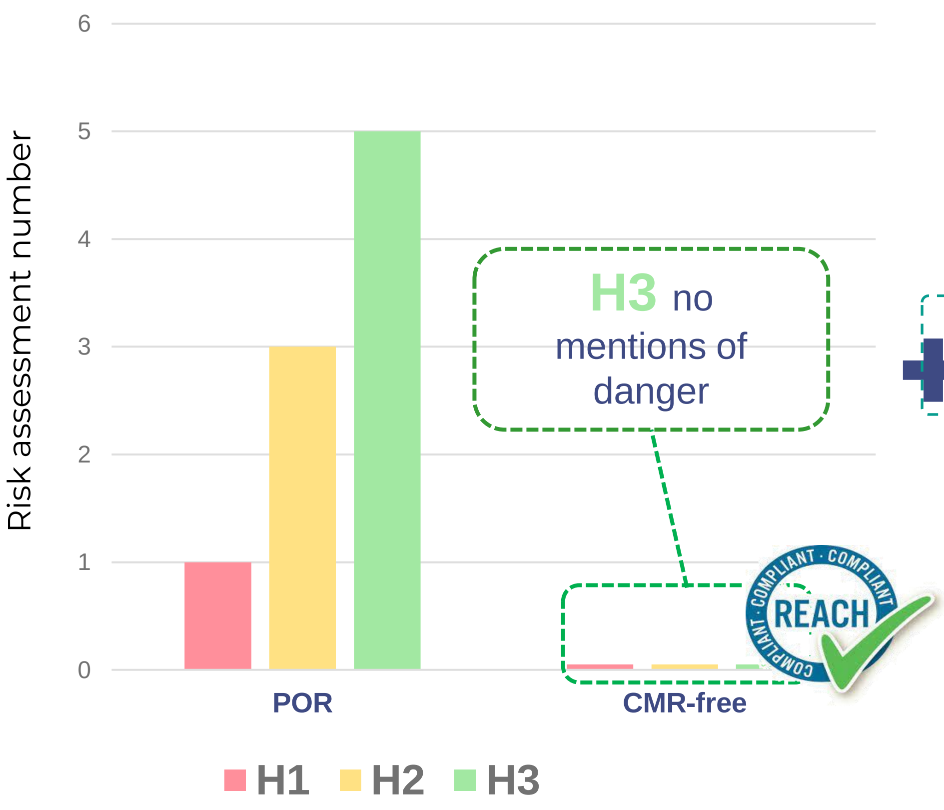


CF = FF × XF × EF [1]

UseTox model complexity

The multiplication of uncertainties in each calculation contributes to the **low reliability** of the **"Human Toxicity"** and **"Eco Toxicity"** impact factors.

SSbD Step 1 CMR-free alternative



Step 2-3

+ Risk score low

SSbD approach confirmes safety gain with toxic-free chemical suppression

[1] Fantke et al., USEtox 2.0 https://usetox.org/model/documentation, 2017

SSbD Toxicity of PAGs

PAG: Photo-acid generators (<1%) added in resists

H1 most harmful substances
H2 substances of concern
H3 other classes.

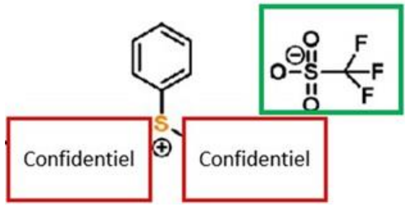
Low TRL

PAG evaluation

1. PAGs commercially available

No **H1** or **H2** identified but most of them are **PFAS*** molecules

2. For synthetized PAGs: bibliography review



Example of sulfonium

Sulfonium [1] + **Triflate [2]**

Tests on Guinea pigs

Dermal irritation: negative
Mutagenicity: negative
Oral toxicity: negative
Skin sensitization: negative

Tests on fish fry

No toxicity identified

PFAS molecule

SSbD step1 compliant

PFAS (–CF2 or –CF3)

Solvent used for synthesis

Examples:

- **Dimethylformamide:** Reproductive toxicity
- **1,2-Dichloroethane:** Carcinogenicity

H1 most harmful substances

To be replaced by safer solvent (**H3** category)

SSbD framework applied at **low TRL** enables to design **safer chemicals**, guides to **non-toxic solvent** BUT does not sufficiently anticipate future restrictions under the **REACH Regulation** (ex PFAS)

* Known as « Forever Chemicals »

[1] Michiasa HIRAYAMA, «*The Antimicrobial Activity, Hydrophobicity and Toxicity of Sulfonium Compounds, and Their Relationship*» (2010)
[2] Younes et al. «*Toxicity evaluation of selected ionic liquid compounds on embryonic development of Zebrafish* » (2018)

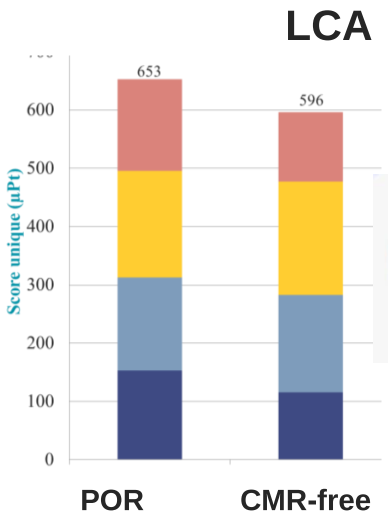
Conclusion

Projects aimed at reducing the **toxicity** of chemicals used in **microelectronics.**

- **LCA of chemicals production** often failed to show any concrete gains despite the **removal of hazardous substances** (REACH complaint)

✓ The results show at worst **no deterioration** in environmental impact.

- Allows to identify the **« hotspots »**



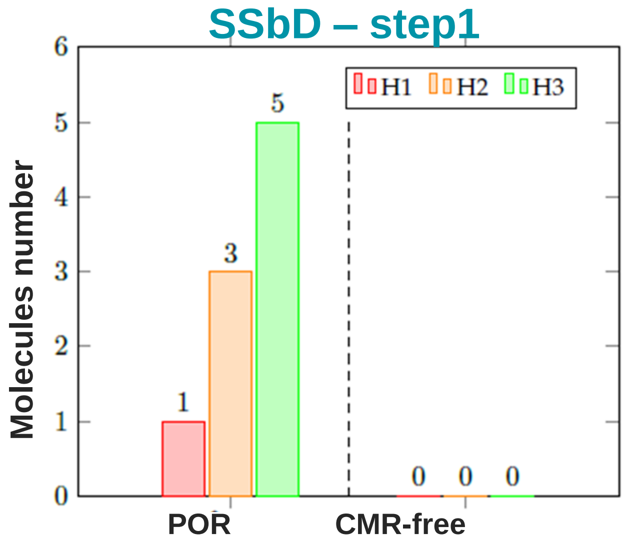
- **SSbD framework** promoted by EU commission

Comprehensive and powerful approach that integrates **environmental** + **safety** concerns for chemicals with increasing TRL

✓ Step 1 : Quantify of the **reduction in toxicity** (HSE & safety concerns)

✓ Steps 2-3 show that the production and use of the products do not pose any particular risk (i.e the risk is minimal)

✓ Complete SSbD requires a great deal of **expertise** to carry out the entire process (toxicology analysis + advanced analysis, in silico study)



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Funded by the European Union
NextGenerationEU

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Funded by the European Union

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