The environmental impact of IC chip manufacturing
Sustain-E Summer School – Thu June 19 2025

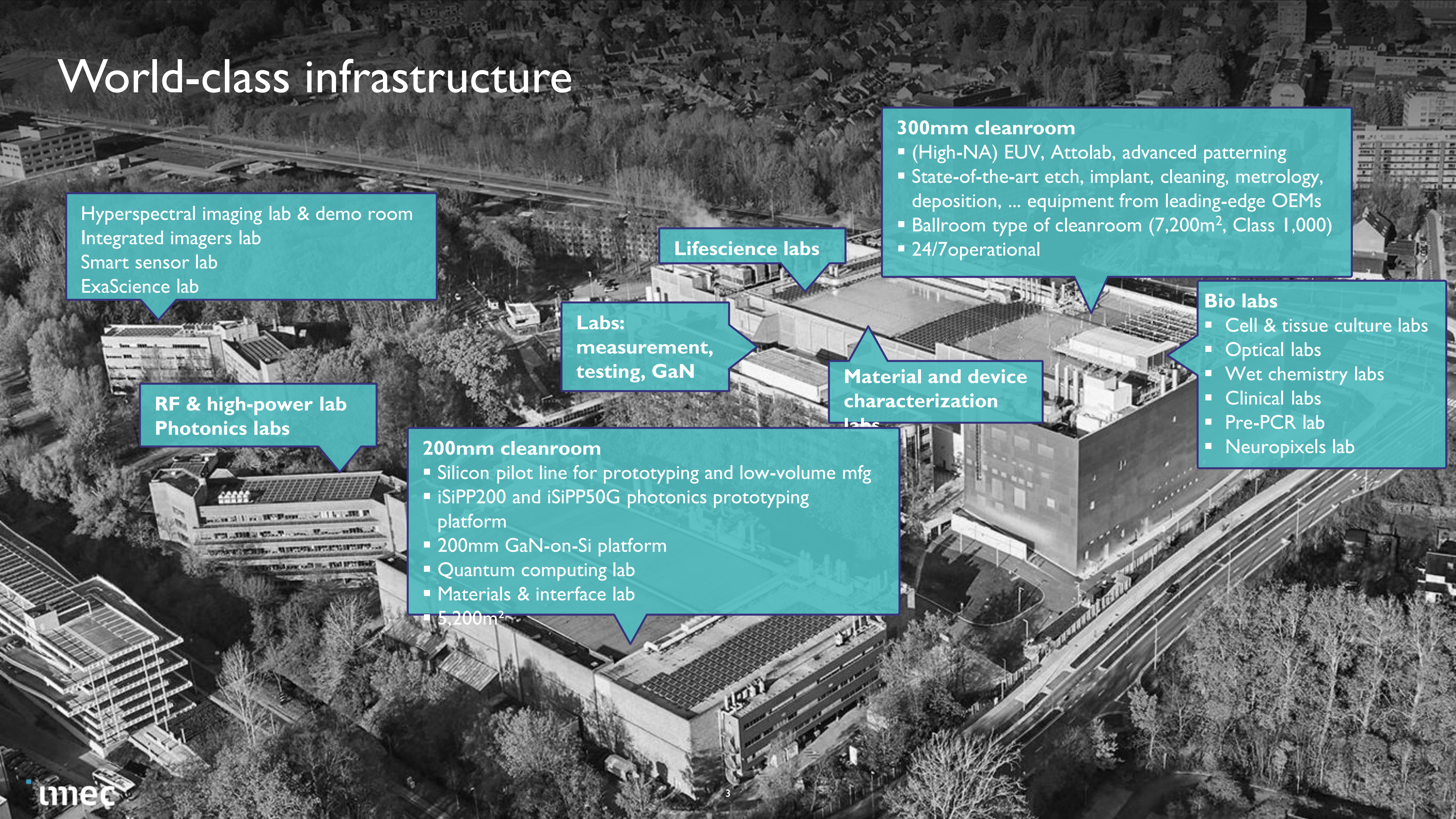
Cédric Rolin

Program Manager Sustainable Electronics

imec

- Founded in1984 in Leuven, Belgium
- Independent non-for-profit organization
- Europe's largest nano/micro-electronics research center
- 846 million € revenue in 2022
  - 69% industry, 24% regional government, 7% EU & regional program
- Collaboration with >600 companies and >200 universities
- >6500 people working at imec of which >500 residents
- >3 billion € infrastructure
- >120 spin-offs created

World-class infrastructure



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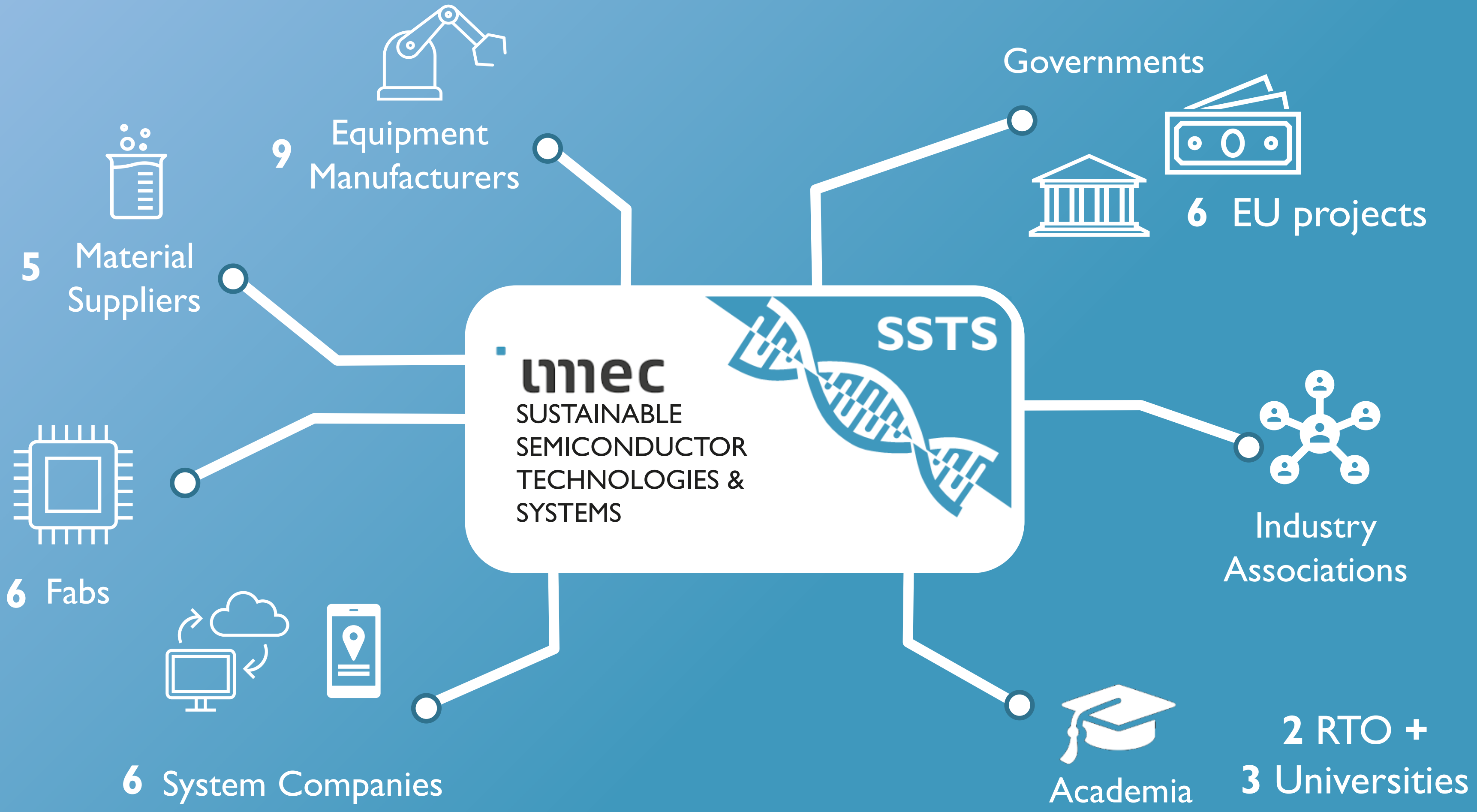

Our mission: Help the IC manufacturing value chain reach its environmental sustainability targets

Macro view: the impact of the semiconductor industry

Scope: focus today is on IC **manufacturing**

How does it compare to the use phase? → Product-dependent, but never negligible

sustainability MDPI

Opinion

Could Unsustainable Electronics Support Sustainability?

Nicolas Moreau [1], Thibault Pirson [2], Grégoire Le Brun [2], Thibault Delhaye [2], Georgiana Sandu [2], Antoine Paris [2], David Bol [2] and Jean-Pierre Raskin [2,*]

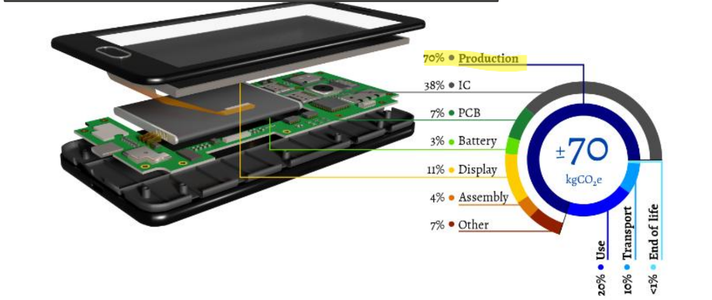

Figure 1. Typical carbon footprint (in kg CO_2 equivalent) generated over a smartphone lifetime. Integrated and printed circuit boards (IC and PCB) account for the largest share of the impacts. The values have been determined by the results presented in [16,21].

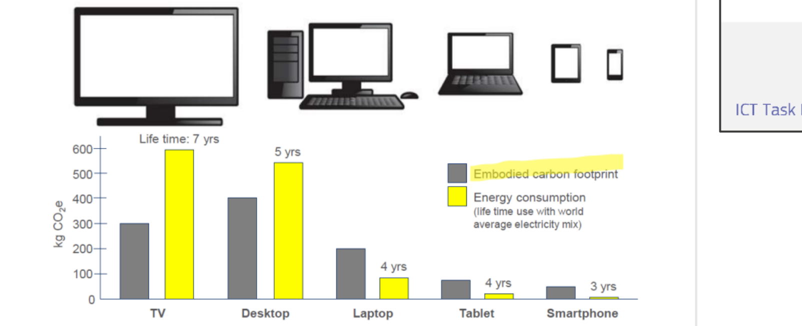

Figure 3: Estimated embodied carbon footprint and use (active lifetime) carbon footprint for common end user ICT devices. Source: Malmodin and Lunden (2018)

SUSTAINABLE AI: ENVIRONMENTAL IMPLICATIONS, CHALLENGES AND OPPORTUNITIES

Carole-Jean Wu [1] Ramya Raghavendra [1] Udit Gupta [1,2] Bilge Acun [1] Newsha Ardalani [1] Kiwan Maeng [1] Gloria Chang [1] Fiona Aga Behram [1] James Huang [1] Charles Bai [1] Michael Gschwind [1] Anurag Gupta [1] Myle Ott [1] Anastasia Melnikov [1] Salvatore Candido [1] David Brooks [1,2] Geeta Chauhan [1] Benjamin Lee [1,3] Hsien-Hsin S. Lee [1] Bugra Akyildiz [1] Max Balandat [1] Joe Spisak [1] Ravi Jain [1] Mike Rabbat [1] Kim Hazelwood [1]

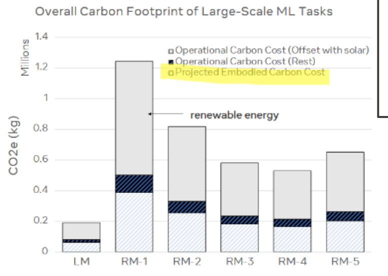

Figure 5. When considering the overall life cycle of ML models and systems in this analysis, manufacturing carbon cost is roughly 50% of the (location-based) operational carbon footprint of large-scale ML tasks (Figure 4). Taking into account carbon-free energy, such as solar, the operational energy consumption can be significantly reduced, leaving the manufacturing carbon cost as the dominating source of AI's carbon footprint.

Coarse rule of thumb:
- For portable devices → manufacturing is ~70%
- For datacenters → manufacturing is ~30%

With more low-carbon electricity, manufacturing increasingly dominates

Scope: focus today is on **IC** manufacturing

How does it compare to the other components? → Product-dependent, often dominant

sustainability MDPI

Opinion

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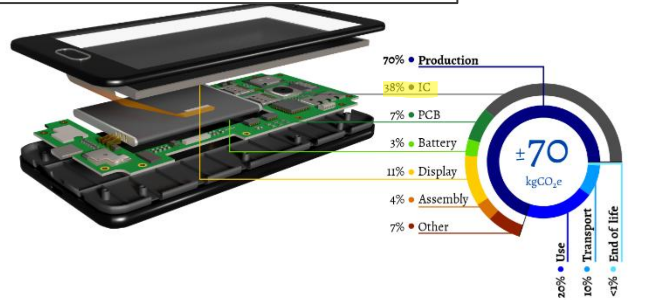

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ICT Task Force study: Final Report

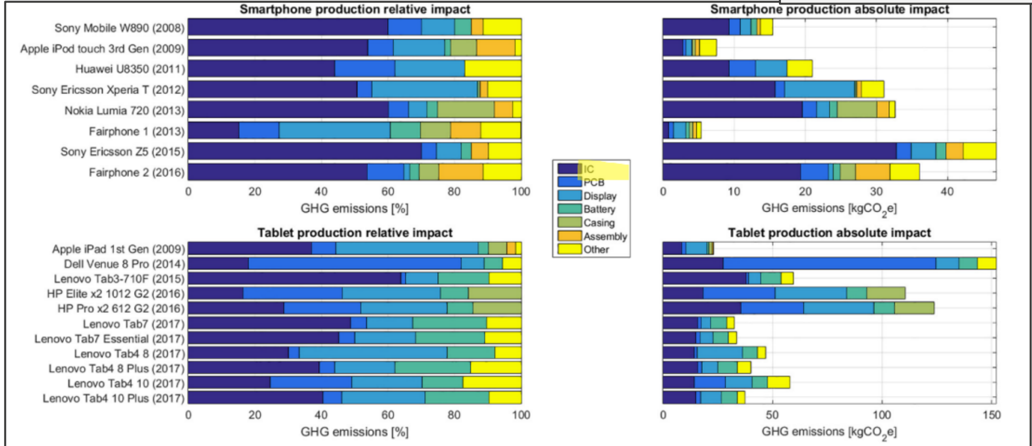
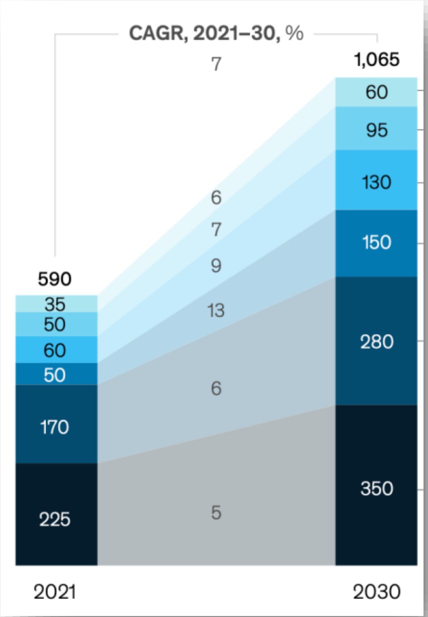


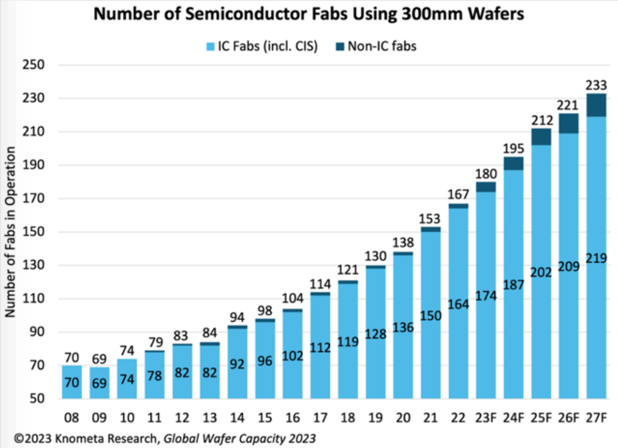
Figure 7: Sub-components production impact. Source: Clement et al. (2020)

Challenge 1: Semiconductor industry is growing fast

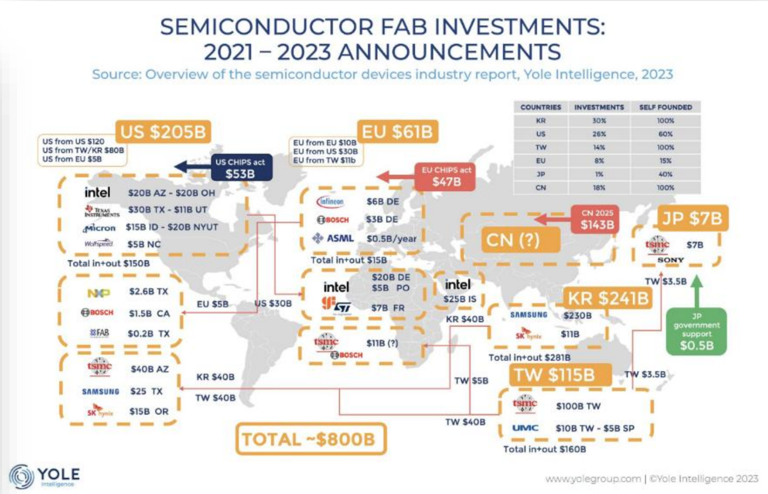
Boosted by Chips Acts, many Fabs scheduled to open despite current market weakness



Strong projected growth



More 300mm Fabs



COUNTRIES	INVESTMENTS	SELF FOUNDED
KR	30%	100%
US	26%	60%
TW	14%	100%
EU	8%	15%
JP	1%	40%
CN	18%	100%

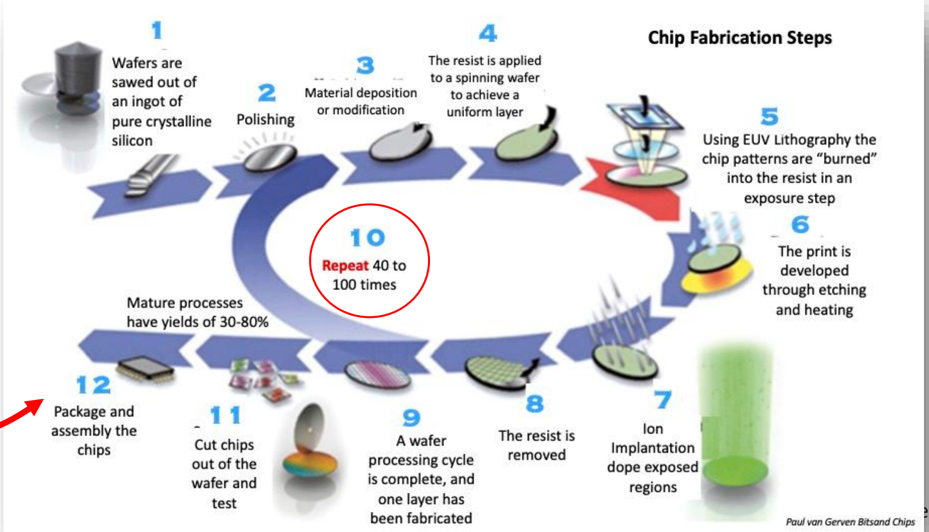
Massive funding

Source: Chip Industry Heads Toward $1T (semiengineering.com)

Challenge 2: IC technology is complex

IC chips = most complex mass-produced objects

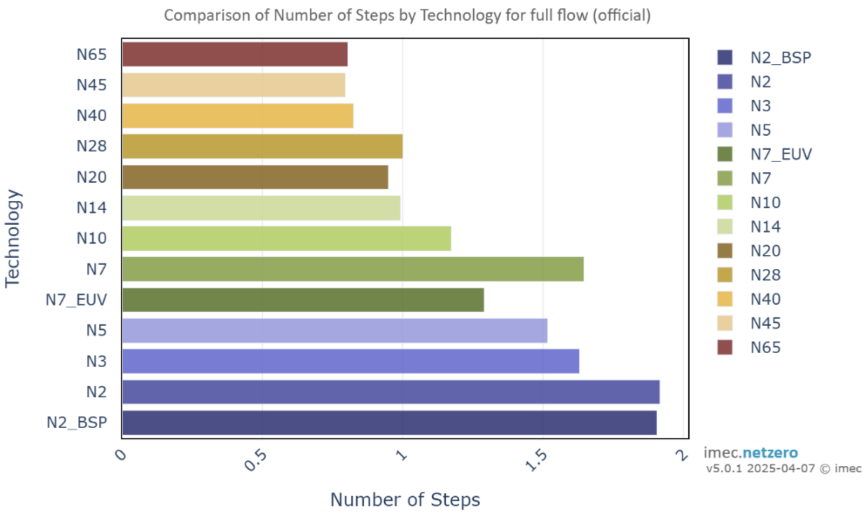
Source: AWS



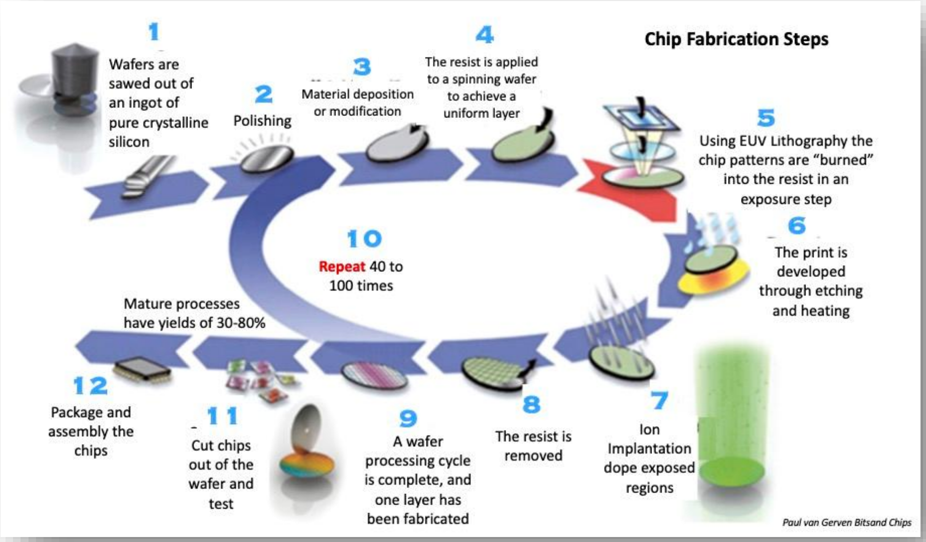
estricted

Challenge 2: IC technology complexity increases

Normalized number of process steps



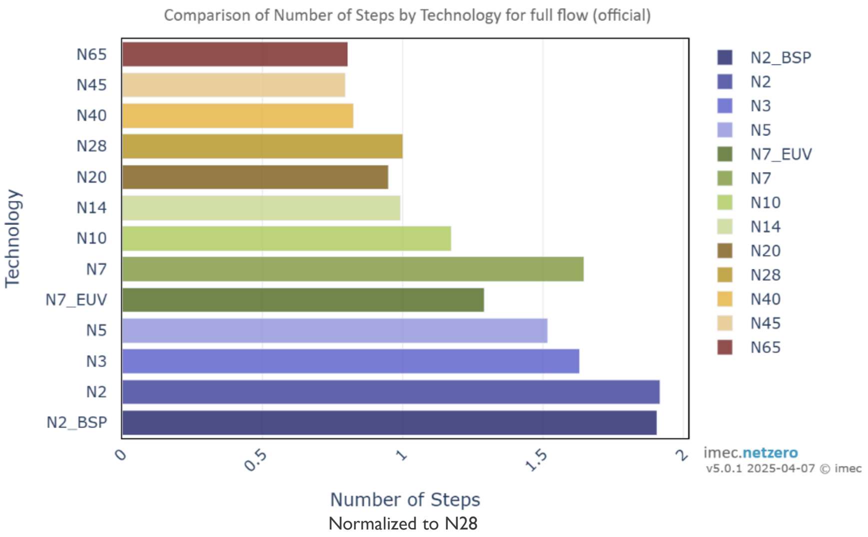
Normalized to N28

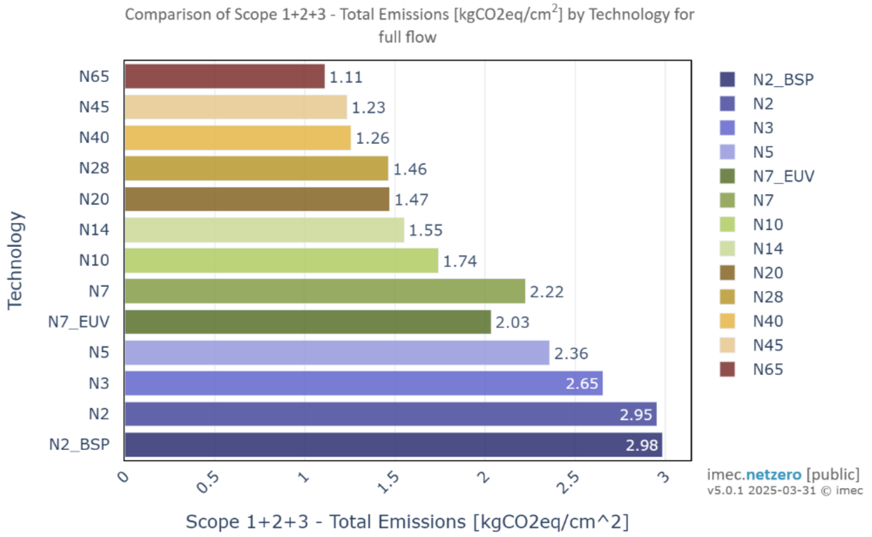


Challenge 2: IC technology complexity **-and emissions-** increase

Normalized number of process steps… correlates well with emissions

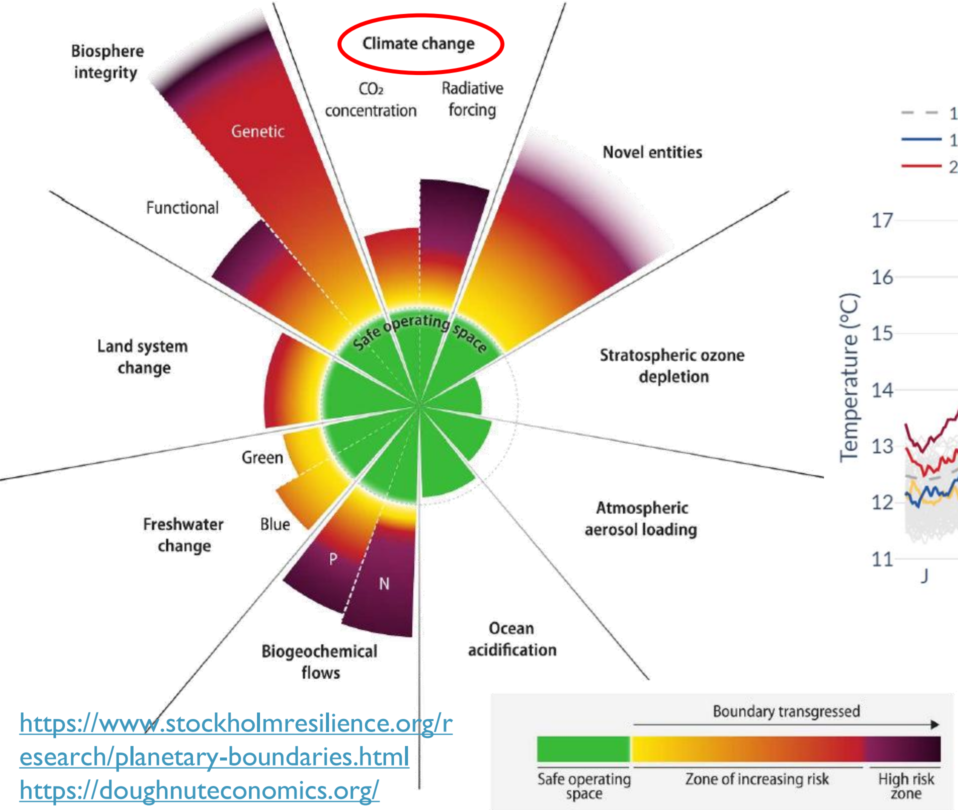
We'll come back to that



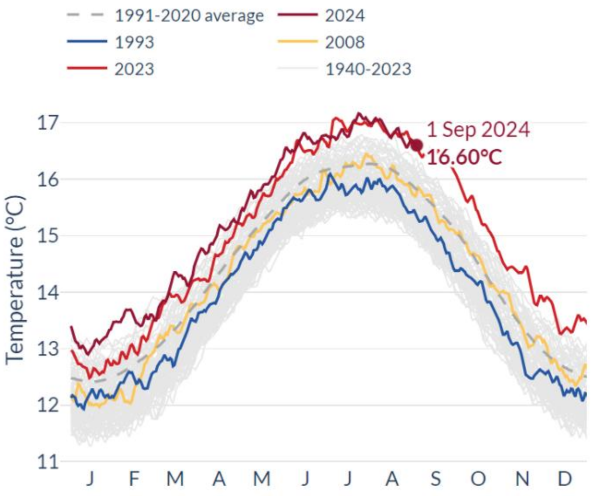


Areas of concern for semiconductor industry – Climate Change

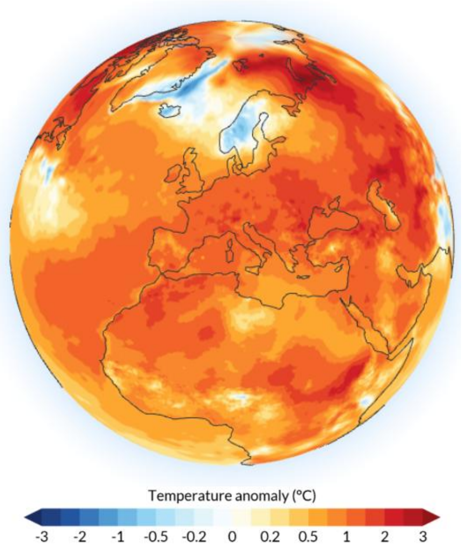
9 planetary boundaries



https://www.stockholmresilience.org/research/planetary-boundaries.html
https://doughnuteconomics.org/



Global surface air temperatures 1940-2024



Annual mean anomaly 2023 vs average 1991-2020

Data: ERA5 / Credit: C3S/ECMWF
WebApp:https://pulse.climate.copernicus.eu/

CO_2 Emissions from Semiconductor Industry in Perspective

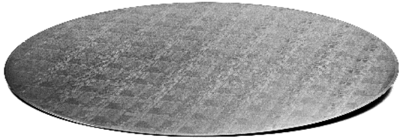
~ 36 billion tons

World-wide

~ 1,2 billion tons

ICT Industry

~ 185 million tons



Semiconductor manufacturing

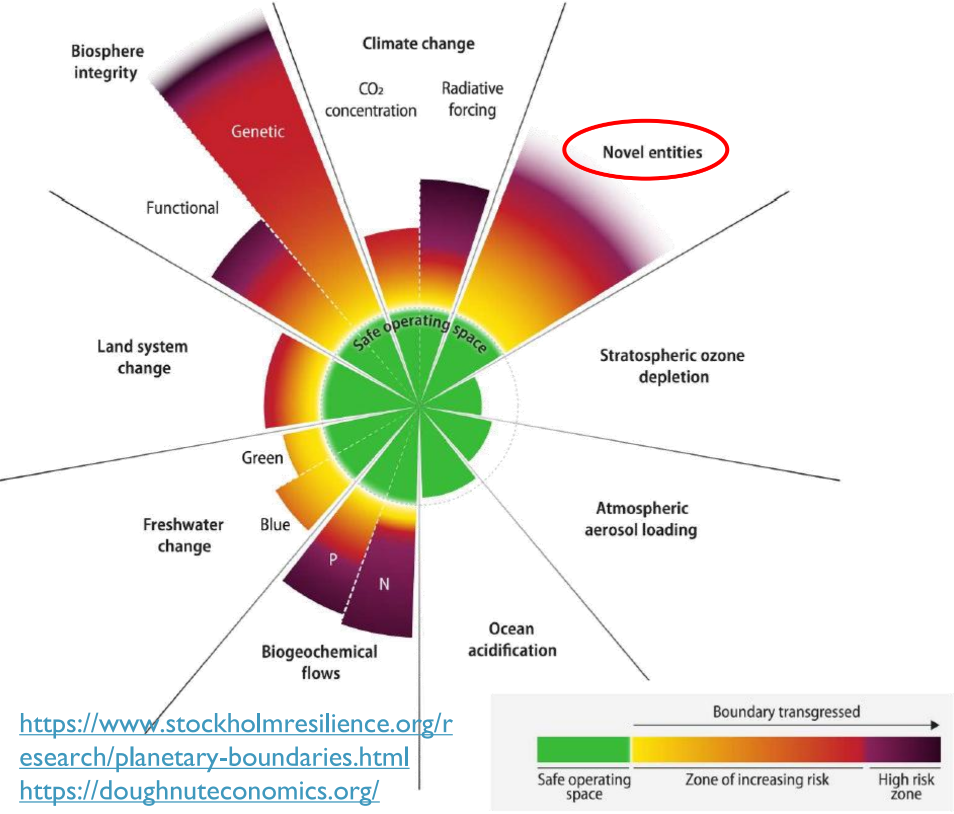
Sources: Liu et al. Nature reviews earth & environment 2023 (Fossil fuels and Cement only)

Source: Freitag, C. Et al. 2021. http://arxiv.org/abs/2102.02622

Includes Scope 1, scope 2 and scope 3 consumables and services. For industry in 2021.
Source: SEMI SCC Whitepaper on Transparency, Ambition, and Collaboration - 2023

Areas of concern for semiconductor industry – Novel entities

9 planetary boundaries



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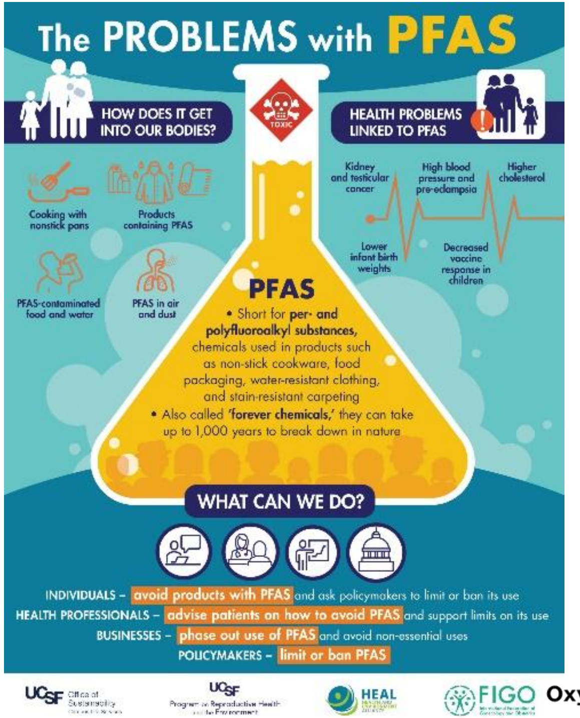
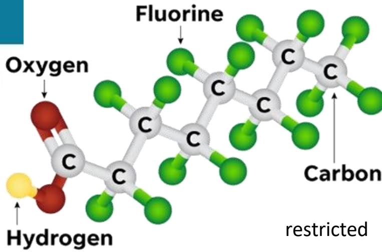
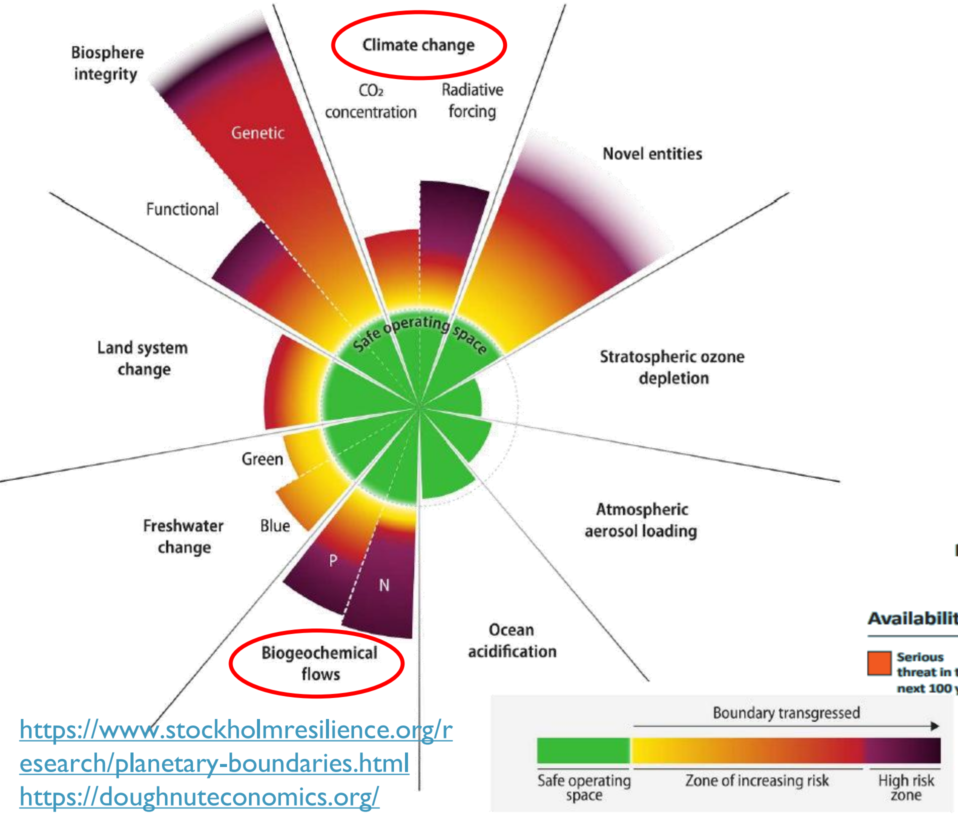


Perfluorooctanoic Acid (PFOA)



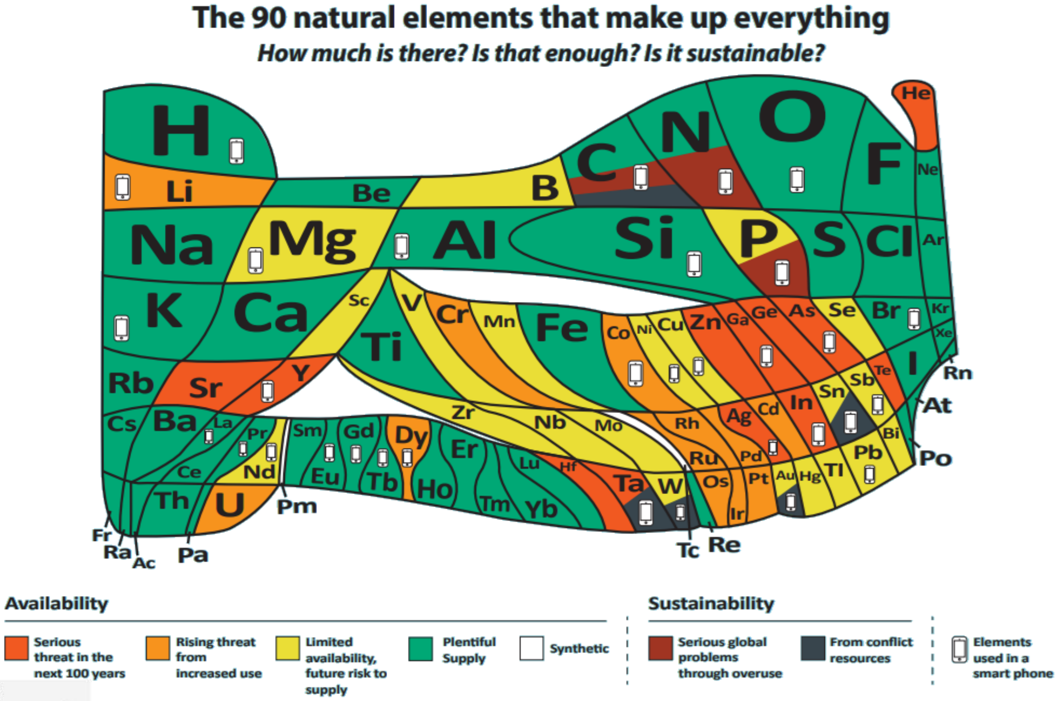
Areas of concern for semiconductor industry – Material Sourcing

9 planetary boundaries



https://www.stockholmresilience.org/research/planetary-boundaries.html
https://doughnuteconomics.org/

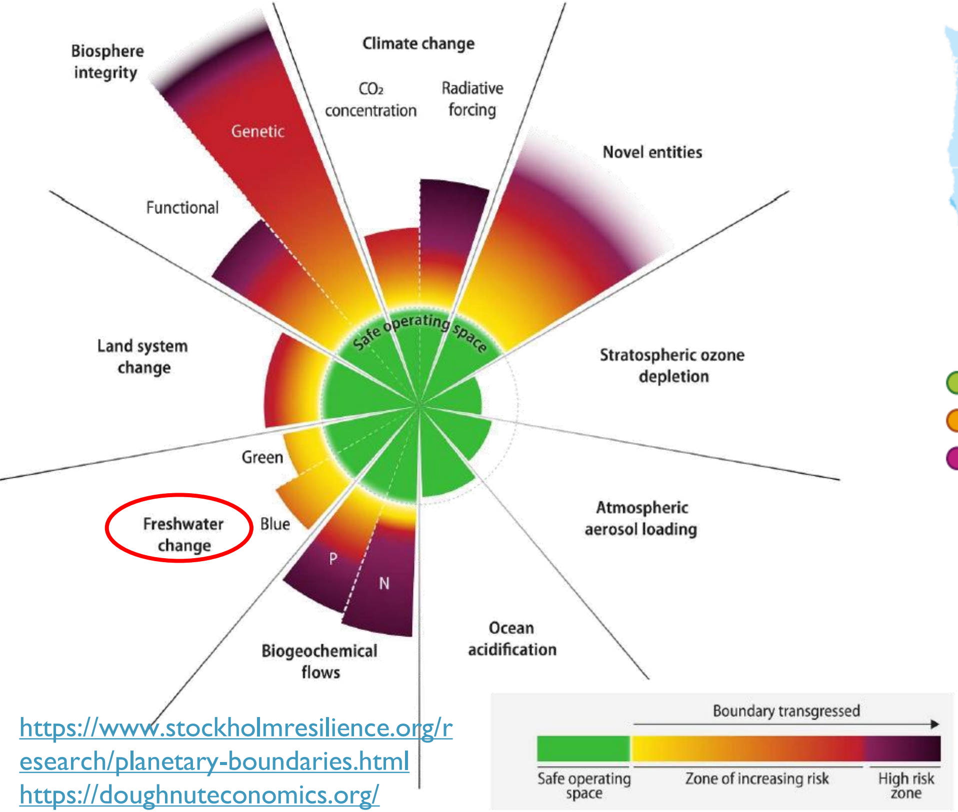
Resource depletion and geopolitical tensions



https://www.euchems.eu/euchems-periodic-table/

Areas of concern for semiconductor industry - Water

9 planetary boundaries



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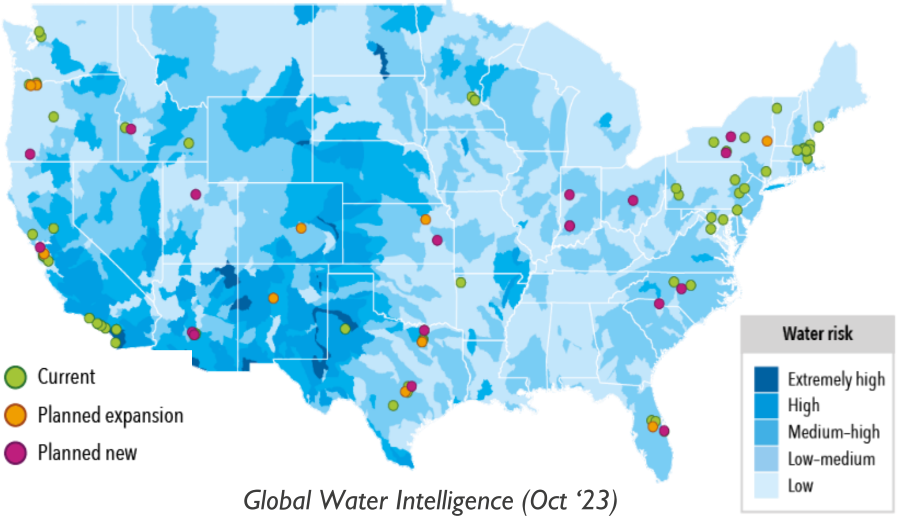


Global Water Intelligence (Oct '23)

Chipmakers in drought-hit Taiwan order water trucks to prepare for 'the worst'

Reuters (Feb '21)

There is strong ambition in the sector...

News - 28 August, 2023

ASM first in semiconductor industry to have net-zero target verified by SBTi

Almere, The Netherlands
August 28, 2023

Press releases | ASM

ASM

PRESS RELEASE • September 12, 2023

Apple unveils its first carbon neutral products

The new Apple Watch lineup marks major progress toward ambitious Apple 2030 climate goal

Product Environmental Report

Advanced materials for sustainable electronics

April 21, 2023 Press release Air Liquide

Air Liquide

January 31, 2023 Press Release Amazon

amazon

Amazon Sets a New Record for Most Renewable Energy Purchased by a Single Company

Transparency, Ambition, and Collaboration:

Advancing the Climate Agenda of the Semiconductor Value Chain

SCC White Paper

Semiconductor Climate Consortium

TSMC Accelerates Renewable Energy Adoption and Moves RE100 Target Forward to 2040

Issued by: TSMC
Issued on: 2023/09/15

tsmc

Press release TSMC

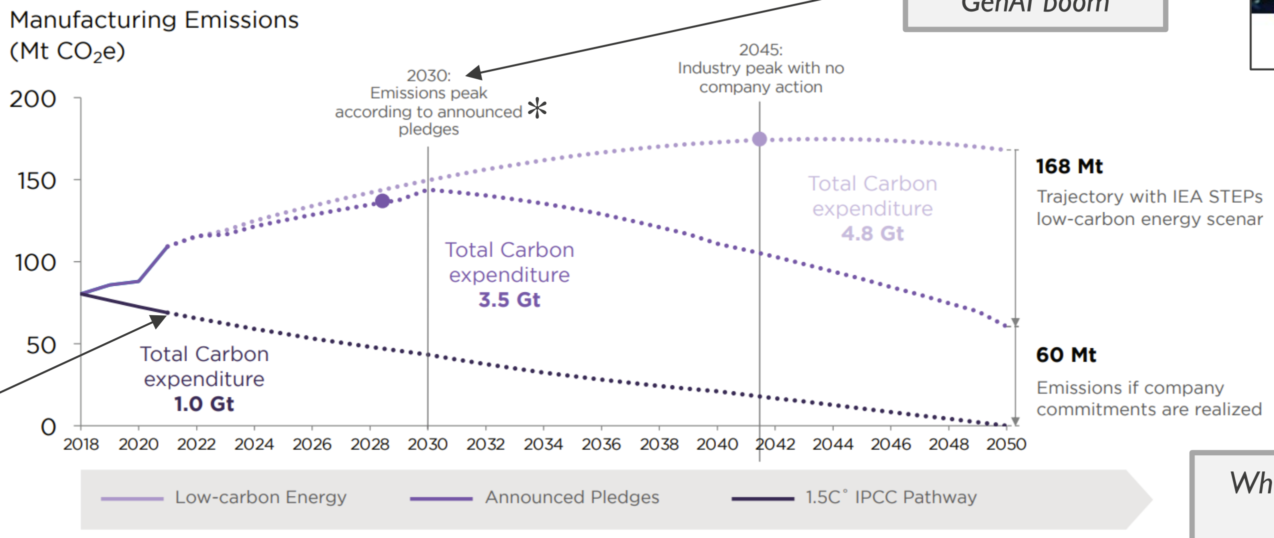
TSMC Accelerates Renewable Energy Adoption and Moves RE100 Target Forward to 2040

There is strong ambition in the sector... But more is likely needed

Announced* plegdes: estimated reduction of ~30% (but we need 100%)

Exhibit 7:

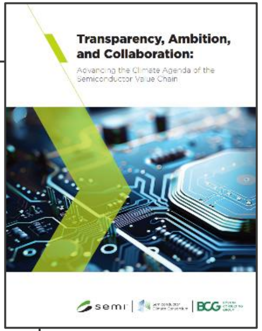
Announced sustainability pledges reduce total 2019–2050 emissions by 30% and are within 60 Mt CO_2e of 2050 net zero



1 Emissions growth based on projected capacity growth (3.25%) and average intensity growth (1.01%), all else constant
Note: Low-carbon energy scenarios use IEA STEPS for North America, Europe, and Asia-Pacific. Source: BCG analyses on data from: CDP, imec, SEMI, IEA

**This was before GenAI boom*

Paris Agreement "fair share"

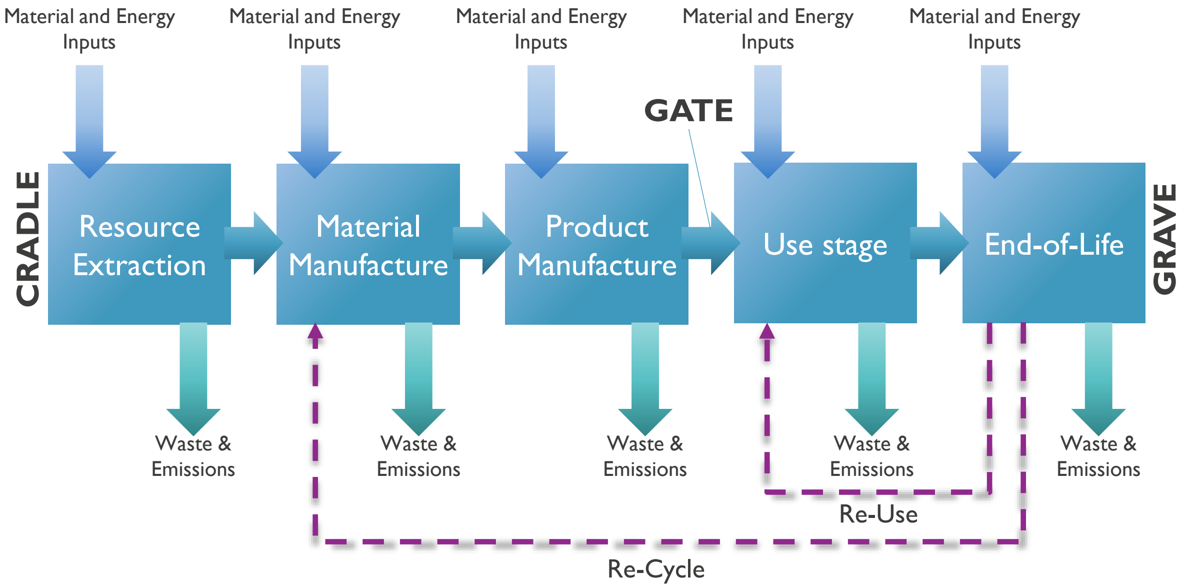


What would be required to close the gap?

Intermezzo: A detour to LCA theory

Life-Cycle Assessment (LCA) in a nutshell

*"A methodology for the assessment of the **environmental impacts** associated with all the stages of the life cycle of a **product** or a **service**"*



Holistic approach: Don't shift the burdens!

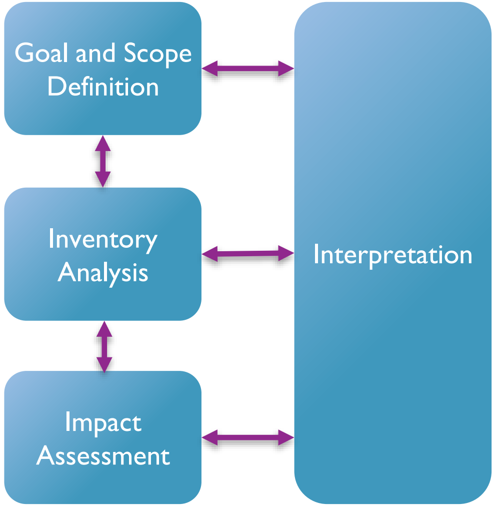
Life-Cycle Assessment (LCA) in a nutshell

Motivation for LCA

- **Compliance**:
  Meet legal requirements
- **Market driven**:
  Meet customer requirements
- **Engaged**:
  Identify improvement opportunities through value chain
- **Shape the future**:
  Inform Eco-design at an early stage

Resources
Engagement
Stewardship

General phases of LCA



From ISO14040 and ISO14044 standards

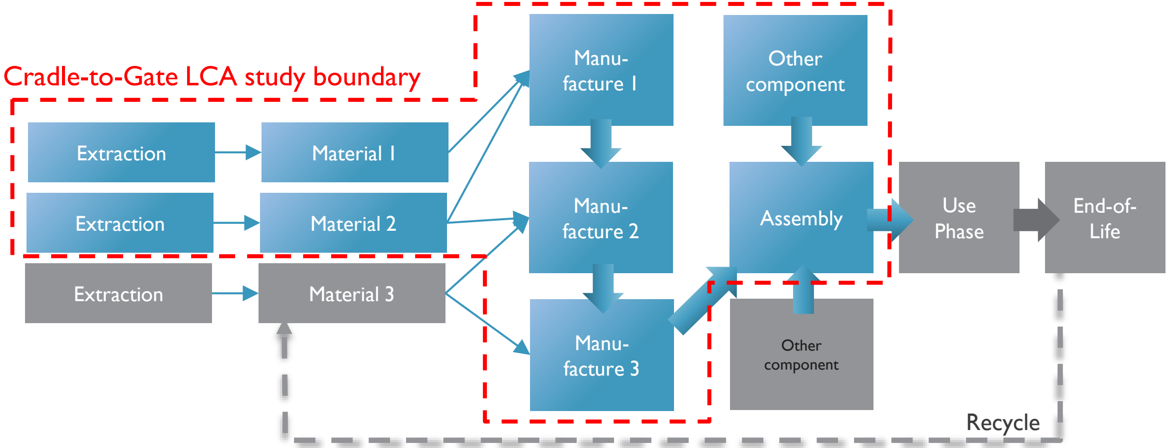
Goal and scope

Set the stage for LCA study by defining:

- The **product system** and its **functional unit** (FU):

  "A quantifiable unit that meets the function requirements"

- The reference **flow** and the **system boundaries**



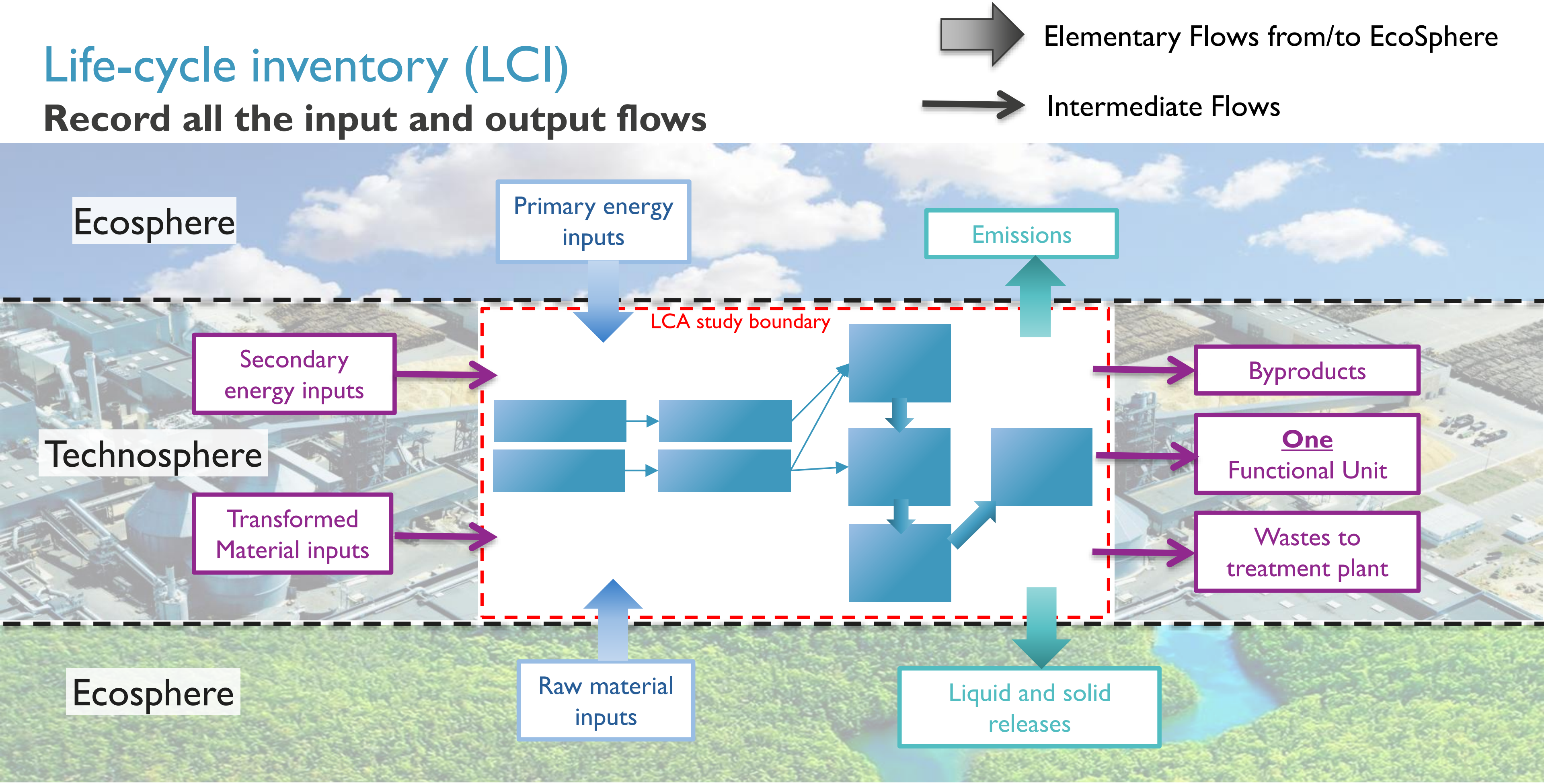
Removing a process must be motivated:
- Out-of-scope of the study
- Known to be negligible
- Lack of information

- The **impact assessment** metrics

  "What impact will the study characterize ?"

Life-cycle inventory (LCI)

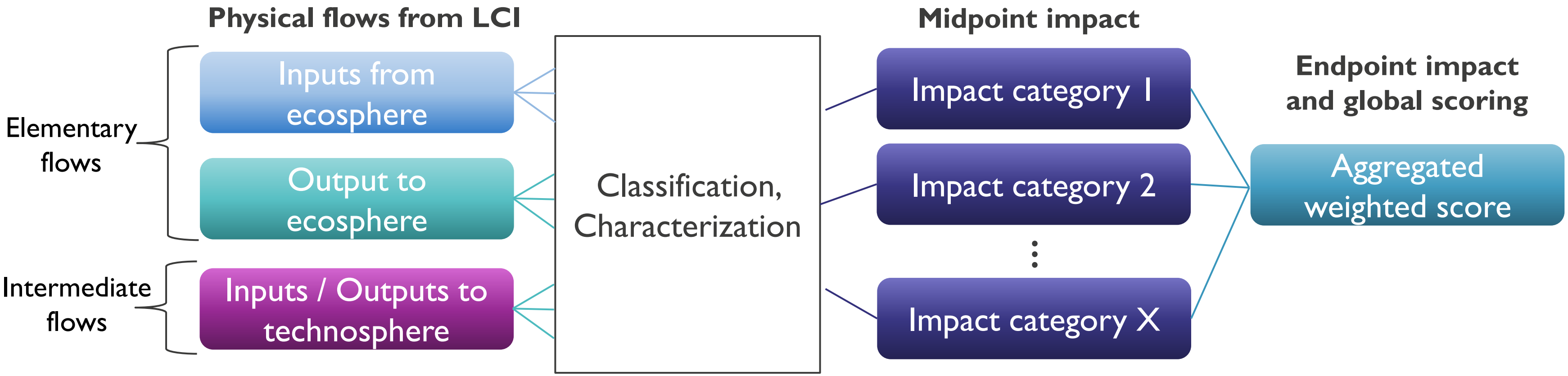
Record all the input and output flows



Source: M. Z. Hauschild, Life Cycle Assessment: Theory and Practice. Springer, 2018

Life-cycle impact analysis (LCIA)

Evaluate the impact



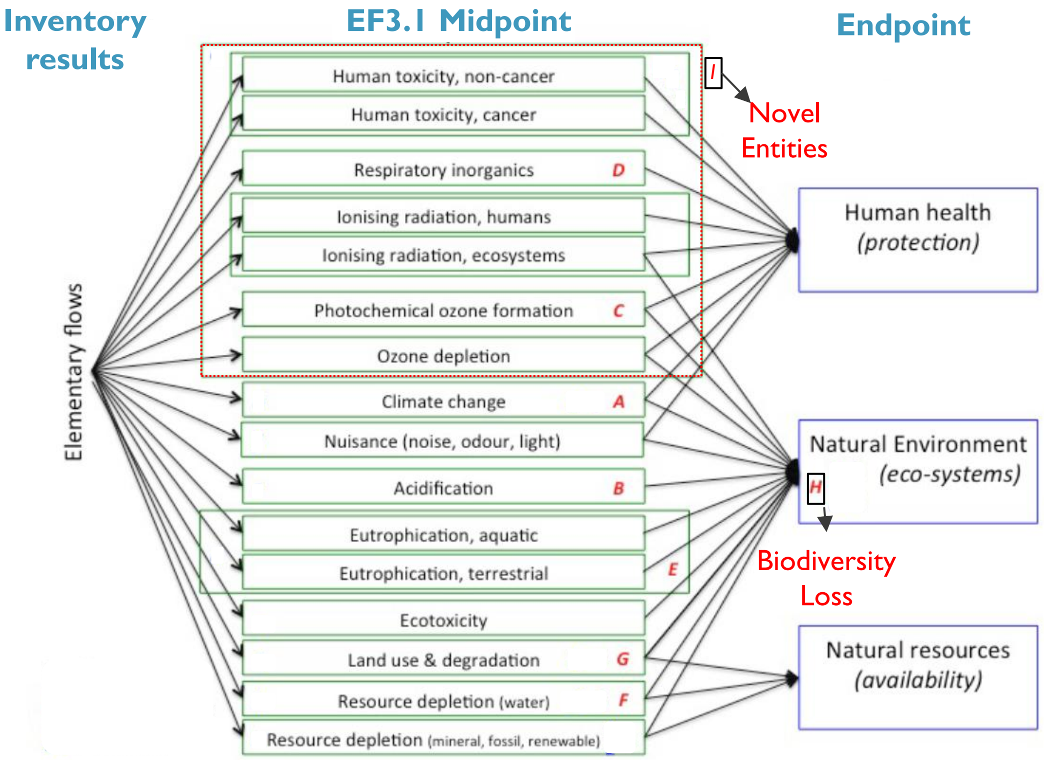
Examples

Impact category	unit	Flow of interest	Characterization factor
Climate Change	$kg_{CO2,eq}$ / FU	All gas released to the atmosphere that yield radiative forcing (GHGs)	**Global Warming Potential** at 100 years (GWP100) in $kg_{CO2,eq}$ / kg_{GHGgas}
Abiotic Resource Use	$kg_{Sb,eq}$ / FU	Metal and Mineral resources extracted from the ecosphere	**Abiotic Depletion Potential** (ADP) $kg_{Sb,eq}$ / $kg_{mineral}$
Water Scarcity Footprint	m^3 / FU	Input water consumption	**Water Scarcity Index** (WSI) m^3-withdrawal /m^3-available. Regional dependence.

Source: M. Z. Hauschild, Life Cycle Assessment: Theory and Practice. Springer, 2018.
M.Z. Hauschild, M.A. Huijbregts, Life Cycle Impact Assessment. Springer, 2015

Embracing the complexity of impacts

Impact indicators beyond climate change…

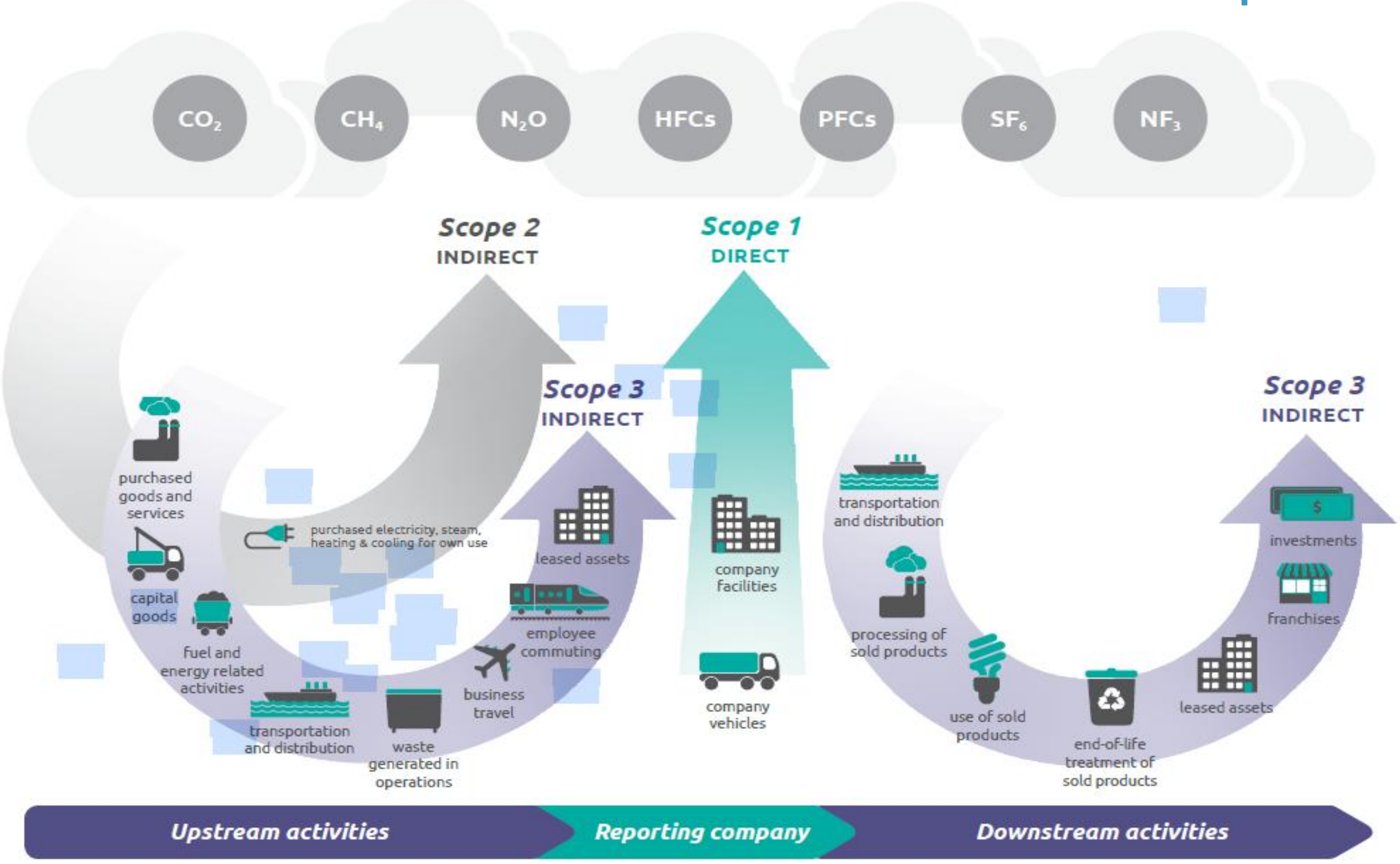


- EC-JRC **EF3.1** framework defines:
  - **3** Endpoint indicators as generic Areas of Protections
  - **16** Midpoint indicators capture a broad diversity of impacts
- Planetary Boundaries A to I fit in a broader set of impact indicators
- Implementing EF3.1 in our modelling to offer a **full Impact Analysis** beyond Climate change only

W. Vermeulen "*Routledge handbook of sustainability indicators*", 2018. p. 59-92.

https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html
https://publications.jrc.ec.europa.eu/repository/bitstream/JRC130796/JRC130796_01.pdf

The Greenhouse Gas Protocol: A method for report **GHG emissions**



Very useful when discussing Carbon Footprint in context of:

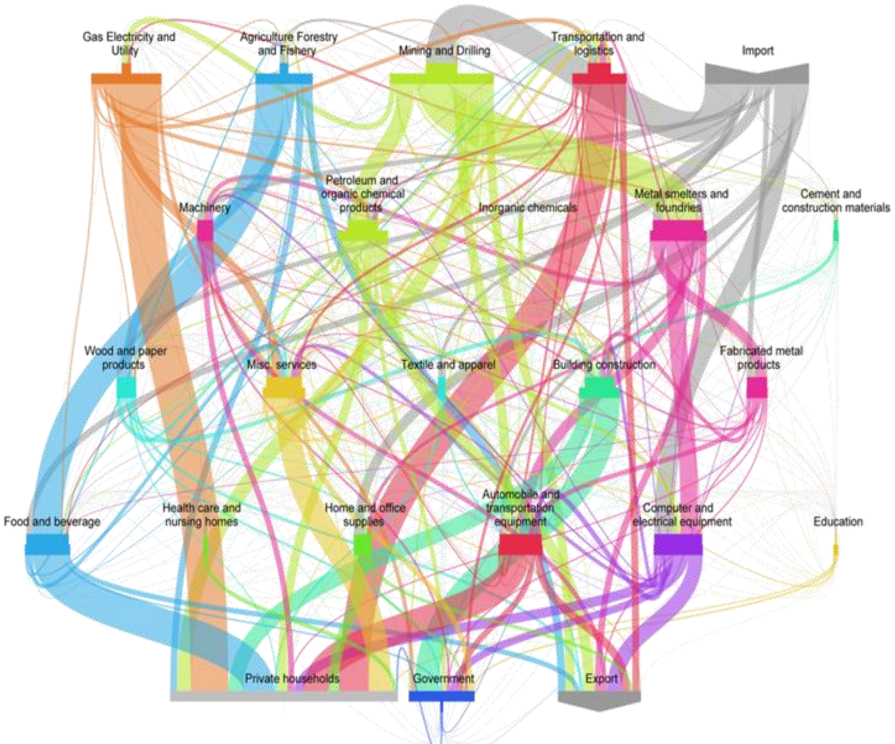
- **Product Carbon Footprint** calculation
- **Corporate Carbon Accounting**

But **Climate Change Only !**

This reporting method can be realized using LCA. But other methods exist for quantifying emissions

Source: GHG Protocol, Technical Guidance for Calculating Scope 3 Emissions v1.0 2013 (link)

LCA in practice



This Sankey diagram shows how environmental impacts are generated and passed down throughout the supply chain of the U.S. economy. [*https://vitalmetrics.com/types-of-life-cycle-assessment*](https://vitalmetrics.com/types-of-life-cycle-assessment)

- LCA is the preferred method for **quantitative environmental impact assessment**.
- The path can be tortuous and the final results are influenced by the analysis choices:
  - **Systematic** following of the LCA guidelines is needed
  - **Transparency** in the methodology is required.

Data is the new gold:

- Data quality is essential, yet practitioner must prefer **data completeness over data accuracy**. **Bridging data gaps** often requires creativity and dedication:
  - In primary data collection
  - Selection of secondary data
  - Usage of proxies as temporary replacement

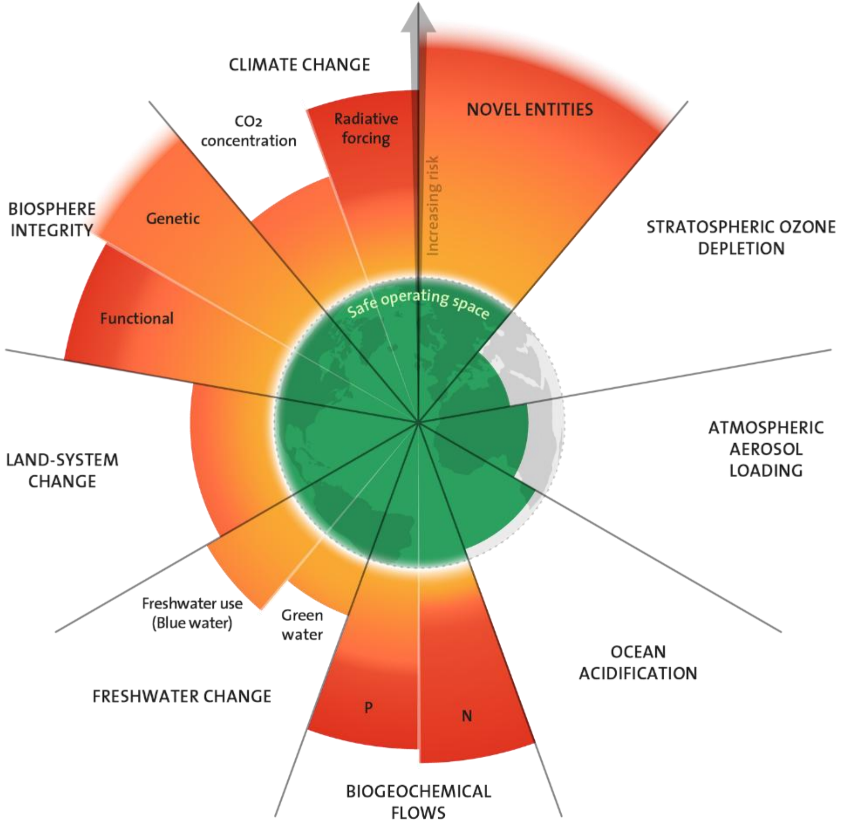
LCA implemented through:

- **Large-scale datasets** of secondary data (e.g. EcoInvent).
- **Softwares** (OpenLCA, SimaPro, GaBi, Activity Browser) that deploy the methodology.

Planet boundaries

Richardson, Katherine, et al. "Earth beyond six of nine planetary boundaries." *Science advances* 9.37 (2023): eadh2458.

Climate change is not the only indicators regarding environmental impact



- Climate change is the most famous indicators regarding environmental impact
  - Well documented
  - Studied for a long time (first IPCC report in 1990)
  - Based on well studied physical phenomeon (GWP)
- 6 / 9 planetary boundaries are transgressed → "Earth is well outside of the safe operating space for humanity"

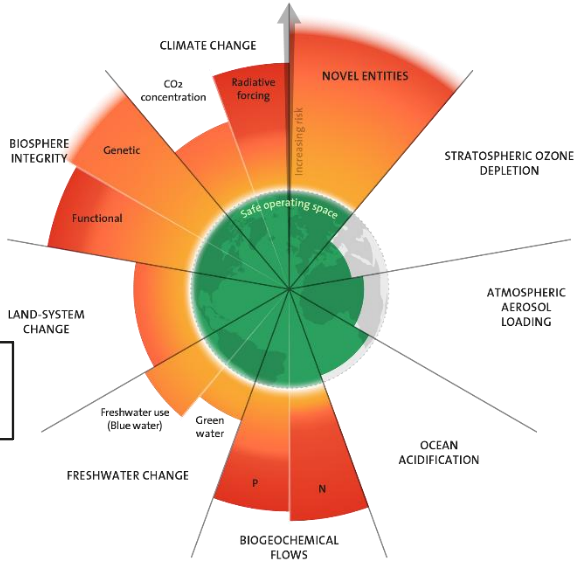
→ Other indicators should be considered!

LCA indicators

Different sets of indicators exist

- CML
- ReCiPe
- IPCC
- **EF**
- …

Matching must be done

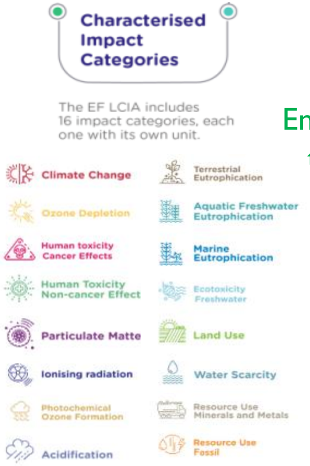


Andreasi Bassi S., Biganzoli F., Ferrara N., Amadei A., Valente A., Sala S., Ardente F., Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method. Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/798894, JRC130796.

LCA limits

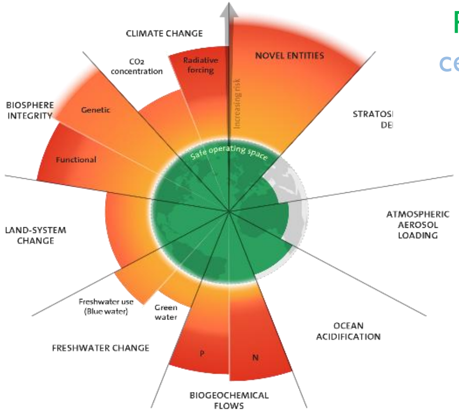
LCA studies environment impact, not sustainability

- LCA used in isolation remains a relative tool shaping innovation beyond Planetary Boundaries (PB)
- Absolute LCA can be used to define the ceiling of the Doughnut leading to sustainability following Kate Raworth's theory

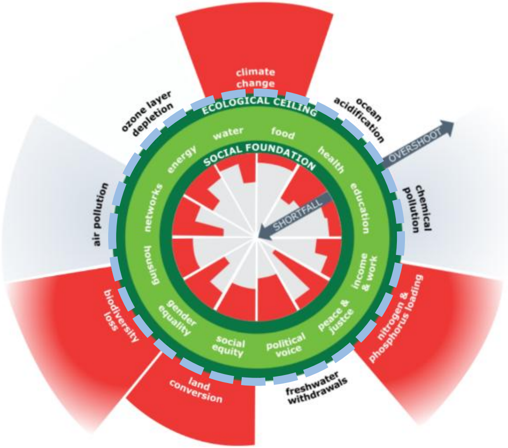


[EF 3.1 impact categories from JRC](#)

Midpoint and Endpoint impacts translate into PBs



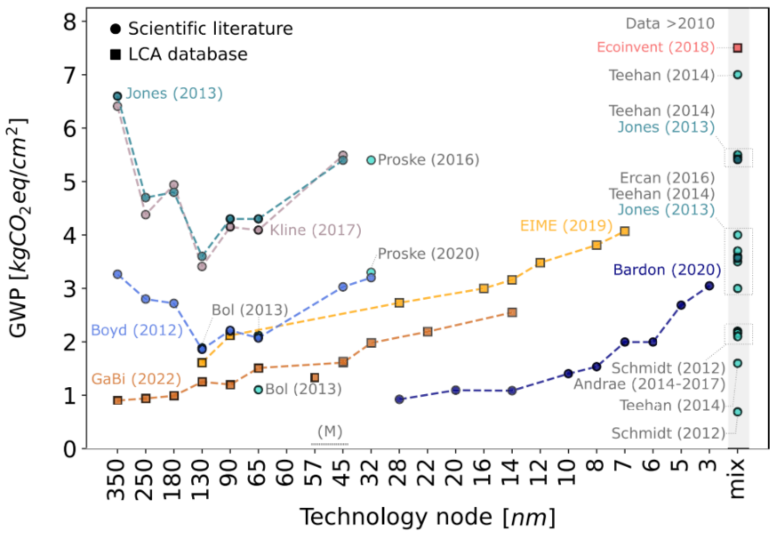
PBs set the ceiling to our economy



[Doughnut | Kate Raworth](#)

Micro view: hotspots in semiconductor manufacturing

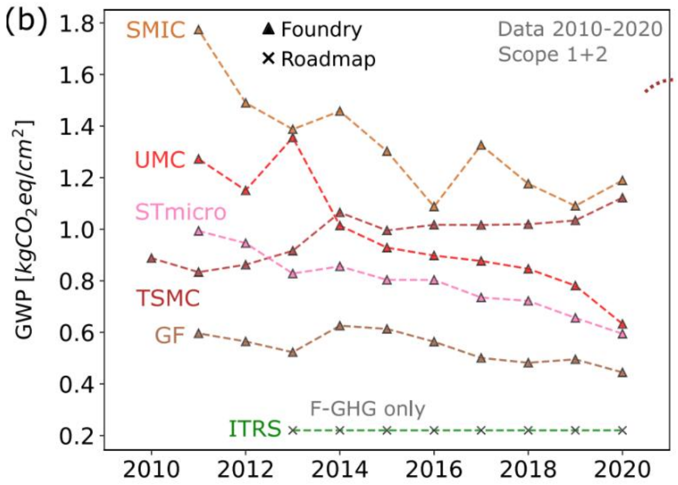
Current LCI situation: varied and outdated



Literature and LCA database data:

- Variable scope
- Variable sources (primary vs. secondary)
- Variable approaches (e.g. bottom-up vs top-down)
- Data gaps require "creative" plugging methods

Source: Pirson et al., 2023 – The Environmental Footprint of IC Production: Review, Analysis, and Lessons From Historical Trends

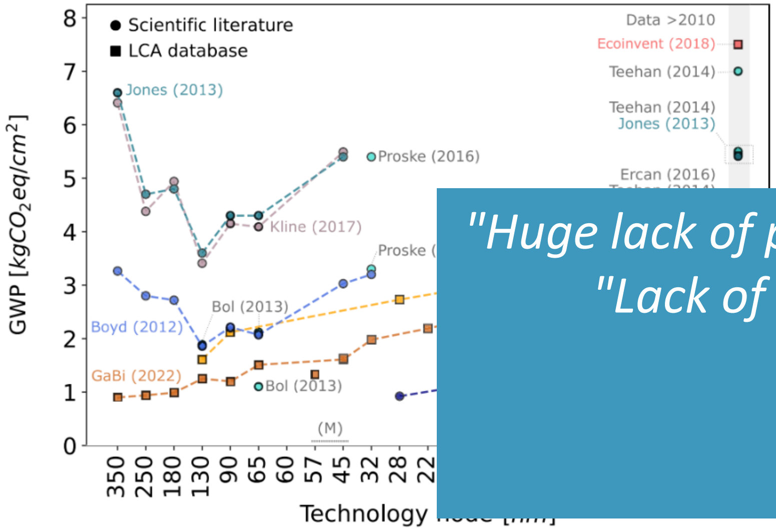


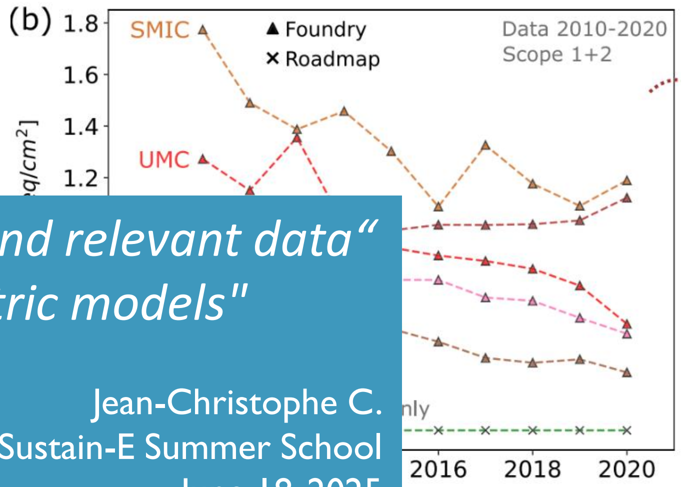
Industry data from public corporate social responsibility report:

- Top-down, primary sourced data
- Aggregated over entire company operation, not "per chip" or "per-node"
- Limited scope
- Non-transparent methodology

GWP: Global Warming Potential

Current LCI situation: varied and outdated





"Huge lack of precise and relevant data"
"Lack of parametric models"

Jean-Christophe C.
Sustain-E Summer School
June 18, 2025

Literature and LCA database data:

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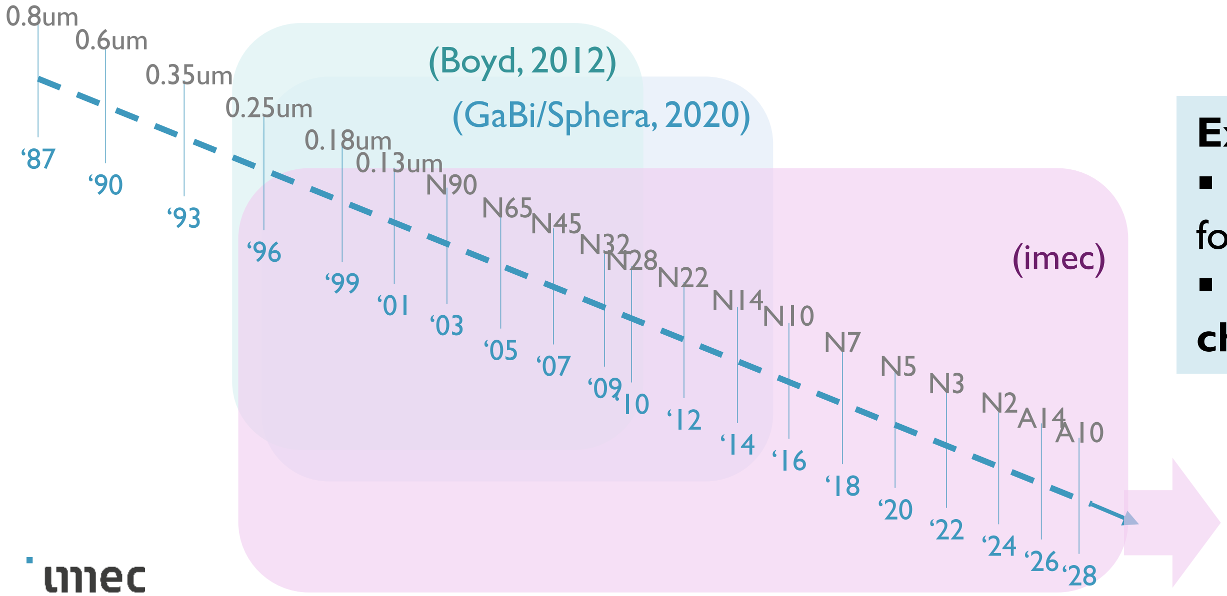
- Non-transparent methodology

GWP: Global Warming Potential

Imec ambition for the SSTS Assess pillar

Close the data gap by providing **quality, transparent** data on environmental impact of IC chip fabrication in a **generic high volume manufacturing plant**



imec.netzero

a *Virtual Fab* model for environmental impact assessment

Expand the analysis to:

- Identify **high impact** problems to focus Improve efforts
- Project **the future impact of IC chip manufacturing**

Other technologies:

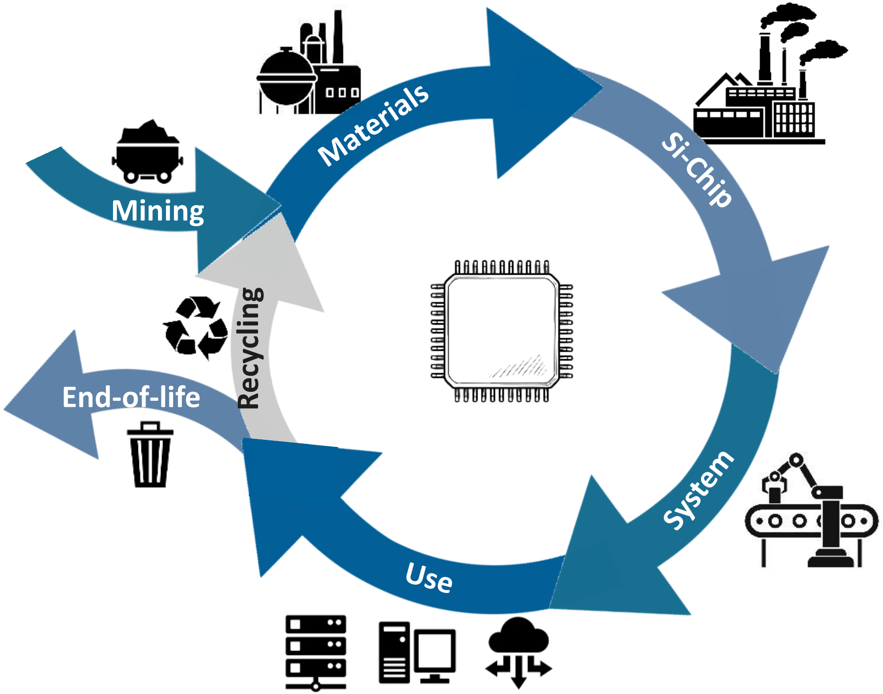
DRAM, 3D NAND, RF, Photonics, 3DIC, imagers

Future extension:

Power Electronics

The life-cycle of a Si-chip

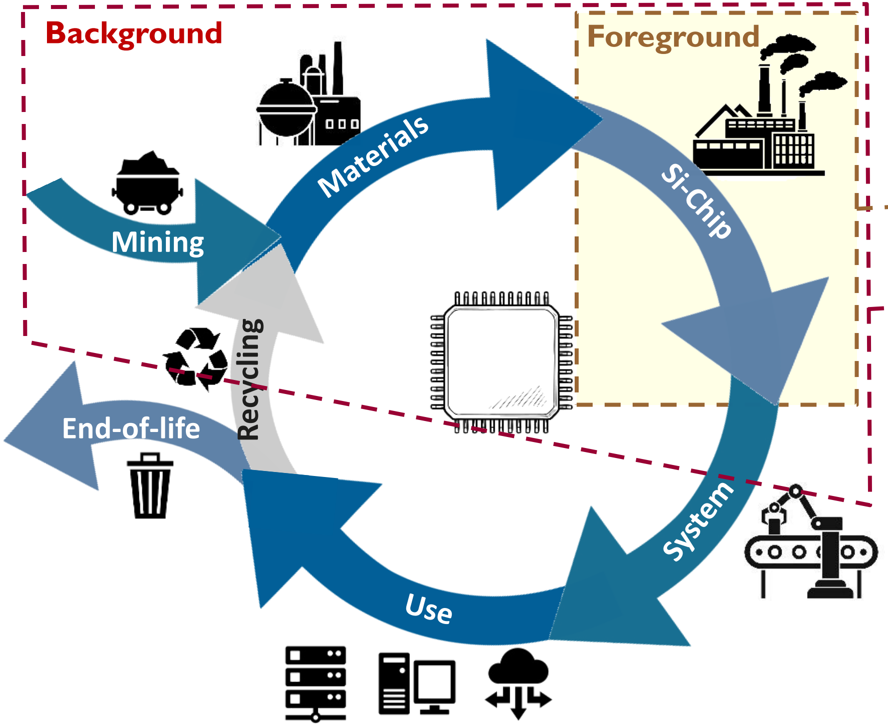
Goal and scope of imec.netzero



- **Product system** – Si chips from HVM
  - Serving several applications (Logic, memory, etc.)
  - Multiple (future) technology nodes
- **Functional Unit**
  - For Manufacturing industry: *"per Wafer"*
  - For IC Chip users:
    - *"per functional die"*
    - *"per functional cm²"*
    - *"per transistor"* or *"per GB"*
- **Impact categories**
  - Current focus:
    - *Climate Change*
    - *Abiotic resource depletion*
    - *Water Usage*
  - Under development:
    - *Ten EF 3.1 impact categories*
    - *Normalization per person*

The life-cycle of a Si-chip

Goal and scope of imec.netzero



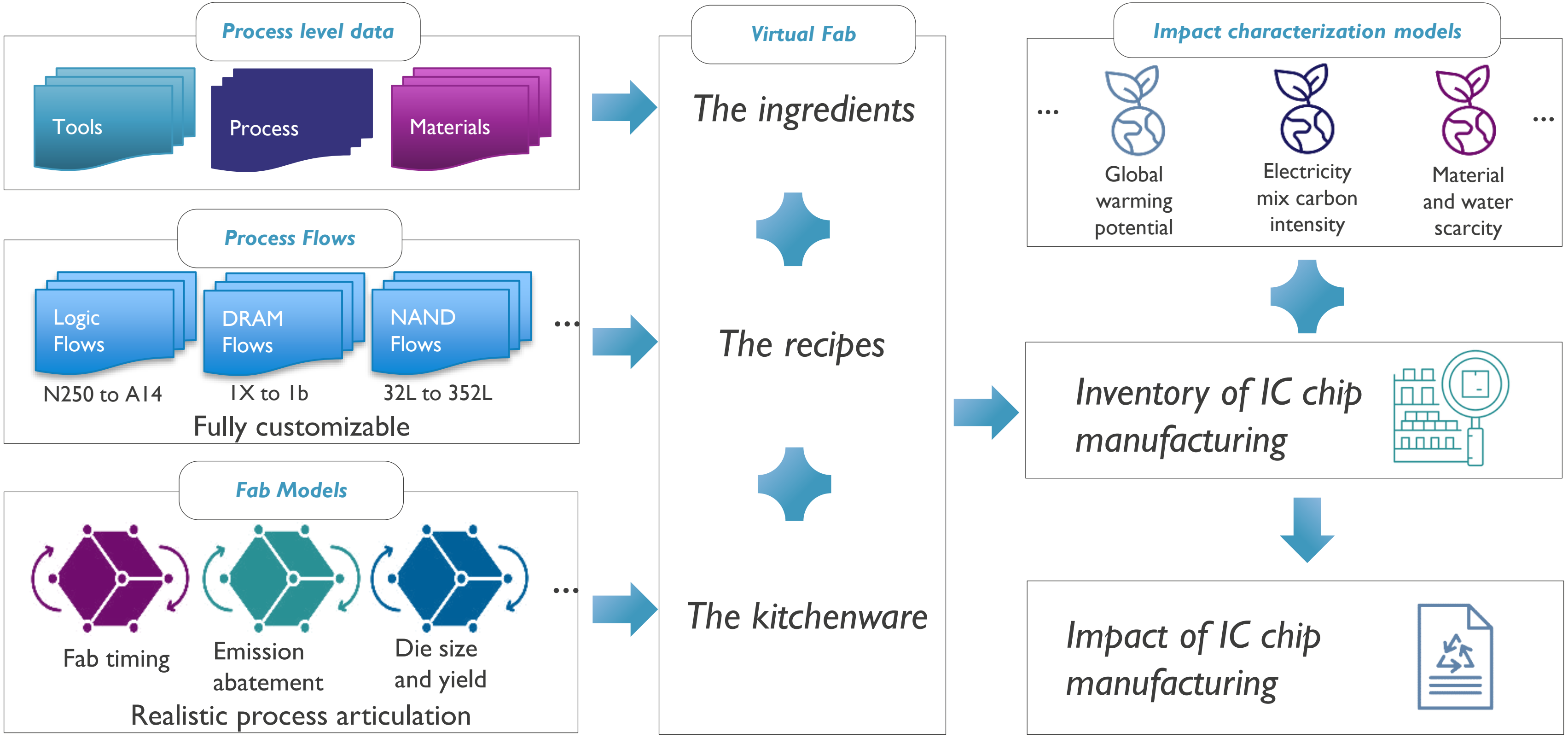
- **Flow** – Covers al operations in generic HVM Fab:
  - Wafer **processing equipment** operation
  - Generation of **utilities**
  - **Infrastructure** operation (clean room, services)

- **System boundaries** – Two sets :
  - Gate-to-Gate semiconductor (or packaging) Fab
    - Imec Fab model
  - Cradle-to-Gate Si-chip manufacturing
    - Upstream material and electricity flows
    - imec Fab model
    - Downstream chip packaging
  - **Recycling** considered at Fab level, e.g.
    - Recycling ultra-pure water
    - Secondary sourcing of scrap materials

- **Not included**
  - Equipment manufacturing
  - Infrastructure construction

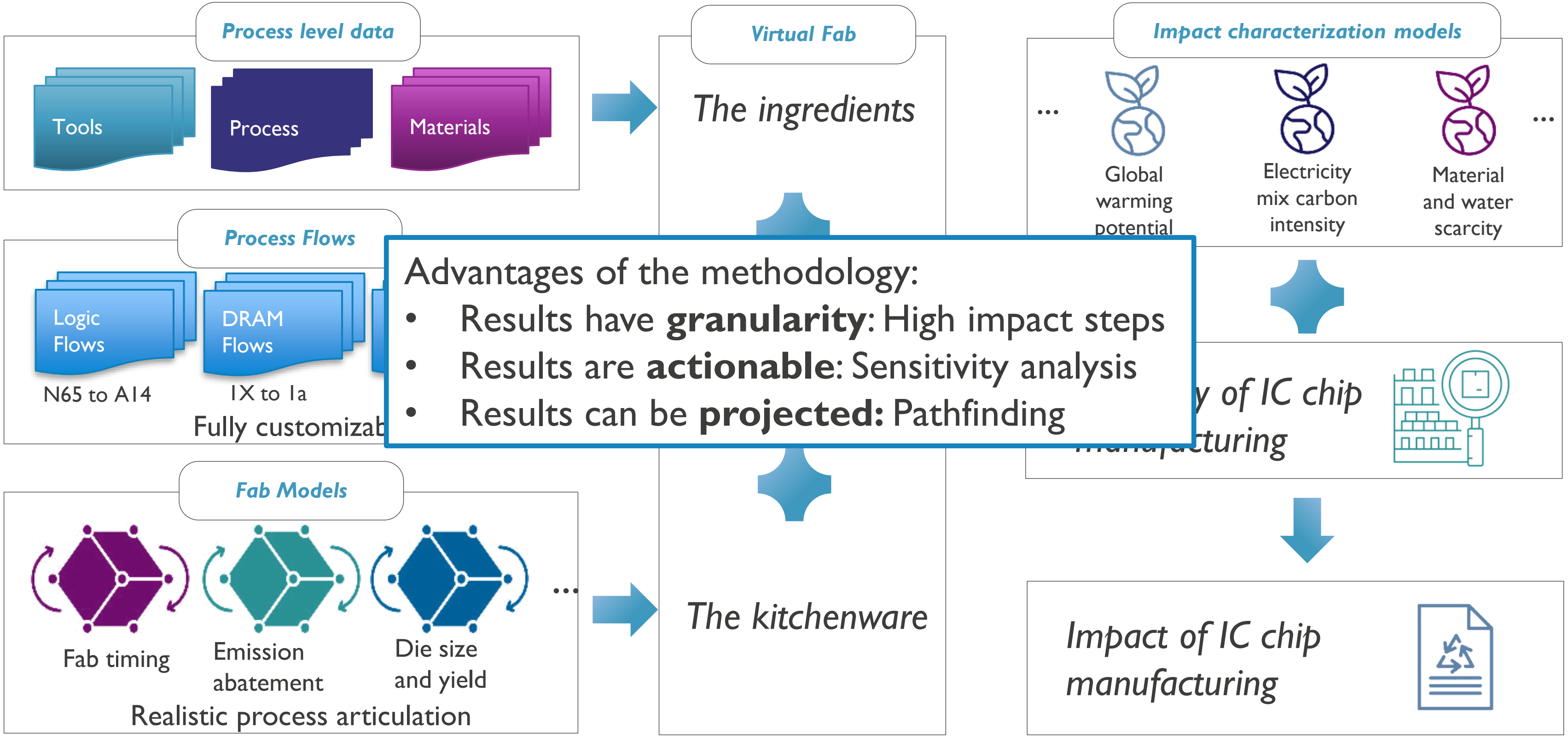
SSTS Assess - Virtual Fab Model

Quantify the footprint of a chip



SSTS Assess - Virtual Fab Model

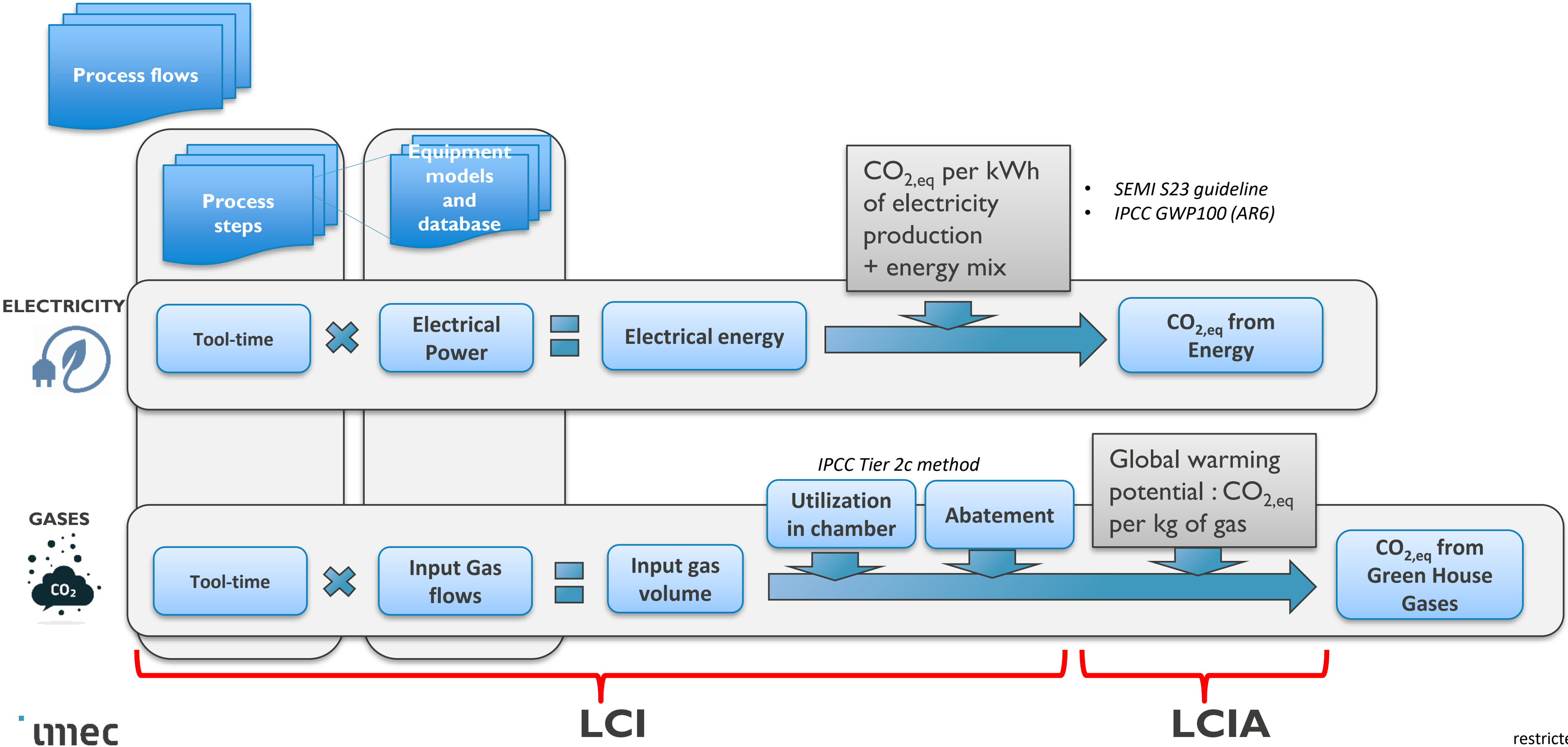
Quantify the footprint of a chip



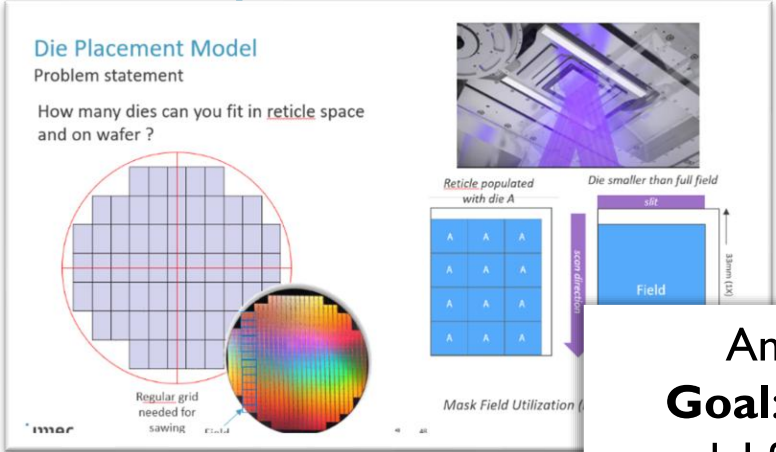
Advantages of the methodology:

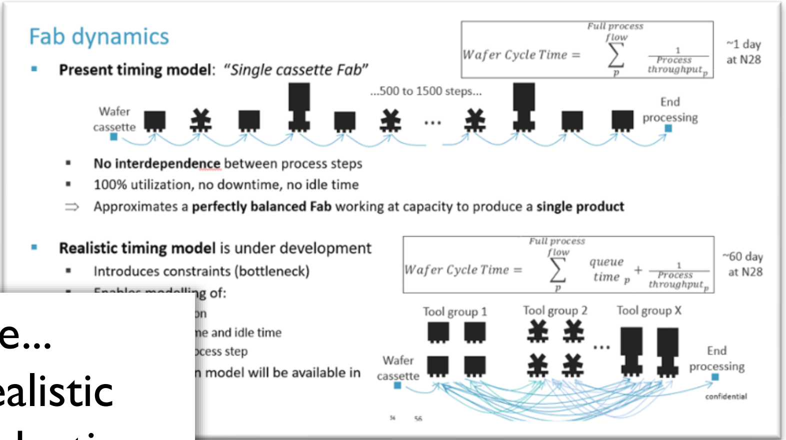
- Results have **granularity**: High impact steps
- Results are **actionable**: Sensitivity analysis
- Results can be **projected:** Pathfinding

From process flows to $CO_{2,eq}$ footprint



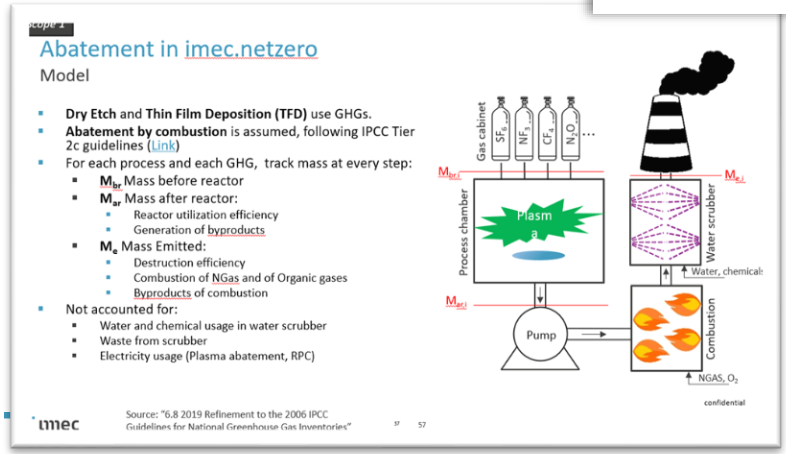
Inventory is built on **Fab Models**

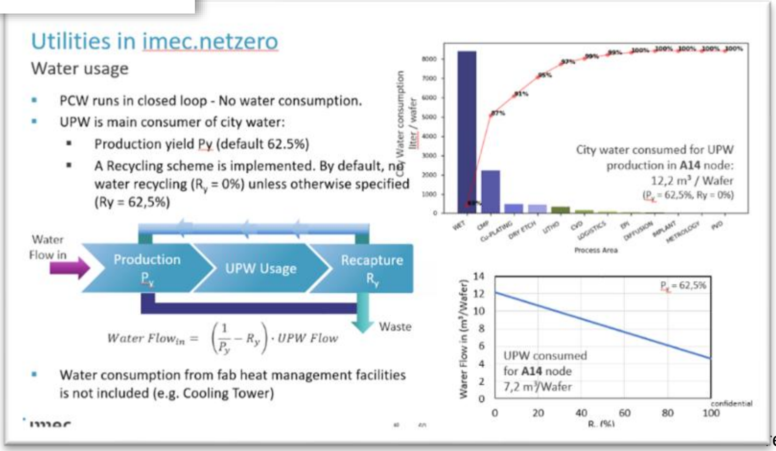




And Many More…

Goal: Provide a realistic model for HVM production

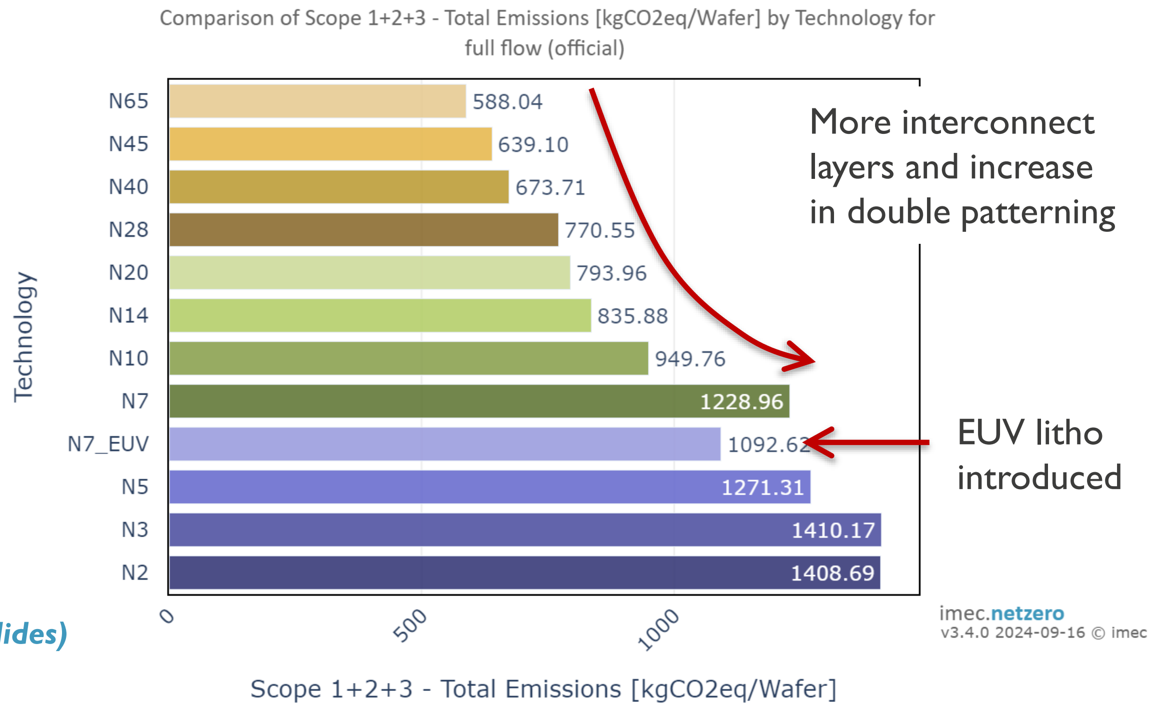




Total emissions for logic technology nodes

Emission trends for advancing technology nodes

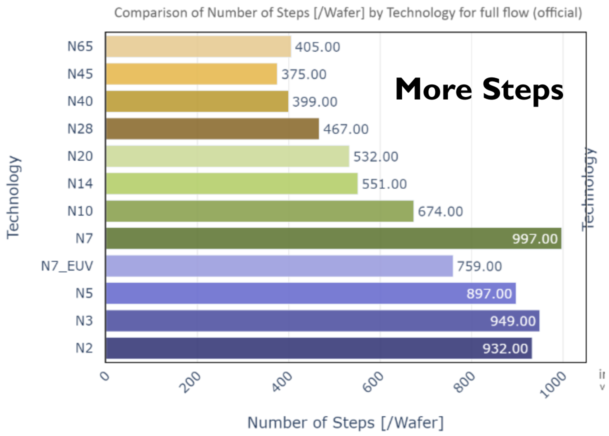
- An increase in the number of process steps directly leads to **increased emissions**
- Introduction of a more advanced lithography process (EUV) reduces the total number of process steps and thus total emissions

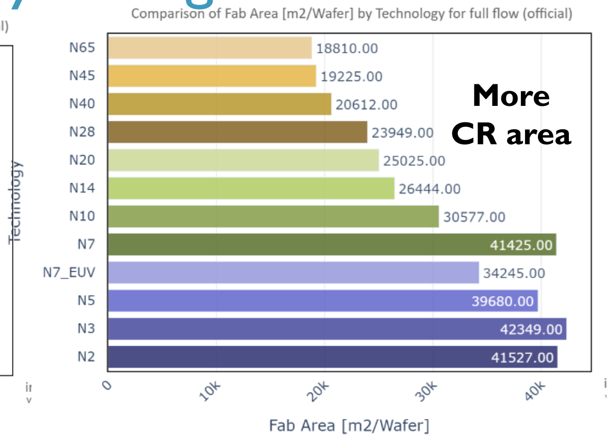


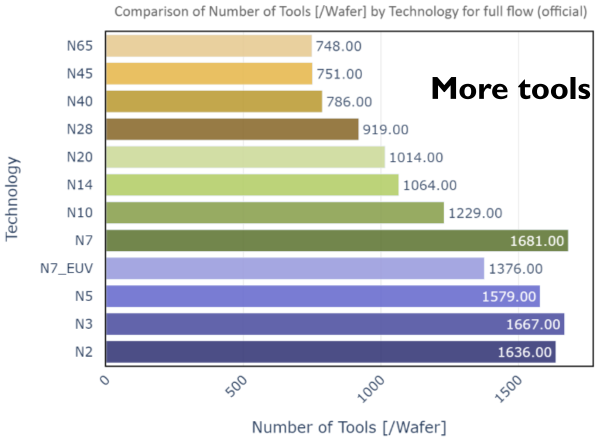
iNZ default model assumptions (also for all next slides)

- *100% Production line yield*
- *10x10mm² die, Murphy yield with 0,15 defect/cm²*
- *IPCC Tier 2C Abatement model (2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories)*
- *GHG global warming potential from IPCC AR6*

Increasing complexity in Logic nodes

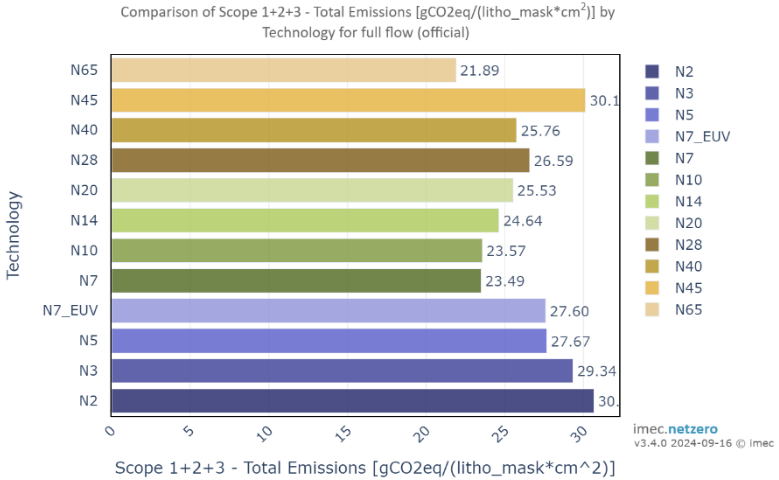






All numbers for:

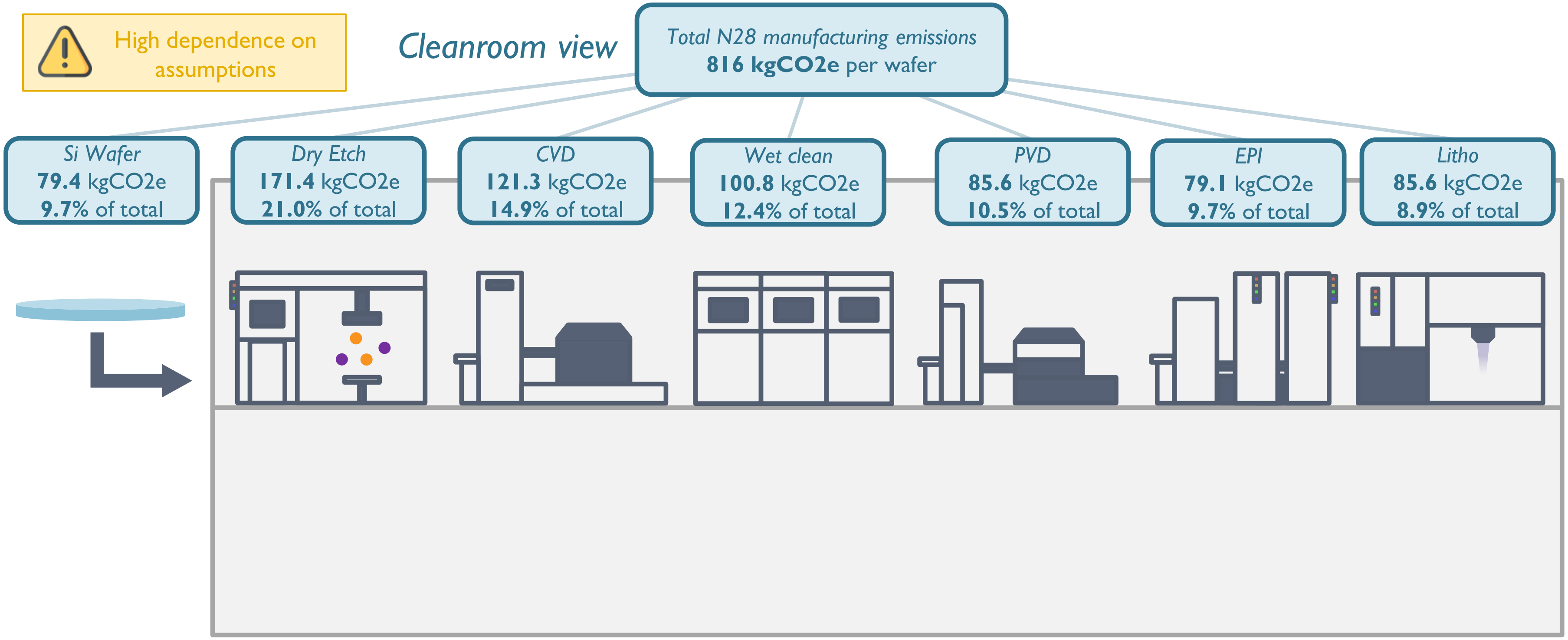
- Fab capacilty of 60.000 wafers/month
- 70% Tool utilization
- 90% Line yield



Functional unit to compare different technologies: **kgCO2eq / (Mask Layer x cm²)**
In this FU footprint is relatively stable.

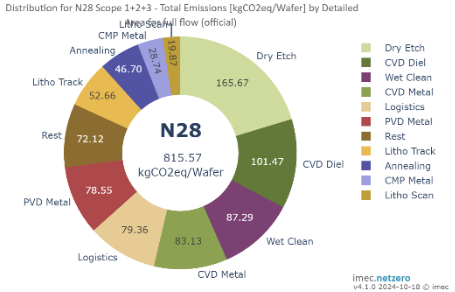
Hotspots for N28 fab carbon footprint

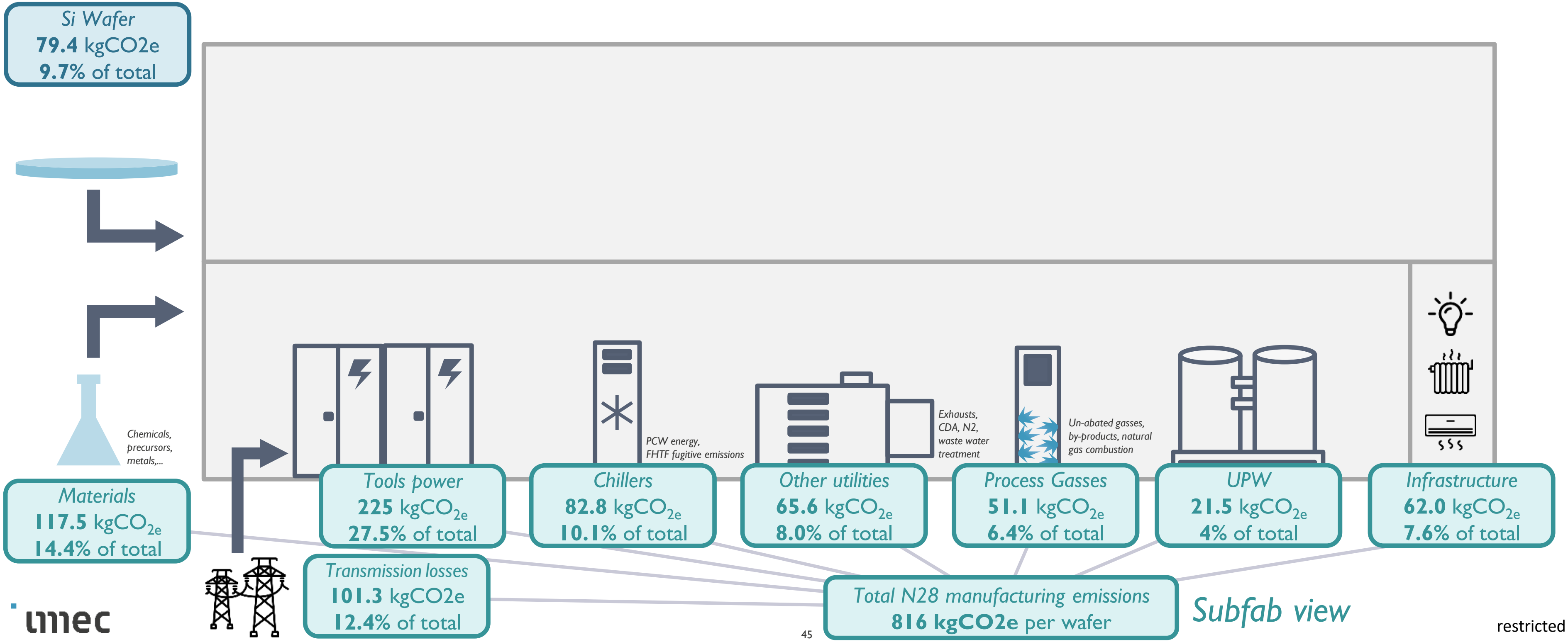
High dependence on assumptions



Hotspots for N28 fab carbon footprint

High dependence on assumptions



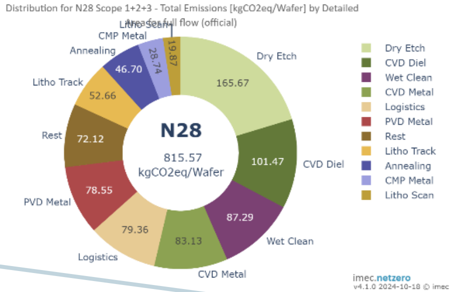


Subfab view

imec

restricted

Hotspots for N28 fab carbon footprint



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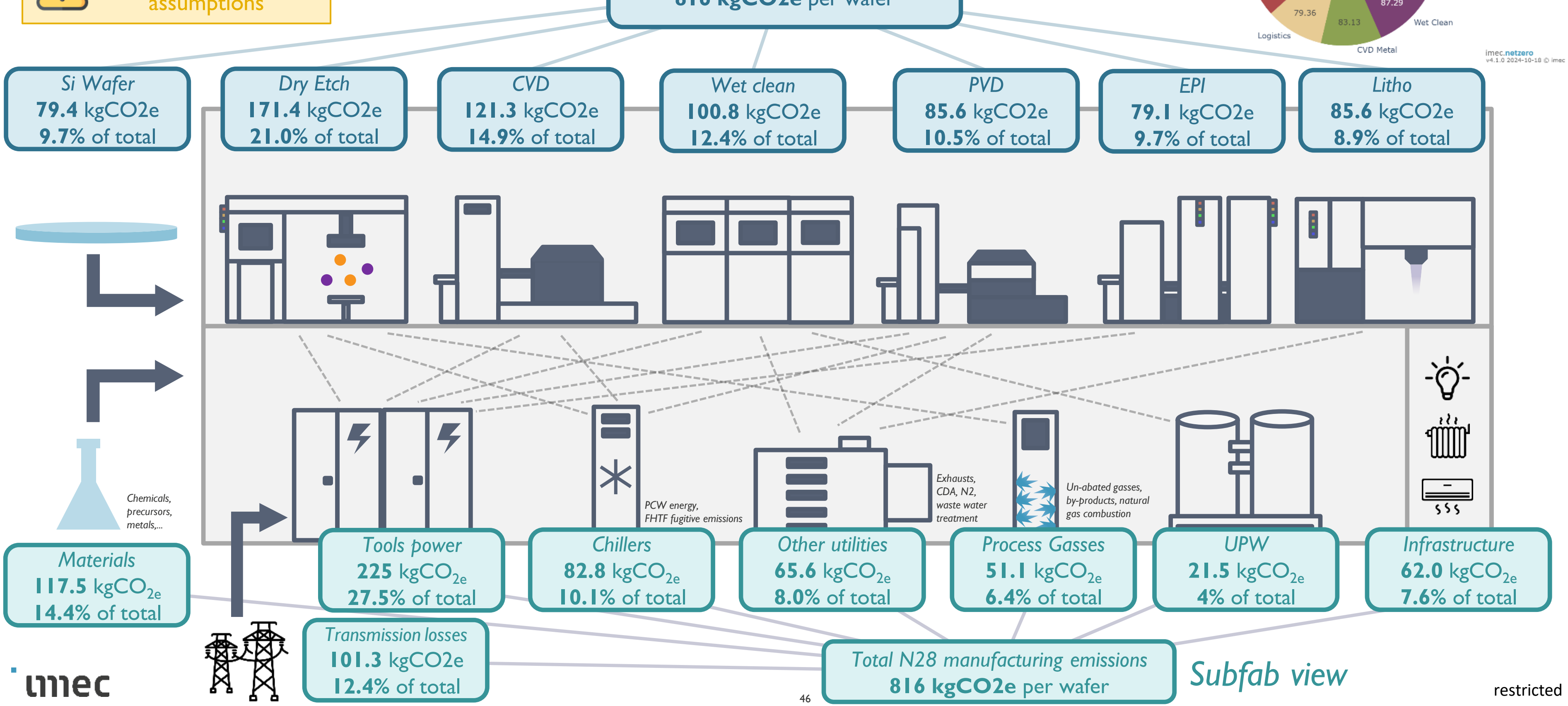

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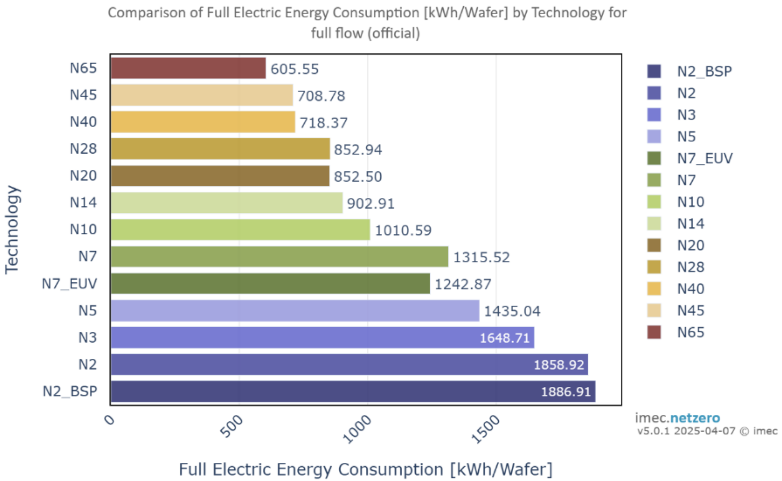
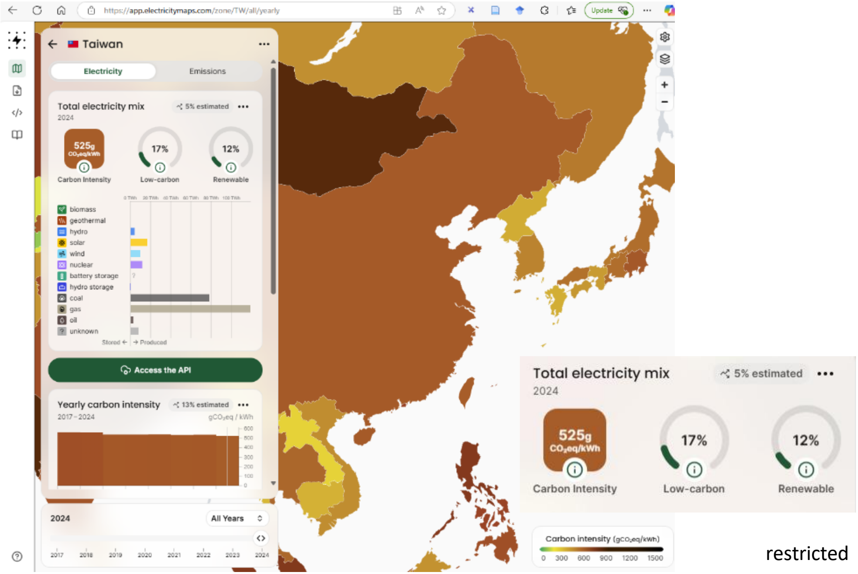
Hotspot: tool electrical energy

Hotspot: tool electrical energy

"Subfab view"

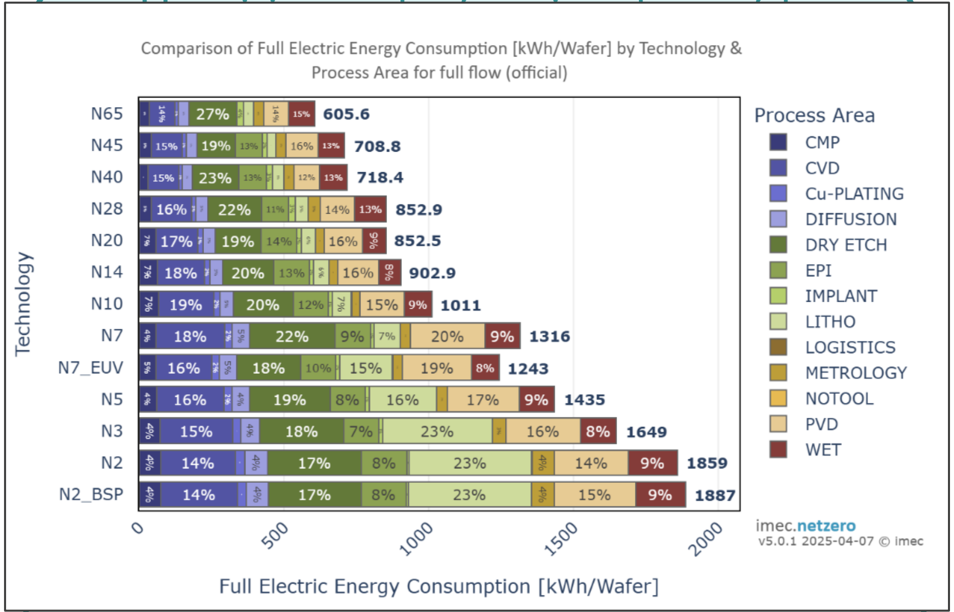
- Electricity needs of semiconductor fabs are very high
  - Typical tool power rating range 5..50 kW (up to 1MW for EUV litho)
  - HVM fabs need several hundreds of tools
- High dependence on electricity mix of fab
  - "Industry average" = 500gCO2e/kWh
  - "Clean grid" < 100gCO2e/kWh
- Transmission losses on the grid are significant





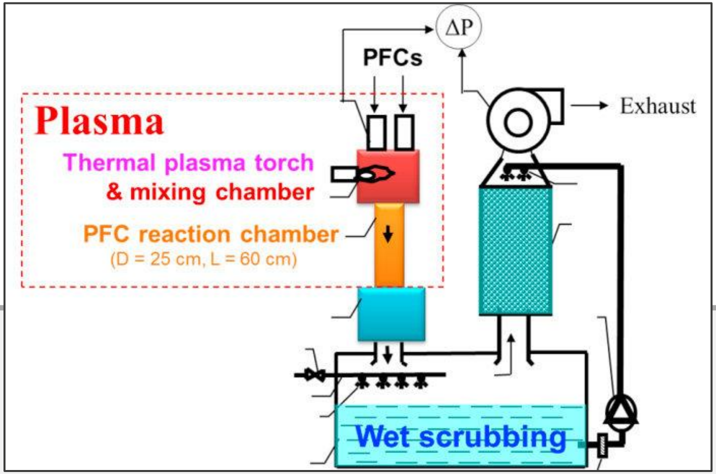
Hotspot: tool electrical energy

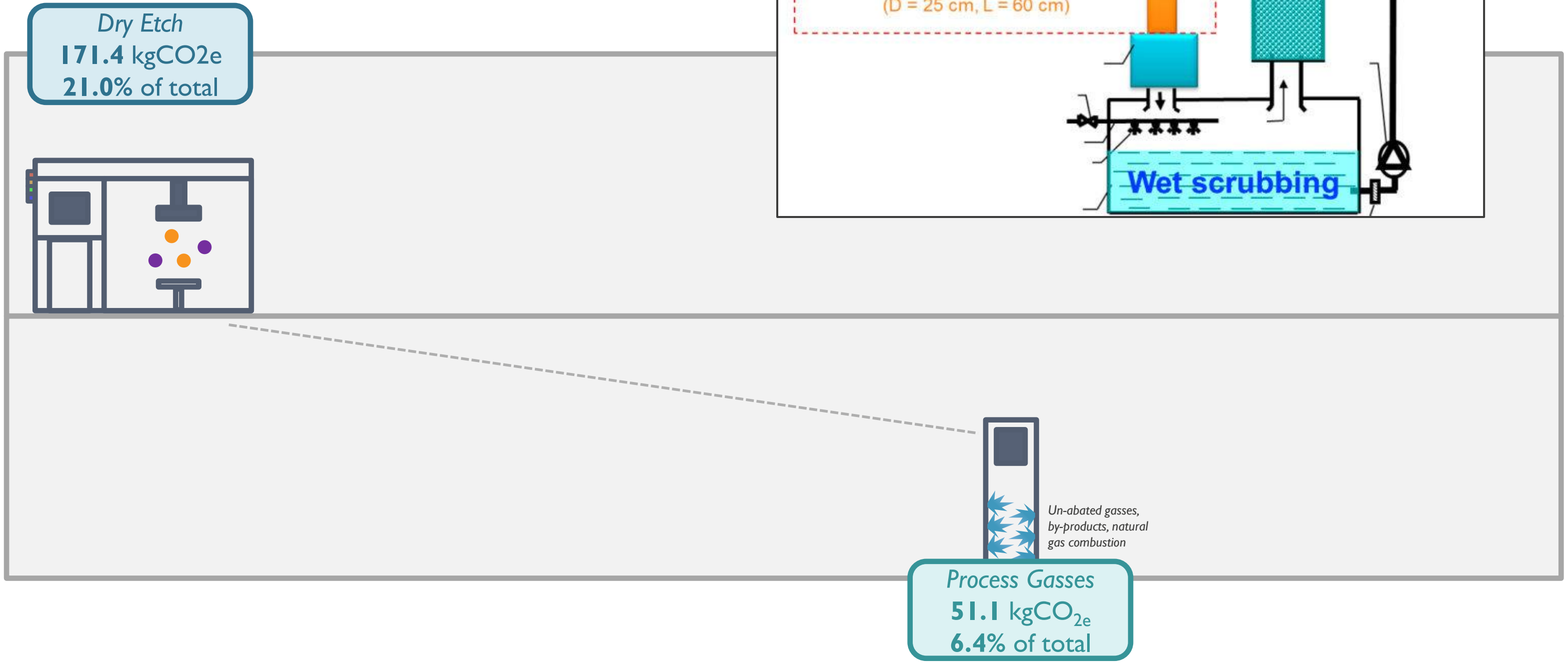
“Cleanroom view”



- Many process areas require lots of energy
  - Deposition processes
    - CVD
    - EPI
    - PVD
  - Dry Etch
  - Litho (post-EUV)
  - Wet cleans
- Driving factors: high temperatures, long processes, giant lasers, water heating/cooling, ...

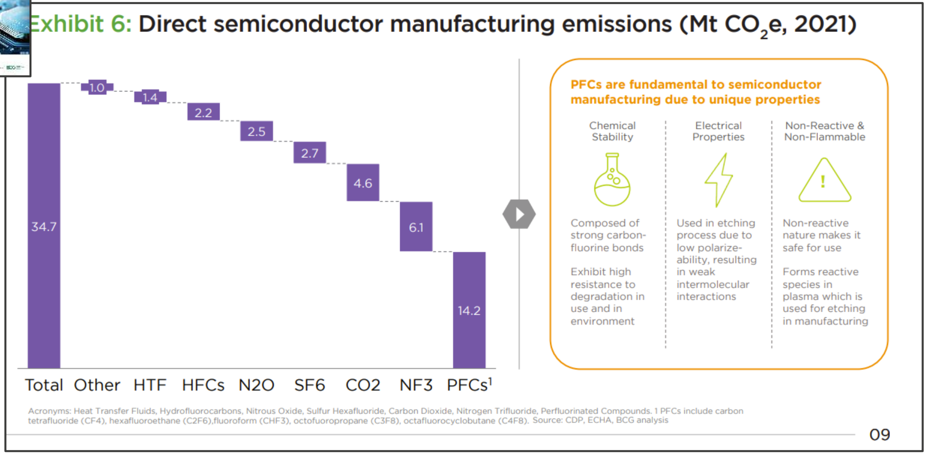
Hotspot: process gas emissions





Hotspot: process gas emissions

"Subfab view"

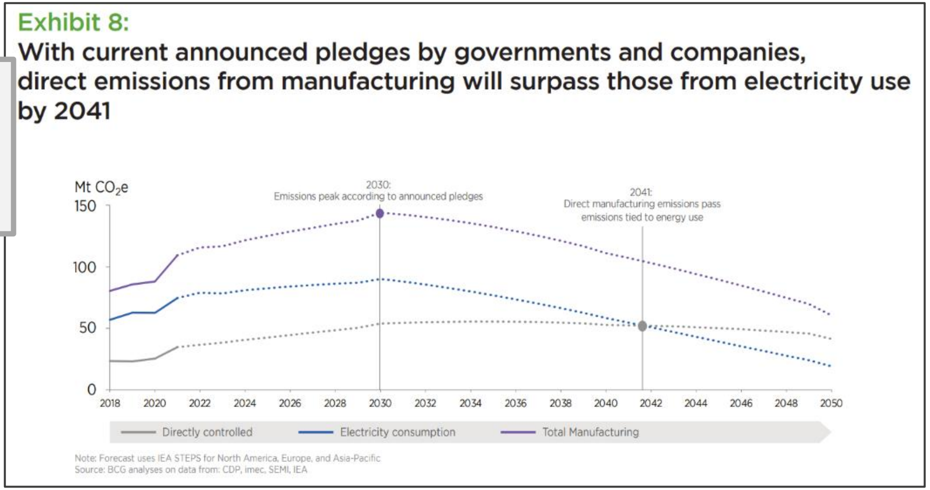


- Semiconductor manufacturing uses some extremely strong GreenHouse Gases
  - Strong radiative forcing
  - Very stable, lifetime in the athmosphere: several **thousands of years**
  - Usual unit: GWP100 = relative warming effect to 1kg of CO2 during 100 years

gas	GWP_{100}
SF6	25 200
NF3	17 400
CF4	6 630
C2F6	12 400

Releasing 1kg of SF6 into the atmosphere has the same warming effect over 100 years as releasing 25 200kg of CO2!

- Abatement technologies exist
  - Combustion- or plasma-based
  - Destruction and Removal Efficiency up to 95~99%



imec

restricted

Hotspot: process gas emissions

“Cleanroom view”

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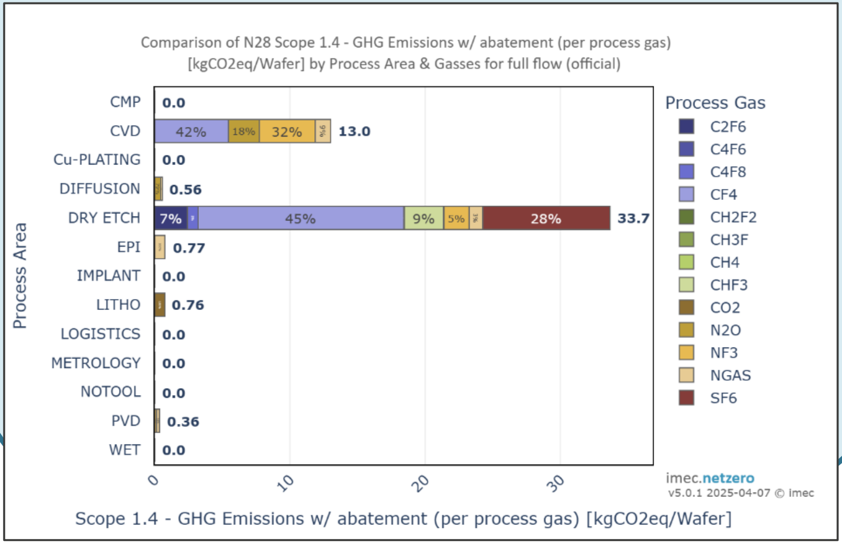
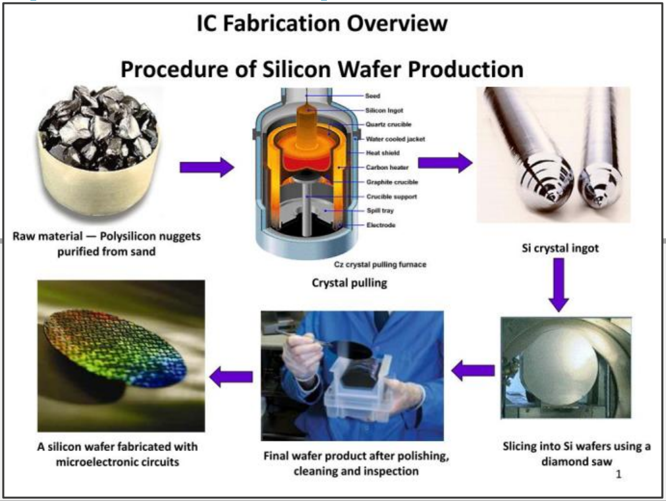
  - Combustion- or plasma-based
  - Destruction and Removal Efficiency up to 95~99%

- Most high GHG are used for etching
  - A fraction of the gas is not used and exits
  - Other GHG are generated as byproducts
- Also appears in some deposition processes
- NF3 used as clean gas



Hotspot: upstream impacts

Si Wafer
79.4 kgCO2e
9.7% of total



- Si Wafer manufacturing requires high temperatures
- Many materials and chemicals needed (way more than what ends up on the wafer), with very high purity requirements
  - Difficult to estimate!

Chemicals, precursors, metals,...

Materials
117.5 $kgCO_{2e}$
14.4% of total

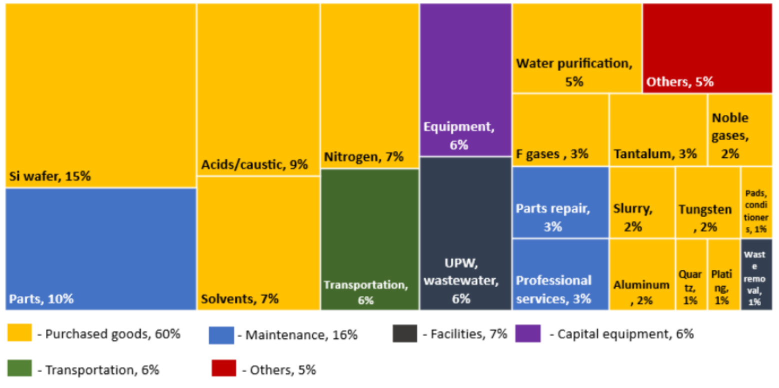
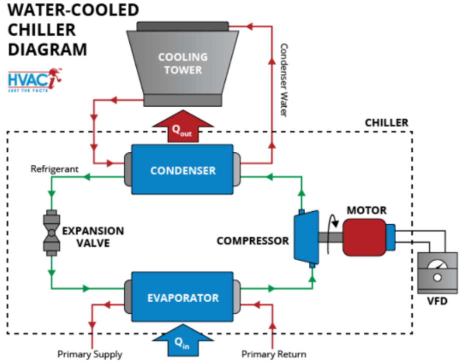
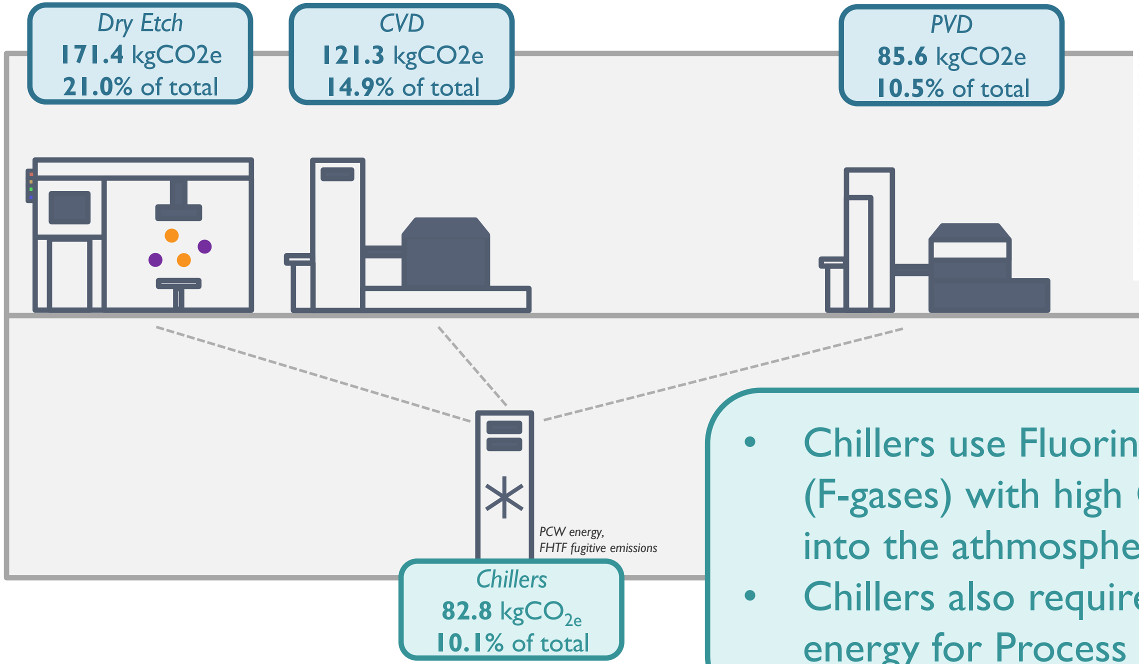


Figure 7. Breakdown of Scope 3 emissions for semiconductor companies [28].

Hotspot: cooling

All the heat generated must be evacuated from the fab



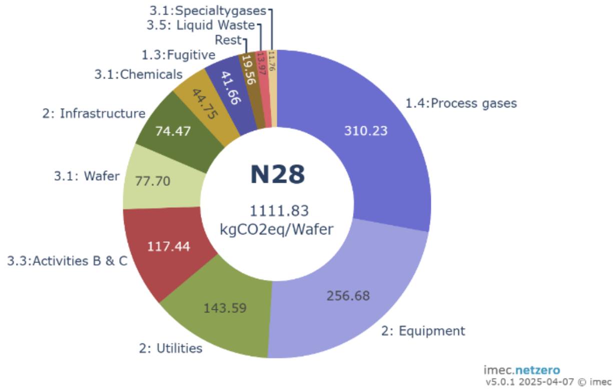


- Chillers use Fluorinated Heat Transfer Fluid (F-gases) with high GWP that eventually leak into the athmosphere
- Chillers also require large amounts of energy for Process Cooling Water

Existing and prospective solutions

Solutions?

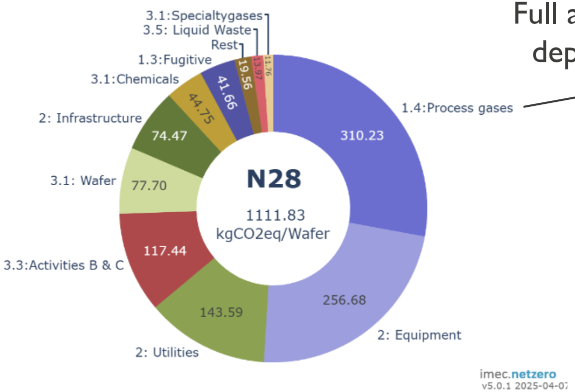
There are many low-hanging fruits already



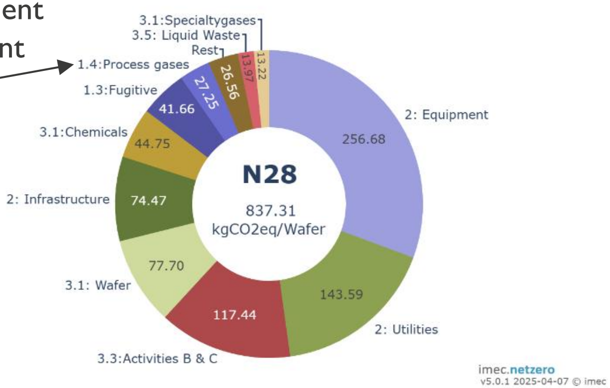
Taiwan electricity mix
25% abatement deployment

Solutions?

There are many low-hanging fruits already



Full abatement deployment

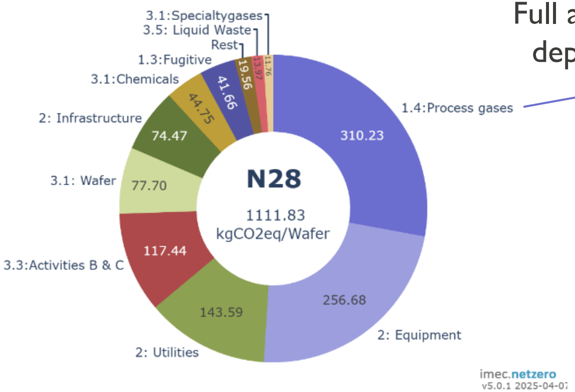


Taiwan electricity mix
25% abatement deployment

Taiwan electricity mix
100% abatement deployment

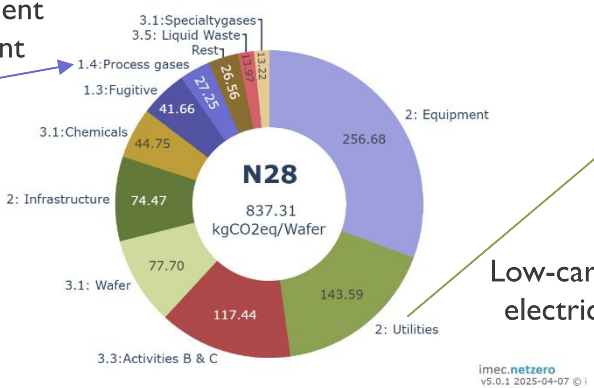
Solutions?

There are many low-hanging fruits already



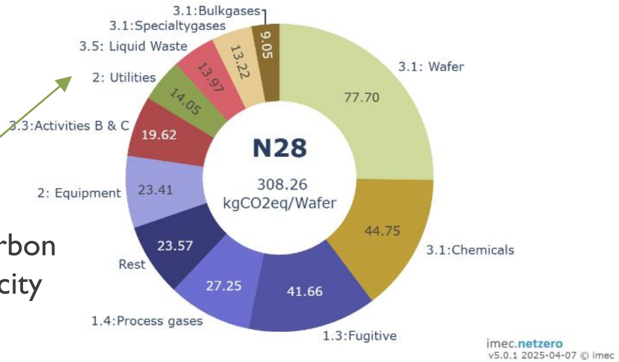
Taiwan electricity mix
25% abatement deployment

Full abatement deployment



Taiwan electricity mix
100% abatement deployment

Low-carbon electricity



French electricity mix
100% abatement deployment

Solutions?

Challenges are **(i) deployment at scale…**

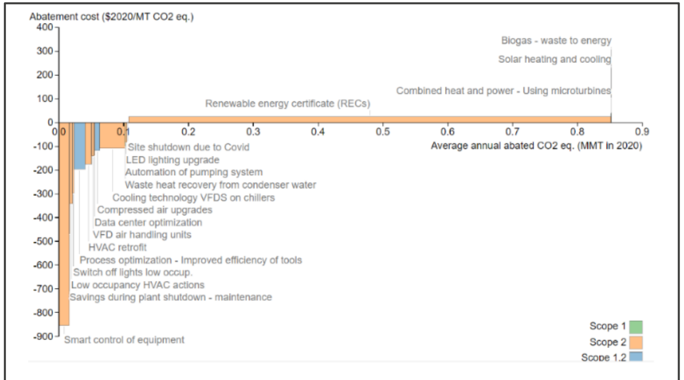


Figure 14. MACC for Intel in 2020.

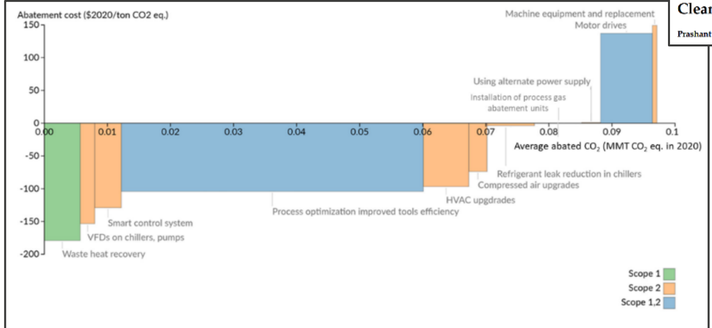


Figure 16. MACC for Micron in 2020.

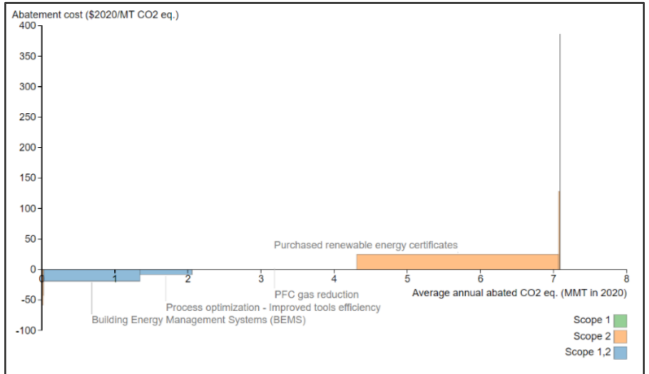


Figure 15. MACC for Samsung Electronics in 2020.

Cost & Environment ***savings*** *(win-win):*
- *Energy efficiency and tool upgrades*
- *Smart processes (optimization)*
- *Leak reductions*
- *Waste (material and energy) recovery*
- *…*

vs.

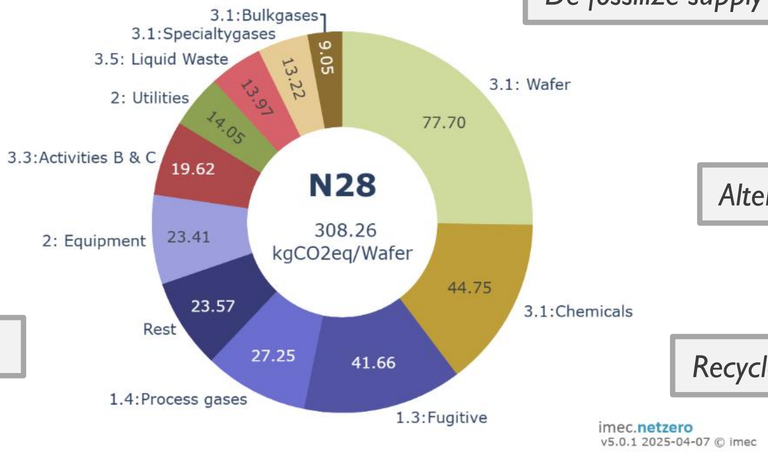
Cost-Environment ***tradeoff*** *(need regulation?)*
- *Abatement*
- *Waste treatment*
- *Renewable electricity (depends…)*
- *Electrification of some processes*
- *…*

Solutions?

Challenges are **(ii) remaining emissions**

Alternative recipes?

De-fossilize supply chain?



Alternative materials/chemicals/gasses?

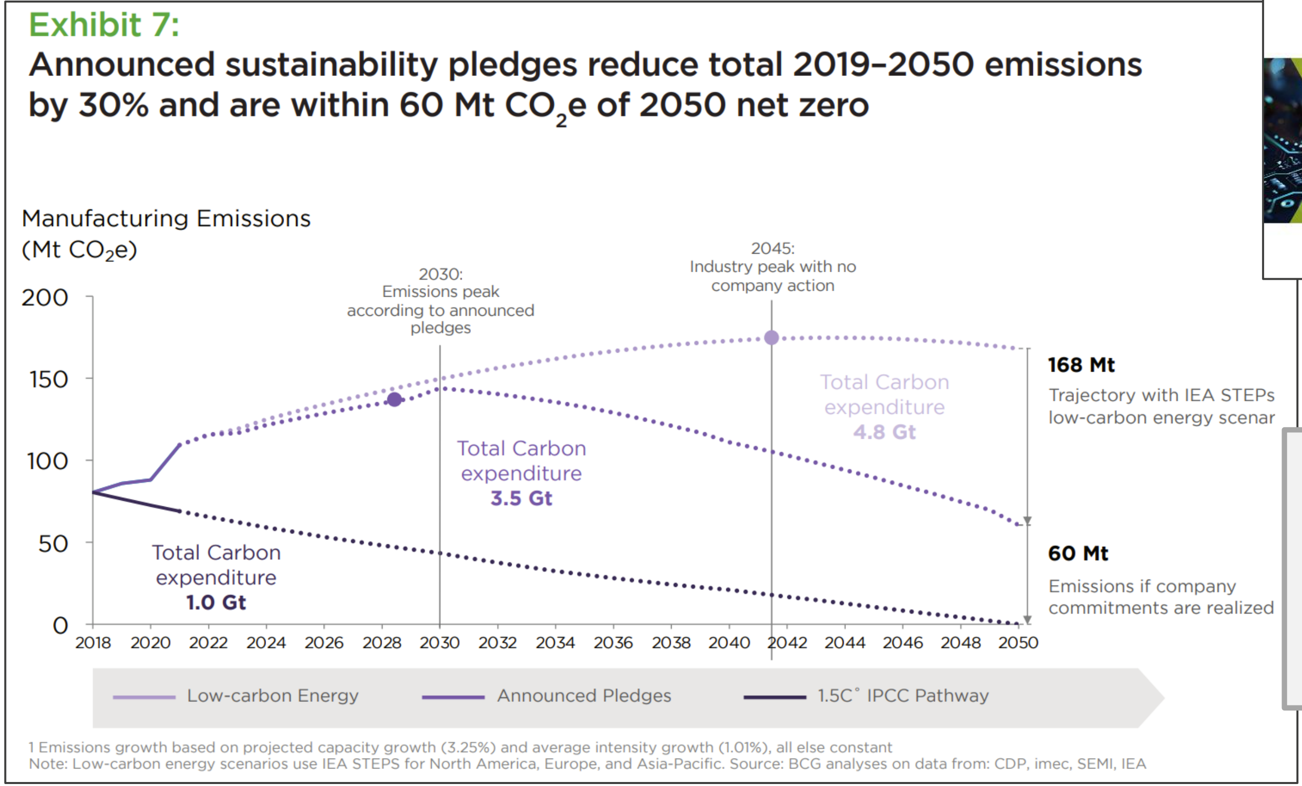
New tools?

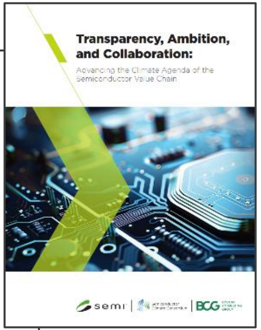
Recycled materials?

*All this is happening already, but slow in a **risk-averse** and **highly complex** industry...*

Solutions?

Challenges are **(iii) absolute impact reduction**





Need for complementary lesser or non-technical solutions? E.g.

- *Incentives/regulations*
- *Other business models*
- *Other consumer habits*

Solutions?

Challenges are **(iv) Environmental metrics deployment in innovation phase**

- Innovation is not driven by sustainability staff but by **expert from the field**.
- Provide **specifications** on environmental impact to engineers
  - Sufficiently **early in the innovation phase**
  - **Acceptable**: Understandable, defensible
  - **Accessible**: User friendly tool for computing
- **E-score** to complement Power-Performance-Area-Cost **PPAC** scorecard. See next section.

Environmental Scoring: A spec to guide innovation

Motivation for E-score tool development

Goals and ambitions

- Main goal for E-score: **infuse the sustainability concern in all innovation processes** at the heart of semiconductor manufacturing technologies. Early-stage embedment in R&D will drive **maximum impact on our industry**.
- Innovation in semiconductor industry is driven by the Power Performance Area and Cost (PPAC) scorecard. With E-score, we want to **add an Environmental (E) metric to the card that becomes:**

PPAC-E

- The deployment of E-score is three-pronged:

E-Metric for PPACE

A defensible metric anchored in Environmental Science practices

Toolbox for quantification

A platform for E-score quantification combining flexibility with user-friendliness

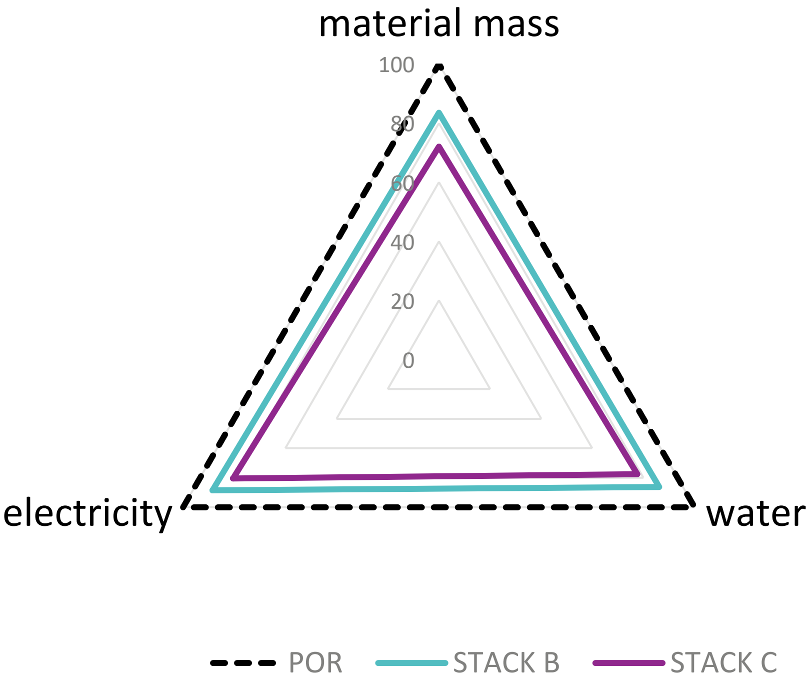
Dissemination

For early platform adoption, feedback and rapid spreading

E-score: Inventory

Using a real example from an etch stack evaluation

1. **Inventory:**
   - **Life Cycle Inventory (LCI)**
   - **Provides concrete information,**
   - **No bias applied**
2. Impact
   - Life Cycle Impact Assessment
   - Convert inventory to impact
   - Slightly harder to communicate in fab
3. Normalization
   - Enables comparison of different impacts
   - Common unit
   - Enables a single E-score
4. Weighting



POR is the reference process of record being compared to two options

E-score: Impact analysis

Real example based on Dry Etch stack Improvement

1. Inventory:
   - Life Cycle Inventory (LCI)
   - Provides concrete information,
   - No bias applied
2. **Impact**
   - **Life Cycle Impact Assessment**
   - **Convert inventory to impact**
   - **Slightly harder to communicate in fab**
3. Normalization
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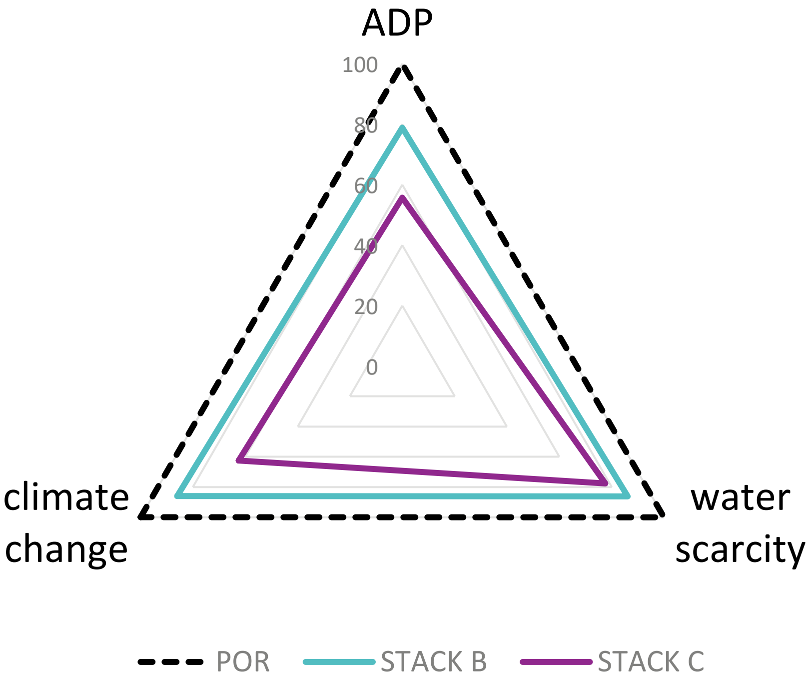

E-score: 3. Normalization

Real example based on Dry Etch stack Improvement

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   - Life Cycle Inventory (LCI)
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3. **Normalization**
   - **Enables comparison of different impacts**
   - **Common unit**
   - **Enables a single E-score**

Normalization Factor (NF_i): average impact of 1 person per year for one specific impact category i :

$$NF_i[unit_i/person] = \frac{Global\ Impact\ i\ (2010)[unit_i]}{Global\ Population\ (2010)[person]}$$

data collection @planet scale

~6.9 billion In 2010

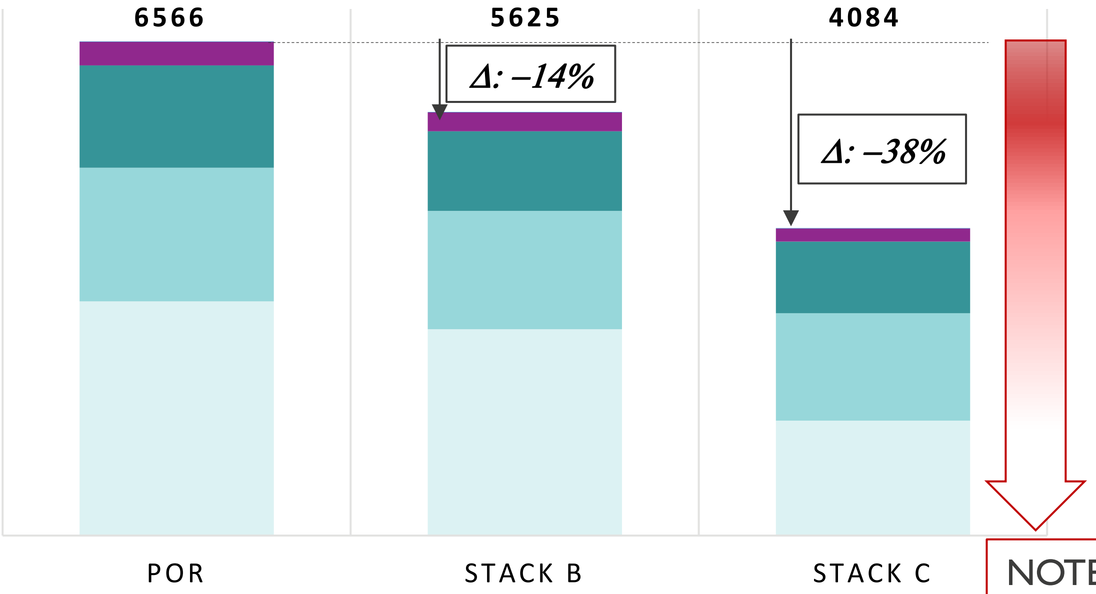
Normalization gives a **unit** of **person**

Weighting gives a **unit** of **points**
(Equal weighting considered here)

E-score: Concatenation to single E-score

Real example based on Dry Etch stack Improvement

E-score version 1 (EF points **per million wafers**)



- water scarcity
- ADP (material scarcity)
- scope 3
- scope 2
- scope 1

Climate change can be **subdivided between Scope** components without affecting total score

NOTE: drive down EF points for less impact

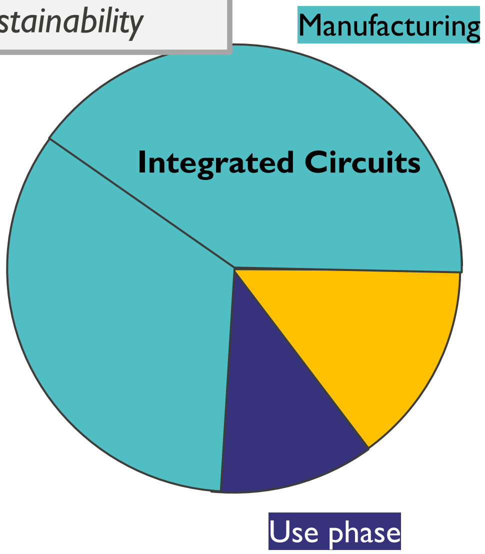
Conclusion

Take home messages

And remember:
- *Environmental sustainability does not stop at climate change*
- *Sustainability does not stop at environmental sustainability*

The climate change impact of IC chip manufacturing is still expected to increase in the future. The industry needs to **work hard to fulfill their pledges and further to achieve net zero by 2050**

The impact of **IC chip manufacturing** is one of the **largest contributors** to the **carbon footprint of ICT devices**:
- Low entropy products from highly complex value chain
- One of highest carbon footprint/ mass ratios
- Consumes massive amount of electricity and high purity materials



The total climate change impact of IC manufacturing can be reduced by:
- Effective **abatement** on high GWP process gases
- **Non-fossil-based electricity** sources
- **De-fossilize supply chain**, specifically Si wafer production
- Adoption of **environmental scoring metrics** early in the technology design phases

What can you do (as an engineer)?

“If you are not part of the solution, you are part of the problem”...?

- **Think holistically about the implications of what you do**
  - For environmental impacts, Life-Cycle Analysis is the standard
  - LCA can be time-consuming, but is flexible in scope/accuracy (better be inaccurate than blind)
  - Don’t forget to also think beyond LCA (rebounds, societal impacts, ...)
- **How to do “eco-design”?**
  - General principles abound (circularity, absolute sustainability, doughnut economy, regenerative, low-tech, ...)
  - At-scale examples are rarer (on the surface ...) but do exist
  - It’s up to you now!
- **Instead of efficiency optimization aim for resilience**:
  - Resilient systems are sub-optimal but adaptative: “From better to good enough”

imec

embracing a better life