



mmeC

Climate-aware semiconductor manufacturing
and what that means to lithography

Emily Gallagher, Lars-Åke Ragnarsson, Cédric Rolin

An aerial photograph of a dense forest, showing the intricate patterns of tree canopies. A semi-transparent circular grid is overlaid on the right side of the image, centered around the text. The grid consists of small squares, each containing a stylized cross or star-like pattern, creating a textured, woven appearance. The text 'introduction' is written in a clean, white, sans-serif font, positioned within the grid area.

introduction

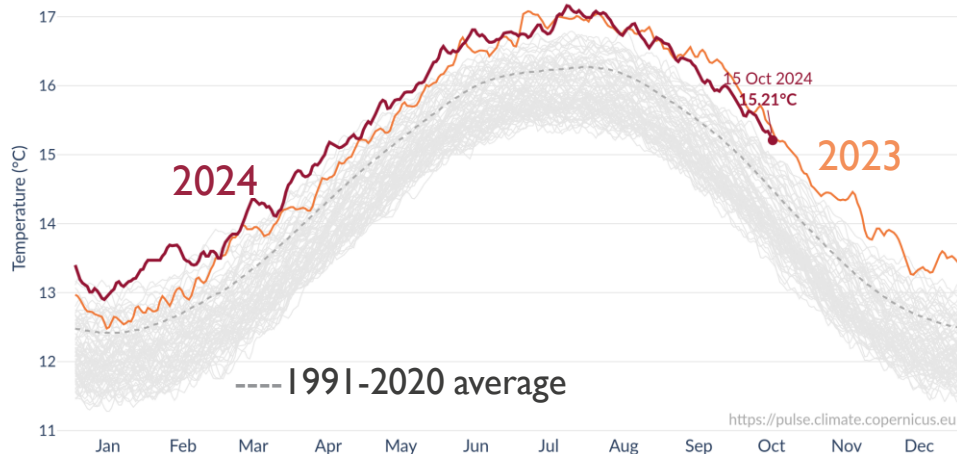
Earth is warming

Global surface air temperatures 1940-2024

Daily global surface air temperature

Data: ERA5 1940-2024 • Credit: C3S/ECMWF

— 2024 — 2023 — 1940-2022 - - - 1991-2020 average



2024

2023

---- 1991-2020 average

<https://pulse.climate.copernicus.eu>



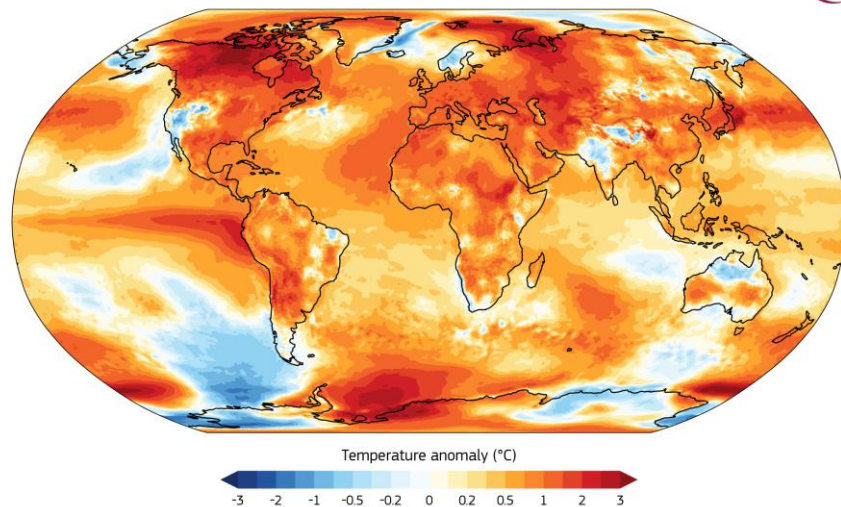
PROGRAMME OF
THE EUROPEAN UNION



2023 mean vs. 1991-2020 average

SURFACE AIR TEMPERATURE ANOMALY • 2023

Data: ERA5 • Reference period: 1991-2020 • Credit: C3S/ECMWF



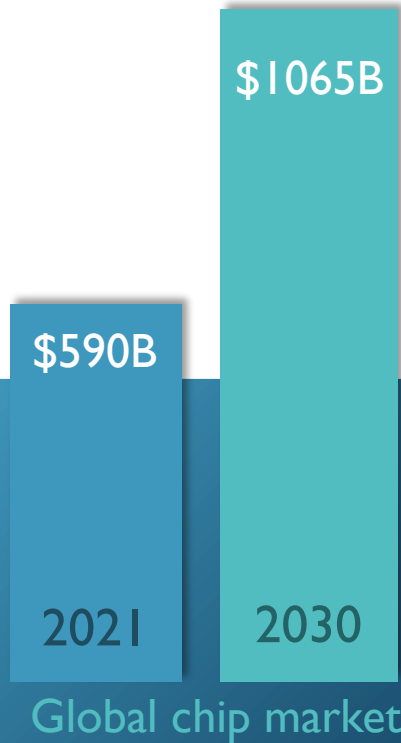
PROGRAMME OF
THE EUROPEAN UNION



Data: ERA5 • Credit: C3S/ECMWF

<https://pulse.climate.copernicus.eu/>

Global chip market continues to grow

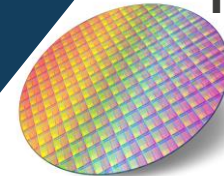


Growing demand for semiconductor chips driven by data centers, wireless communication, automotive, etc. increases production demand and emissions



Global emissions
37 Bton CO₂eq

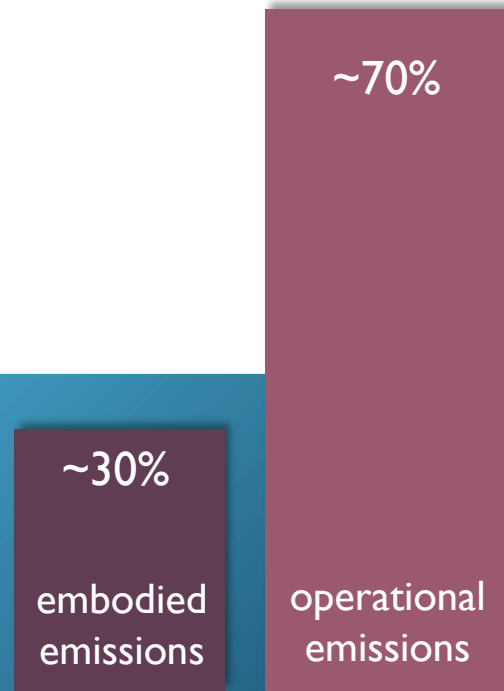
IC manufacturing
185 Mton CO₂eq



<https://semiengineering.com/chip-industry-heads-toward-1t/>

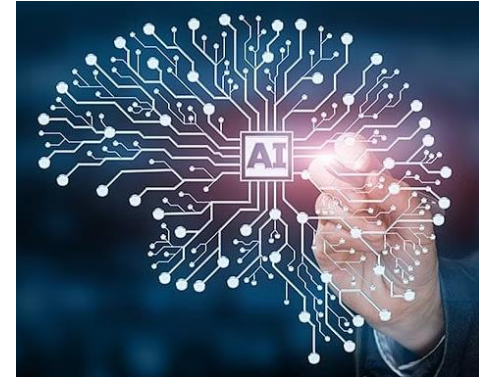
*Emissions from fabrication and supply chain. Source: SEMI SCC Whitepaper on Transparency, Ambition, and Collaboration - 2023"

Artificial intelligence (AI)



AI deployment is growing exponentially
(model training, data center power consumption, ...)

IC chips are a critical part of embodied emissions



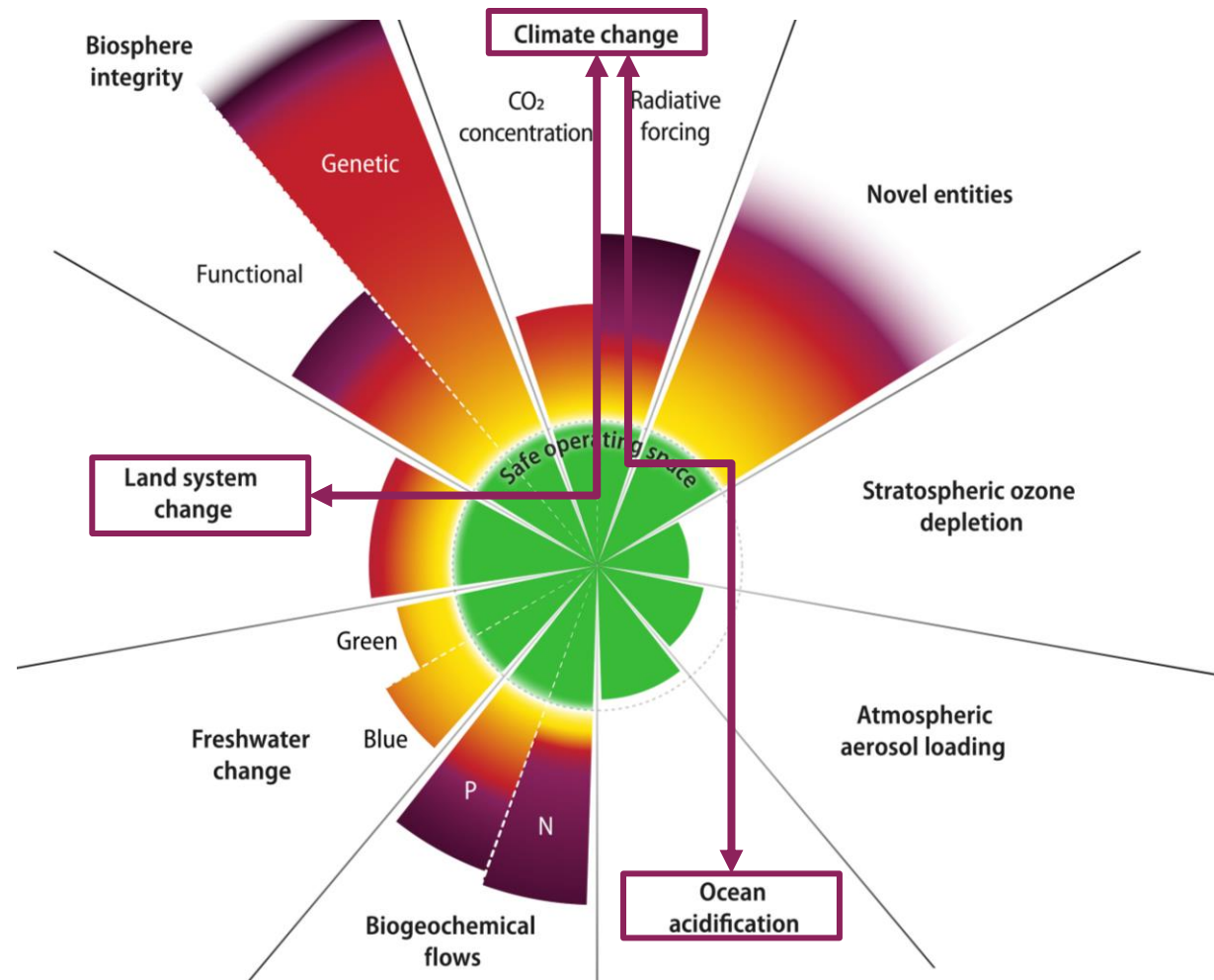
Need standard,
reliable, methods for
reporting and
minimizing AI
embodied impact

<https://arxiv.org/abs/2309.14393>

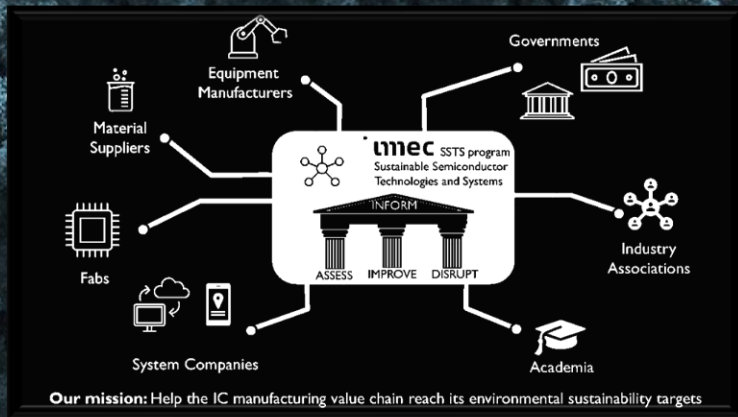
image from: <https://www.simplilearn.com/advantages-and-disadvantages-of-artificial-intelligence-article>

Beyond climate change

- Planetary boundaries framework: nine processes critical for Earth's stability
- Planetary systems are linked
 - Ocean acidification and atmospheric CO₂
 - Land use and local climate
- Semiconductor manufacturing impacts extend beyond climate change emissions
 - Water use, chemicals (including PFAS)

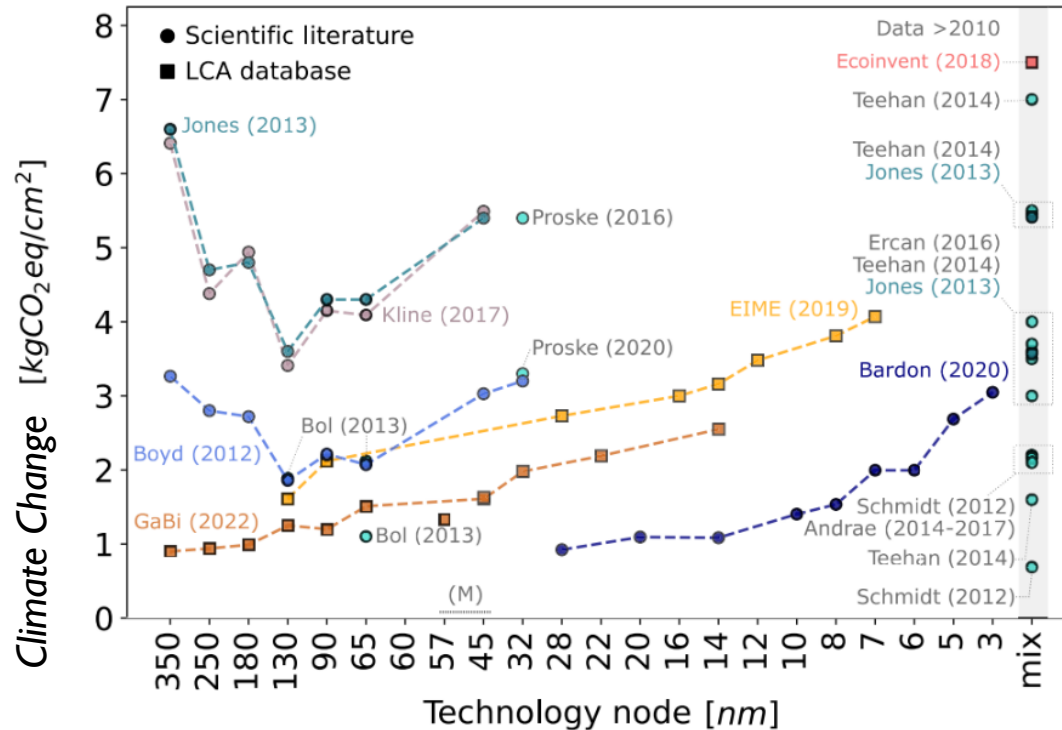


K. Richardson et al., "Earth beyond six of nine planetary boundaries" *Sci. Adv.*, vol. 9, no. 37, Sep. 2023, doi: [10.1126/sciadv.adh2458](https://doi.org/10.1126/sciadv.adh2458).



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Literature / LCA prior to imec.netzero



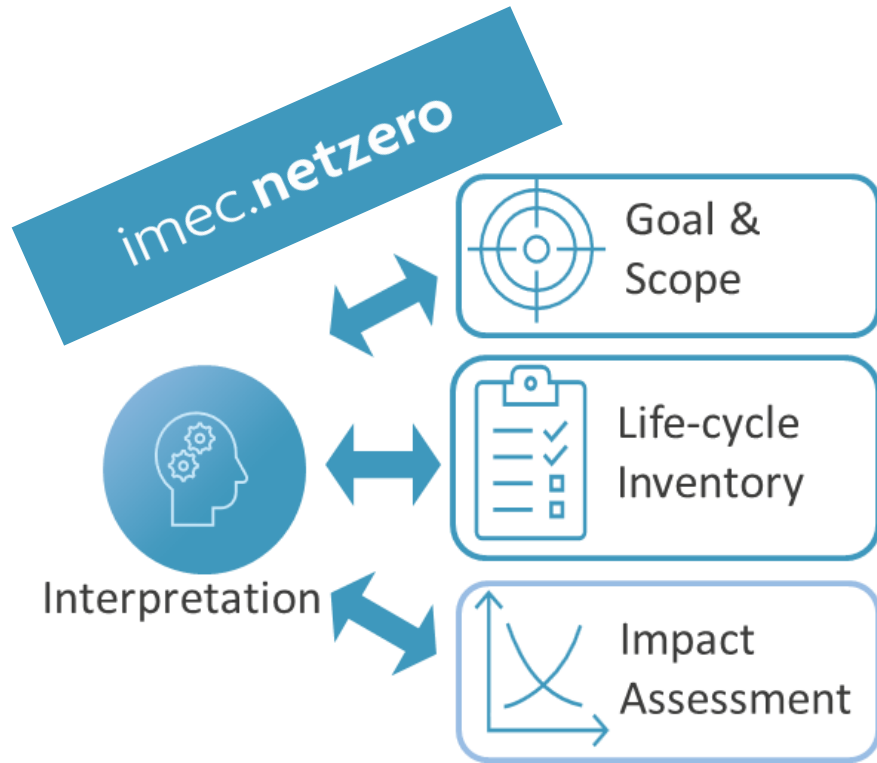
Literature / LCA database uses variable:

- Scope
- Data sources (primary vs. secondary)
- Approaches (bottom-up vs top-down)
- “creative” plugging of data gaps

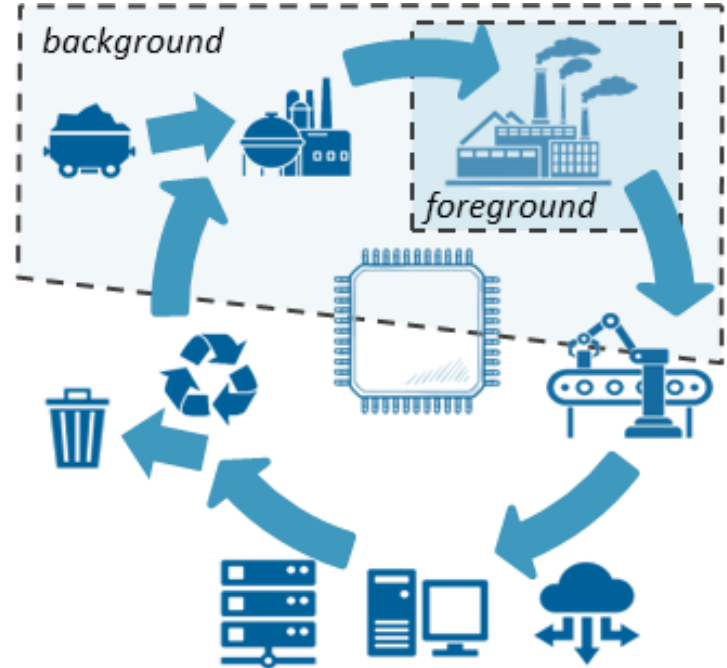
Source: Pirson et al., 2023 – The Environmental Footprint of IC Production: Review, Analysis, and Lessons From Historical Trends

Incomplete node coverage with huge variation in impact (7X) makes conclusions impossible

Life cycle analysis of IC manufacturing using the virtual fab

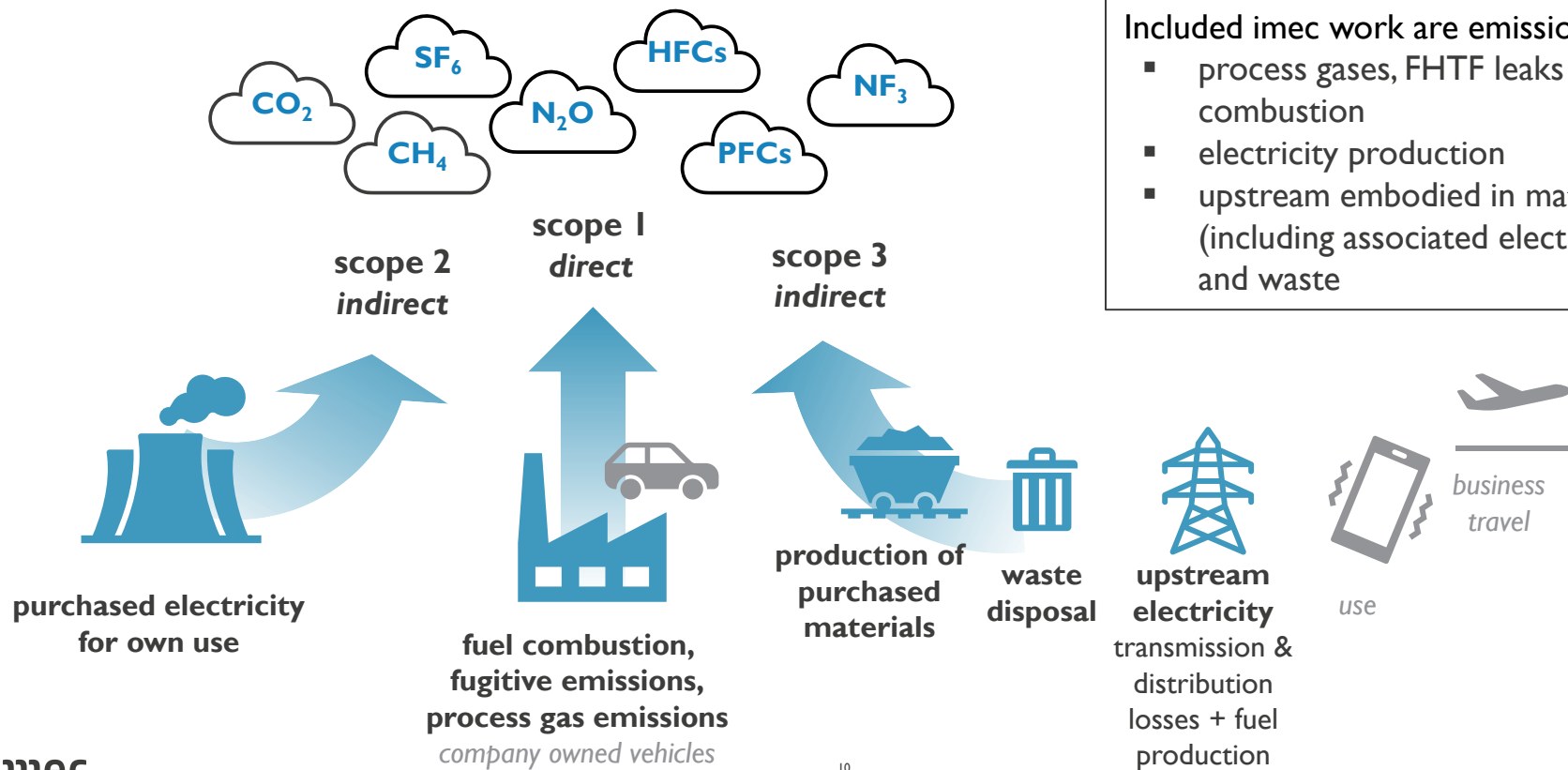


Methodology audited ISO 14040,44,67



Simplified product life cycle
of an IC logic chip.

Greenhouse Gas (GHG) protocol: scopes 1, 2 and 3

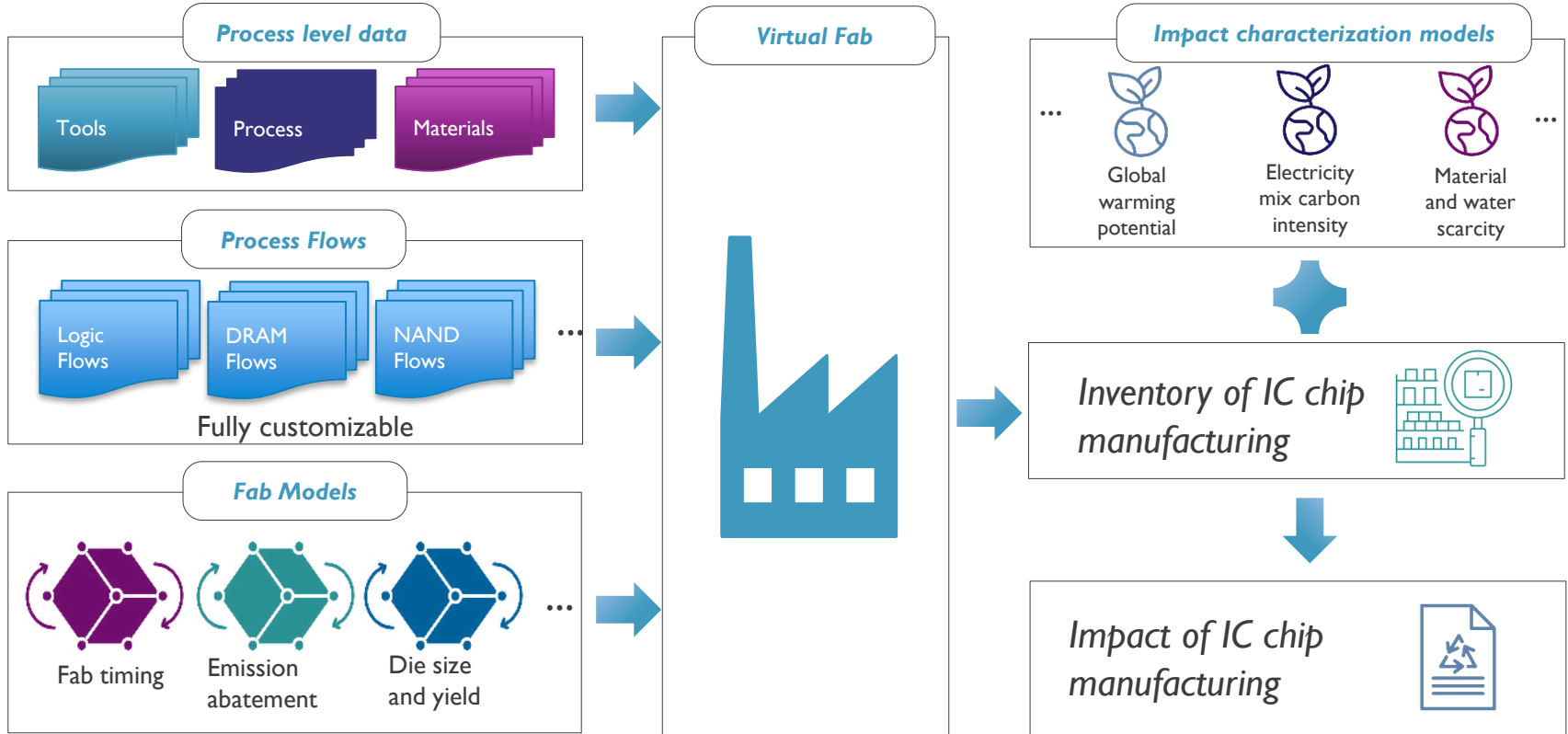


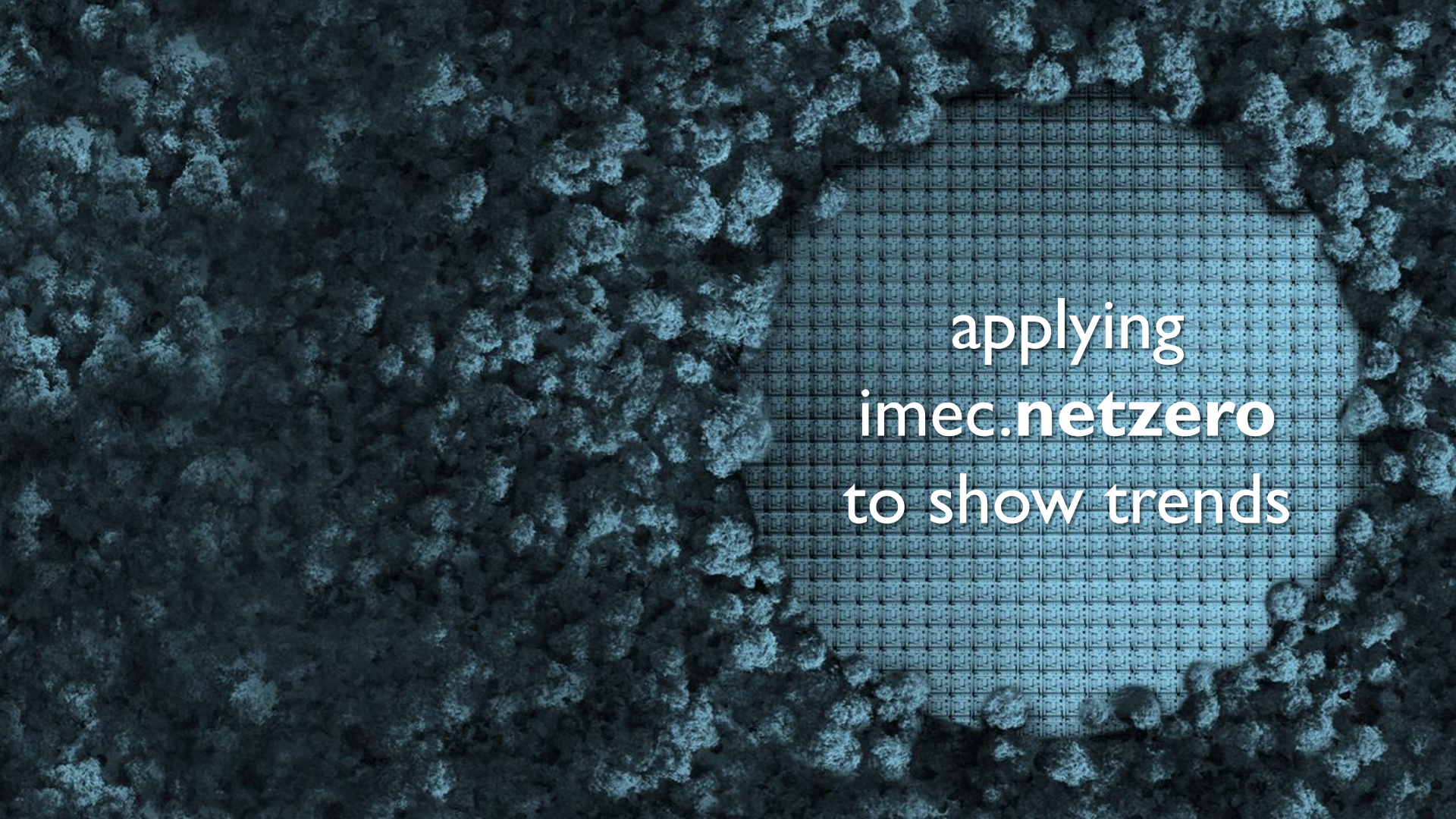
Included imec work are emissions from:

- process gases, FHTF leaks and fuel combustion
- electricity production
- upstream embodied in materials (including associated electricity) and waste

Virtual fab model embedded in imec.netzero

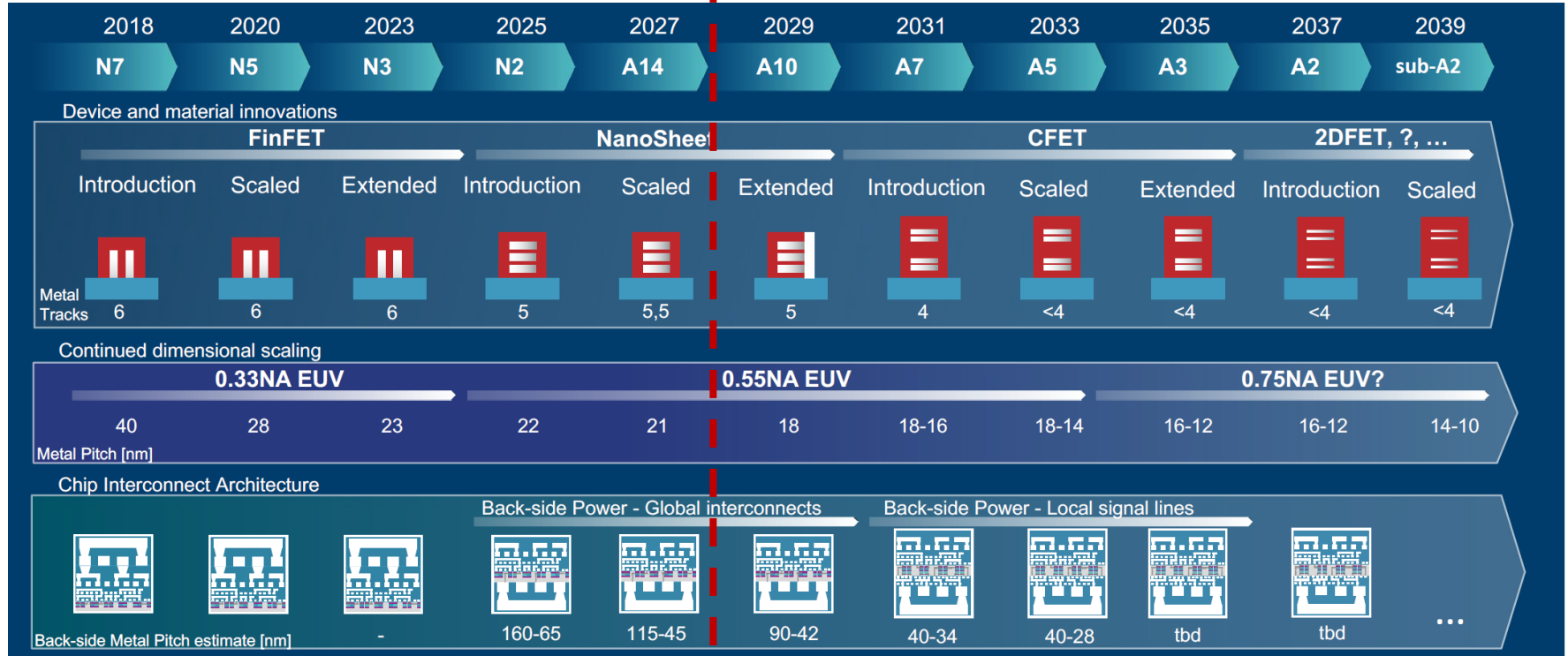
Quantify the footprint of a chip



An aerial photograph of a dense forest, rendered in a dark teal or blue color palette. A circular area on the right side of the image is overlaid with a fine, light-colored grid pattern, creating a contrast with the organic texture of the trees. The text is positioned within this grid area.

applying
imec.netzero
to show trends

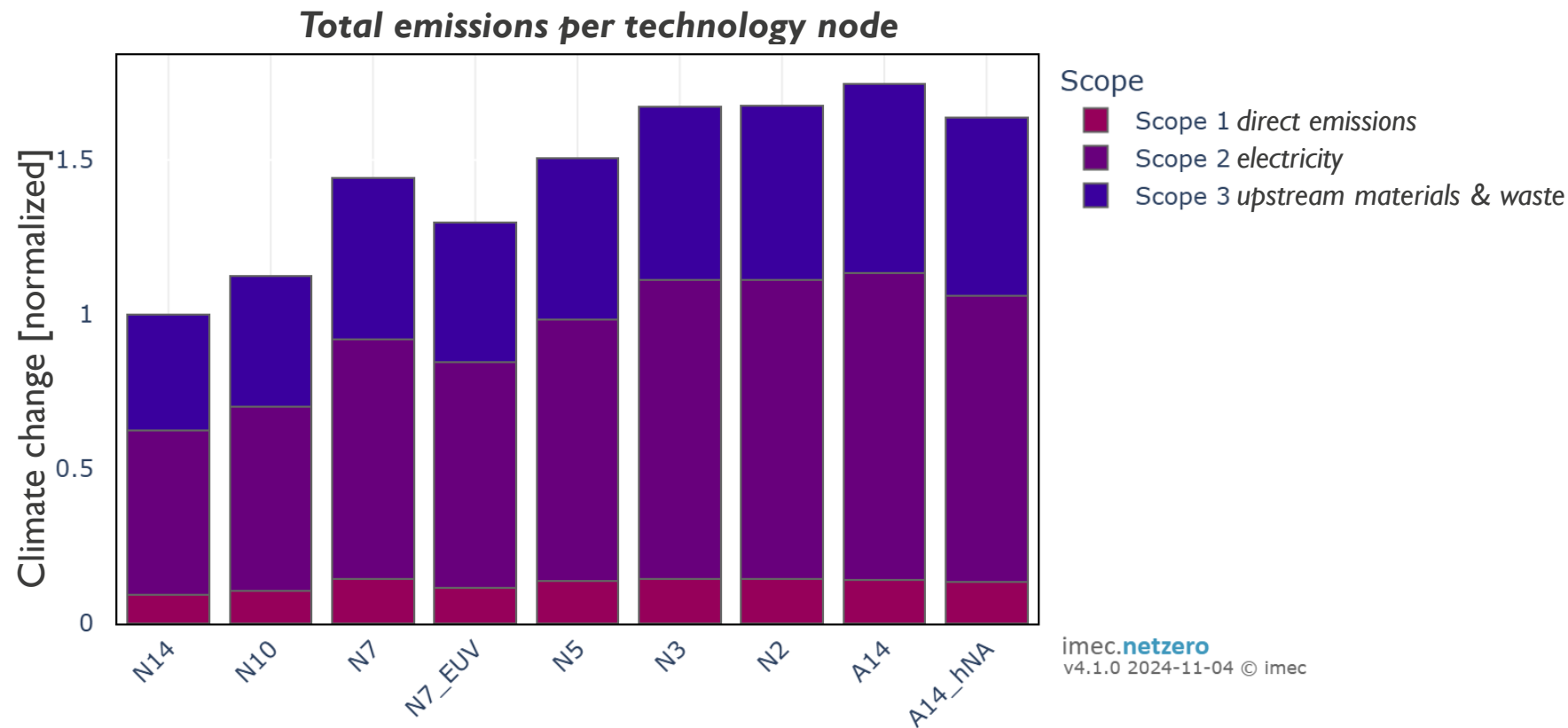
Logic technology roadmap



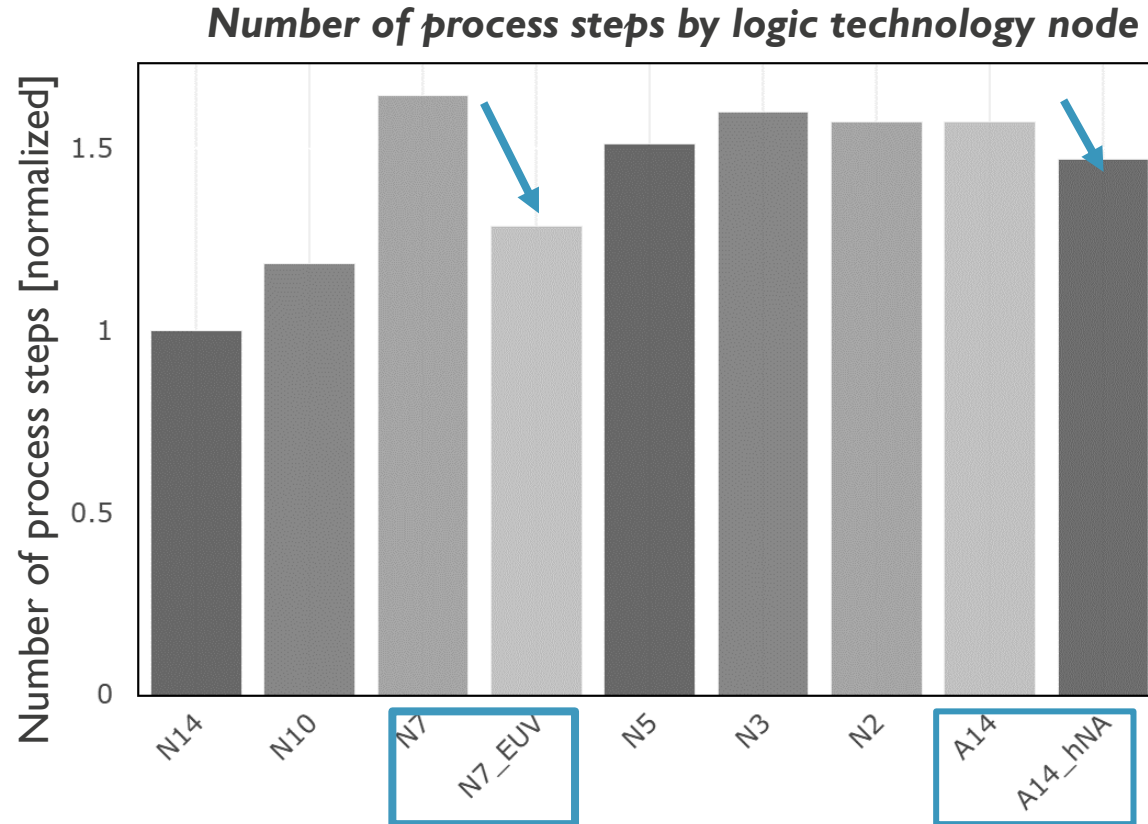
N14 to A14 logic nodes used to illustrate trends

Luc Van Den Hove, imec technical forum, May 2024

Climate impact by logic node



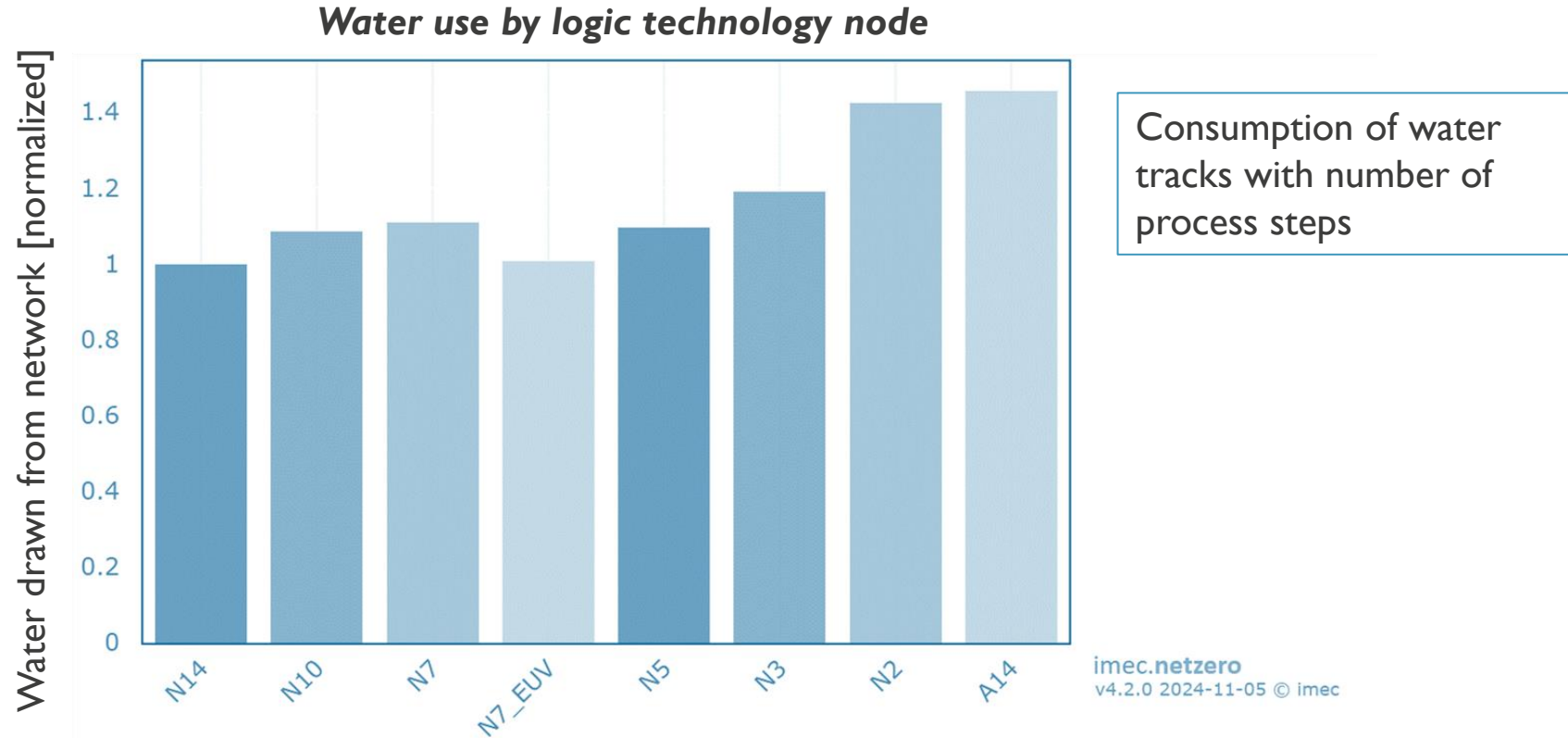
Process steps by logic technology node



High resolution lithography reduces multi-patterning steps and simplification reduces environmental impact

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Water use by logic technology node



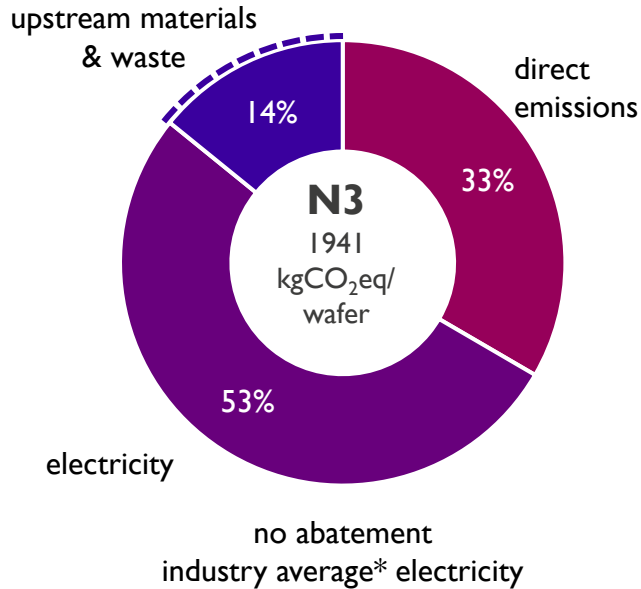
An aerial photograph of a dense forest, rendered in a dark teal or blue color palette. A circular area on the right side of the image is highlighted with a semi-transparent grid pattern. Overlaid on this grid is the text 'applying imec.netzero to show reduction pathways' in a white, sans-serif font.

applying
imec.netzero
to show reduction
pathways

N3 logic node: fab emission reduction

Overall emissions

Without process gas abatement:
significant direct emissions

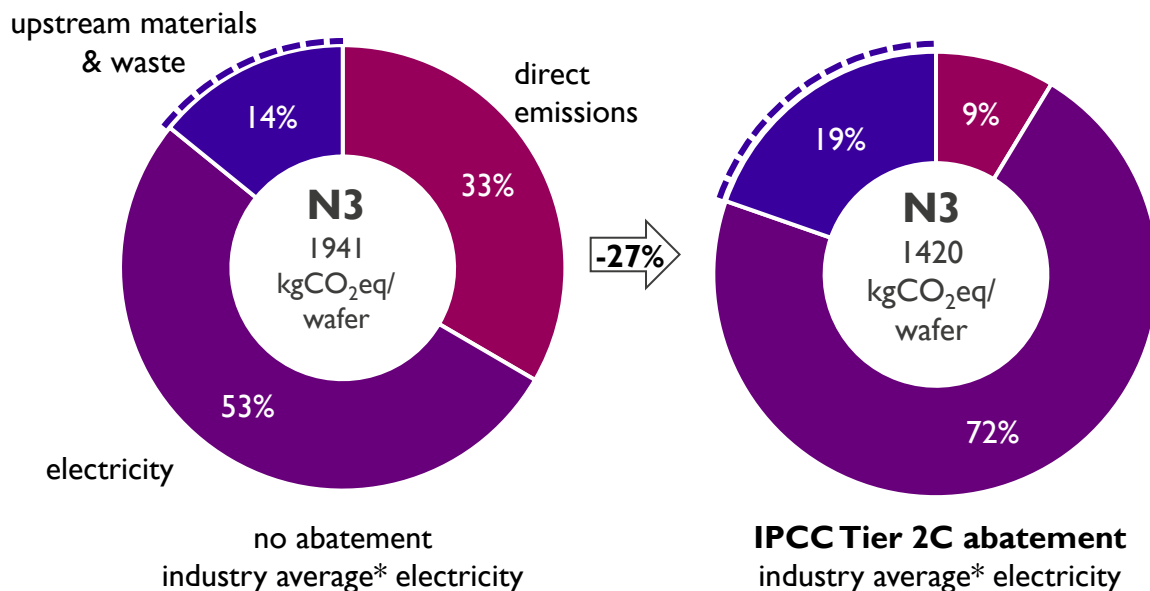


N3 logic node: fab emission reduction

Overall emissions

Without process gas abatement:
significant direct emissions

Deploying 100% abatement:
electricity dominates



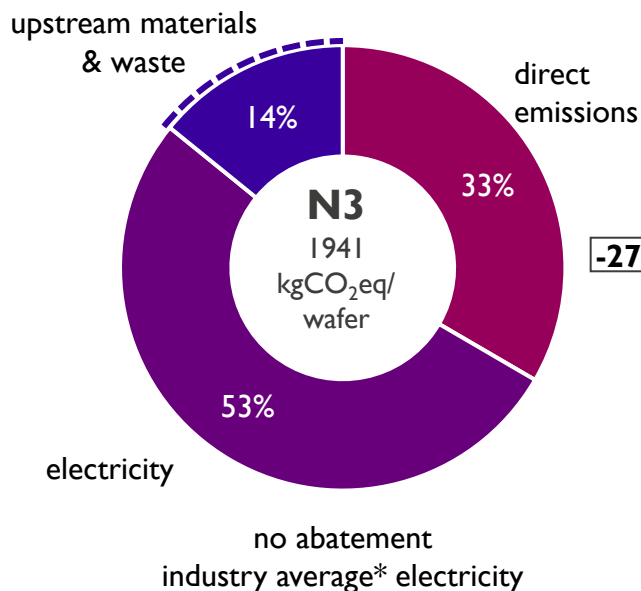
N3 logic node: fab emission reduction

Overall emissions

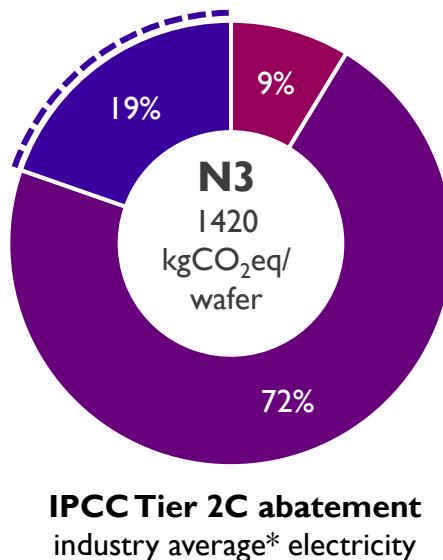
Without process gas abatement:
significant direct emissions

Deploying 100% abatement:
electricity dominates

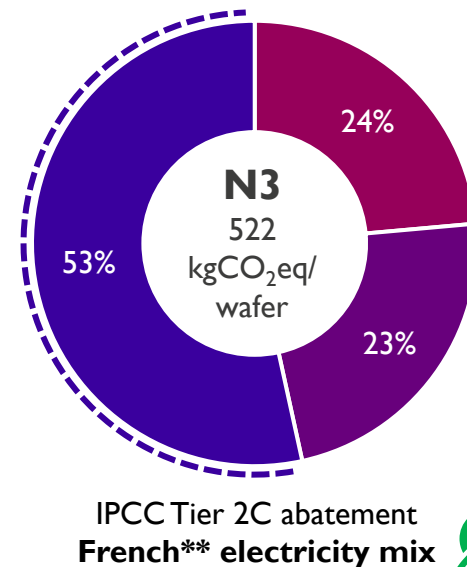
Clean electricity: **upstream materials and waste** grow



-27%



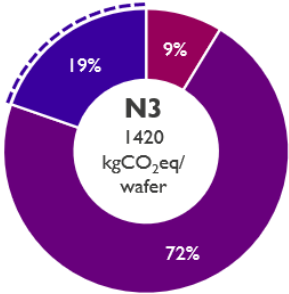
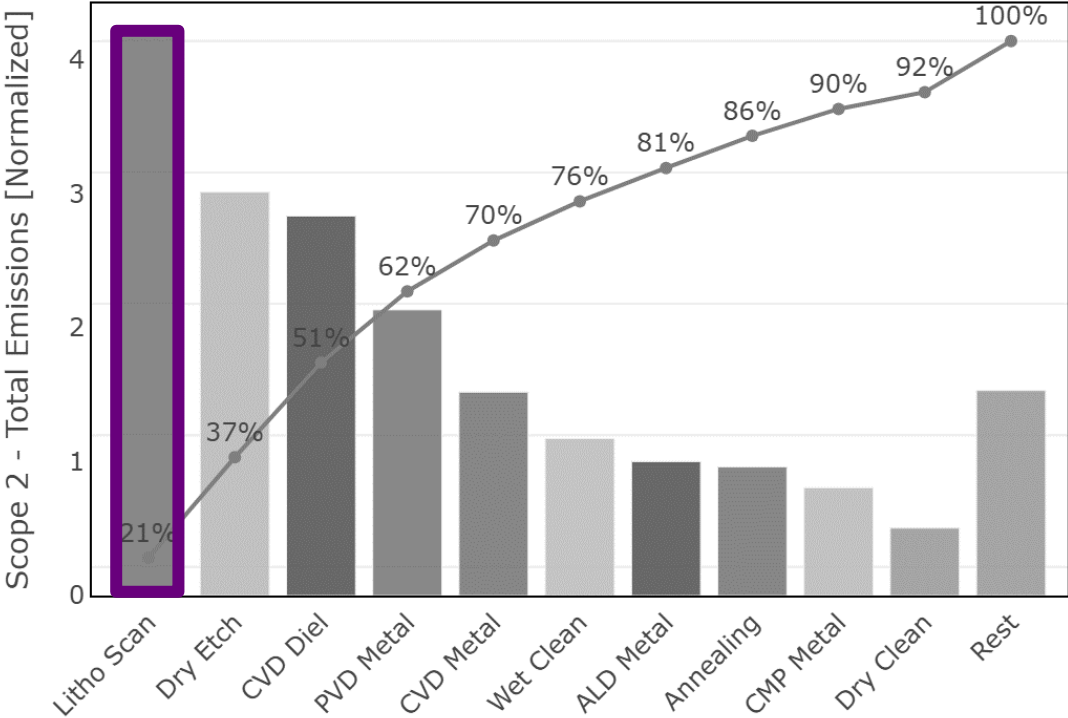
-63%



N3 logic node: electricity use by process

Process focus

N3 logic : energy consumption by process area



*Industry Average:
0.509 kgCO₂eq/kWh

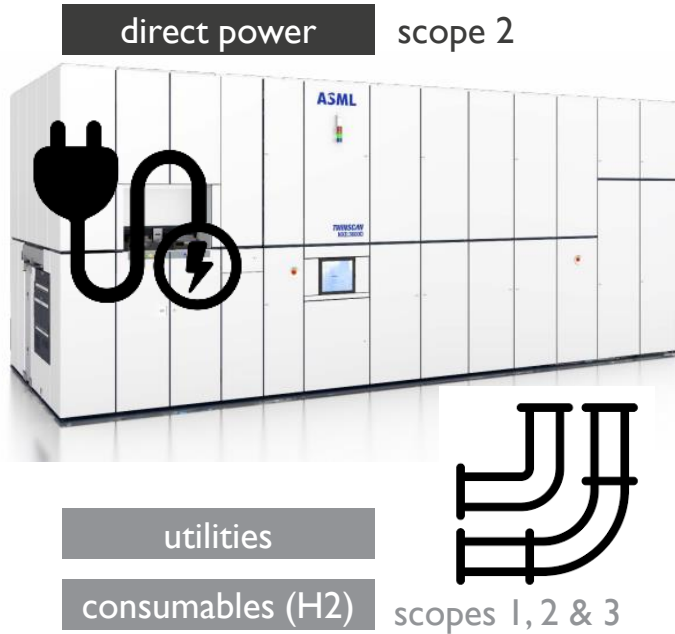
IPCC Tier 2C abatement
industry average* electricity

Litho scanner
dominates energy
consumption

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Lithography emissions by scope

Process focus: EUV 0.33NA scanner



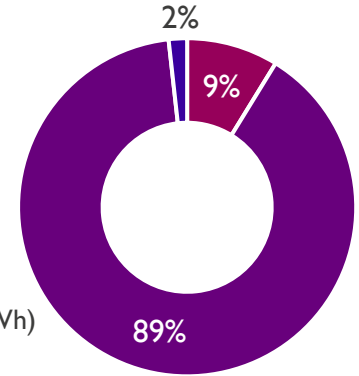
conversion
factors

Litho scanner only

- direct emissions
- electricity
- upstream materials and waste

industry
average
energy
mix

0.5 (kgCO₂eq/kWh)



Direct emissions dominated by fugitive emissions from fluorinated heat transfer fluids

Electricity contribution can be reduced by maximizing scanner throughput and reducing wafer dose (already a focus to reduce cost)

Lithography emission by scope

Process focus: EUV 0.33NA scanner



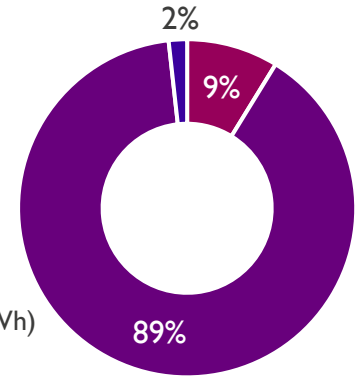
Low-carbon energy increases importance of upstream embodied emissions like hydrogen

Litho scanner only

-  direct emissions
-  electricity
-  upstream materials and waste

**industry
average
energy
mix**

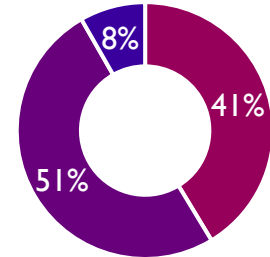
0.5 (kgCO₂eq/kWh)



total litho emissions
reduced by 79%

**low-
carbon** 
energy mix

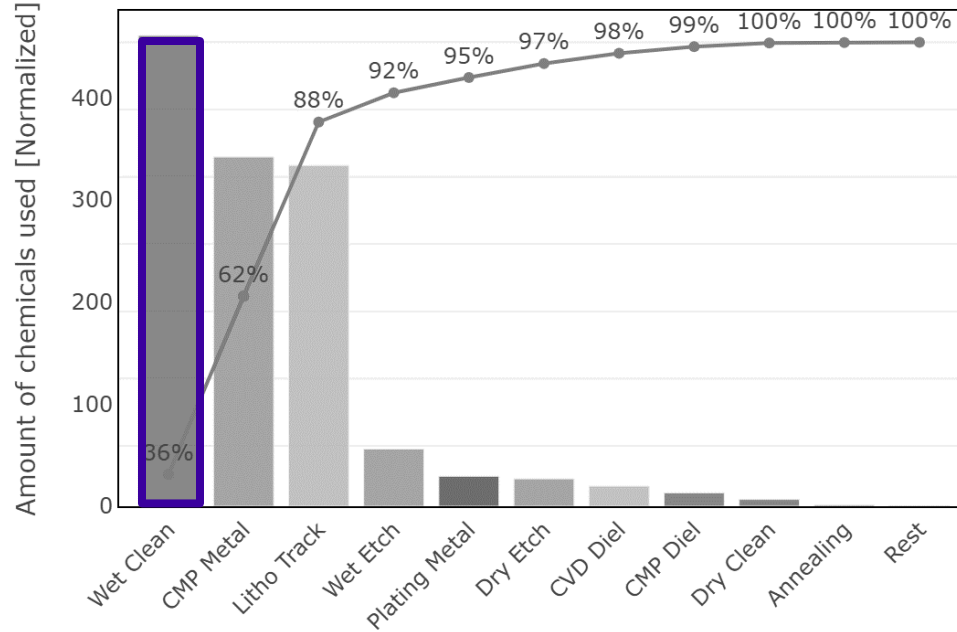
0.052
(kgCO₂eq/kWh)



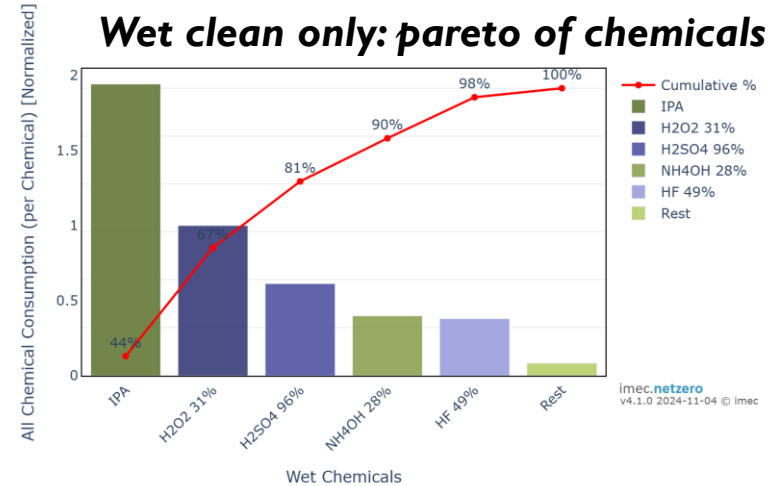
N3 logic node: chemical use

Wet clean: IPA and H2O2 dominate

N3 logic : chemical consumption by process area



Wet clean only: pareto of chemicals

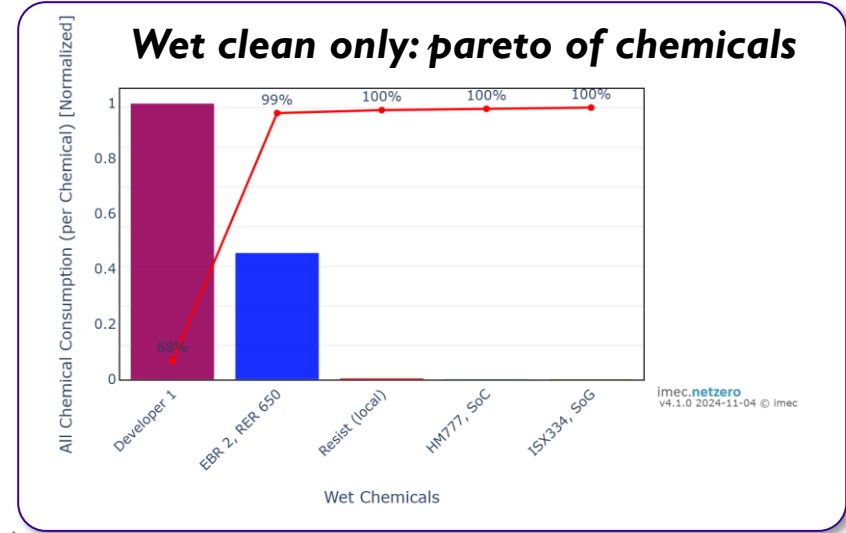
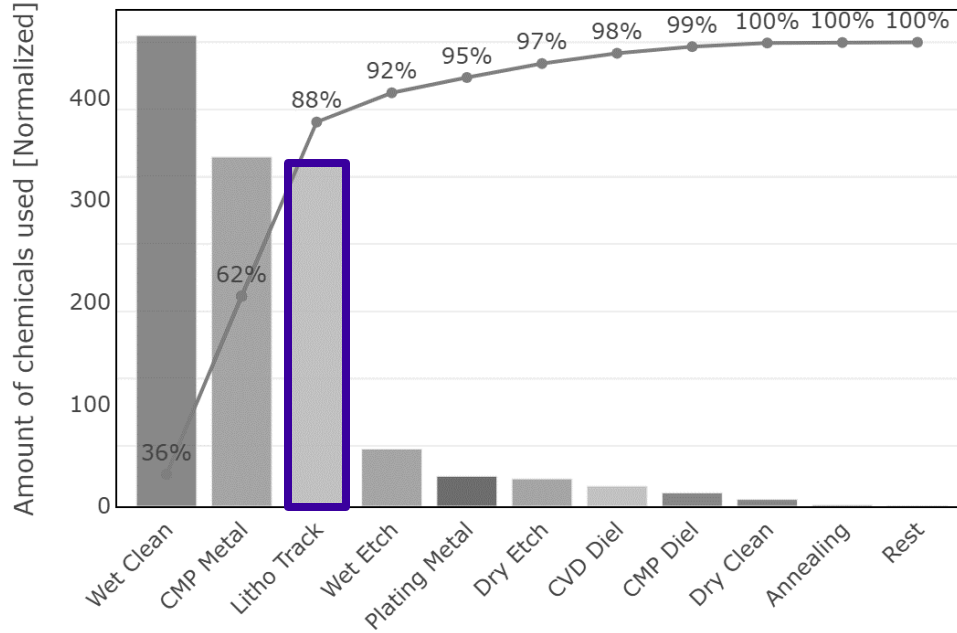


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N3 logic node: chemical use

Litho track: developer use dominates

N3 logic : chemical consumption by process area

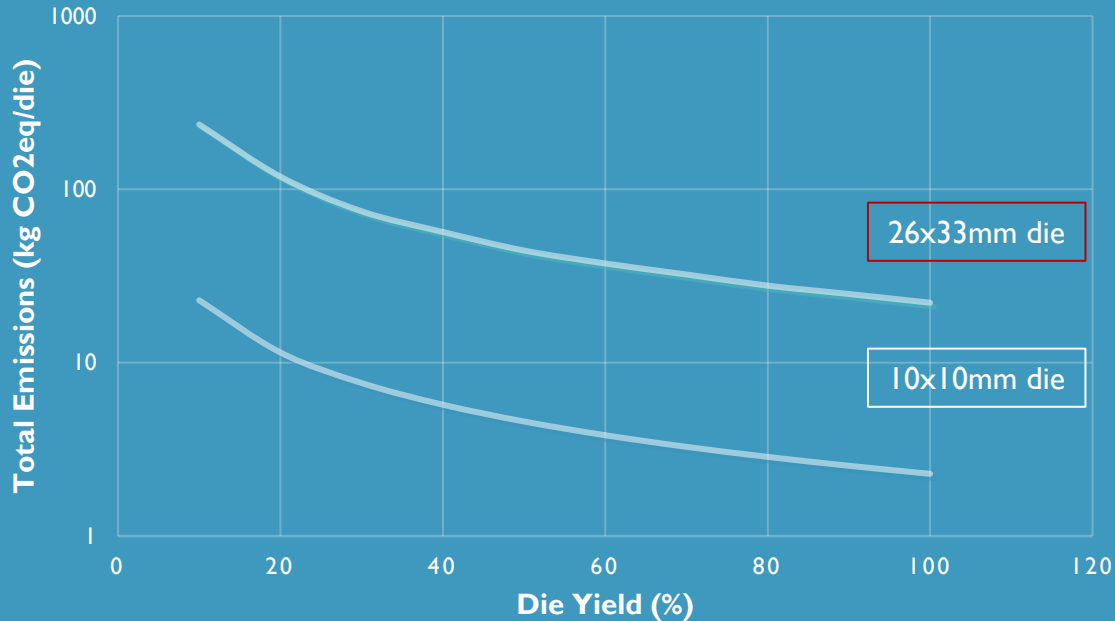


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Yield always matters; impact on total emissions

Small and large (full field) die sizes for N3 logic node

YIELD IMPACT ON TOTAL EMISSIONS

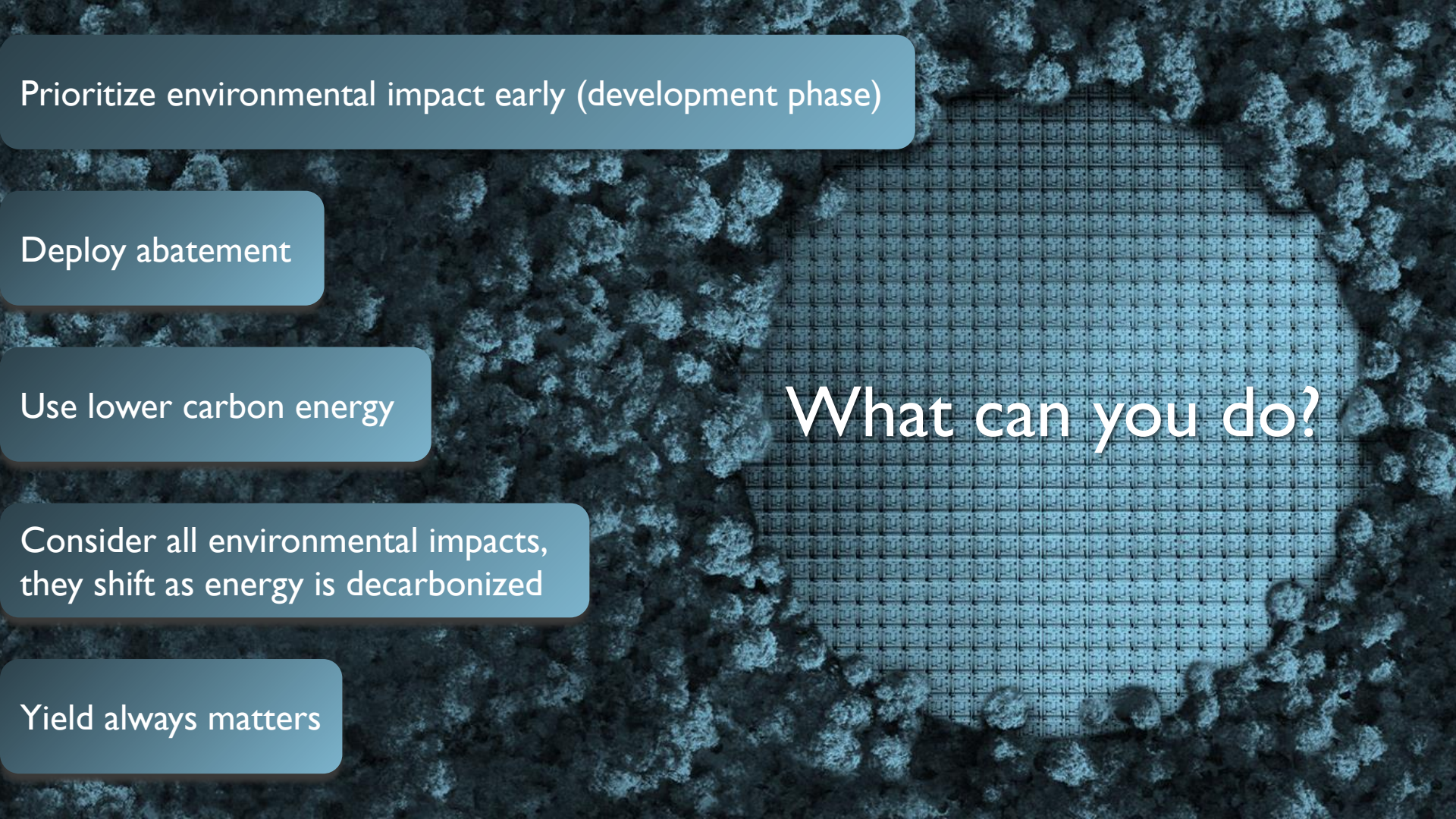


Generated by the imec.netzero v4.1.0 web application on 2024-10-28

- imec.netzero assumptions:
 - industry average carbon intensity of energy
 - IPCC AR6 abatement
 - HVM fab starts: 60k per month
- Assuming a large die, 1% yield loss will result in ~ 16 tCO₂eq
 - Comparable to US per capita total emission for one year
 - Target for what the Earth can support is 2t CO₂eq/year

An aerial photograph of a dense forest, viewed from above. The trees are dark green and form a textured canopy. A large, semi-transparent circular grid is overlaid on the right side of the image. The grid is composed of small squares, each containing a small crosshair. The word "Summary" is written in white, sans-serif font across the middle of the grid.

Summary

An aerial photograph of a dense forest, viewed from above. A semi-transparent grid pattern is overlaid on the right side of the image, creating a textured effect. The text is contained within semi-transparent blue rounded rectangles.

Prioritize environmental impact early (development phase)

Deploy abatement

Use lower carbon energy

Consider all environmental impacts,
they shift as energy is decarbonized

Yield always matters

What can you do?



mec

embracing a better life

...s don't always change minds

...e formed, your own beliefs solidify

...orically we rely on each other's expertise;
...ans cooperate exceptionally well but blur
...ndaries between

our knowledge

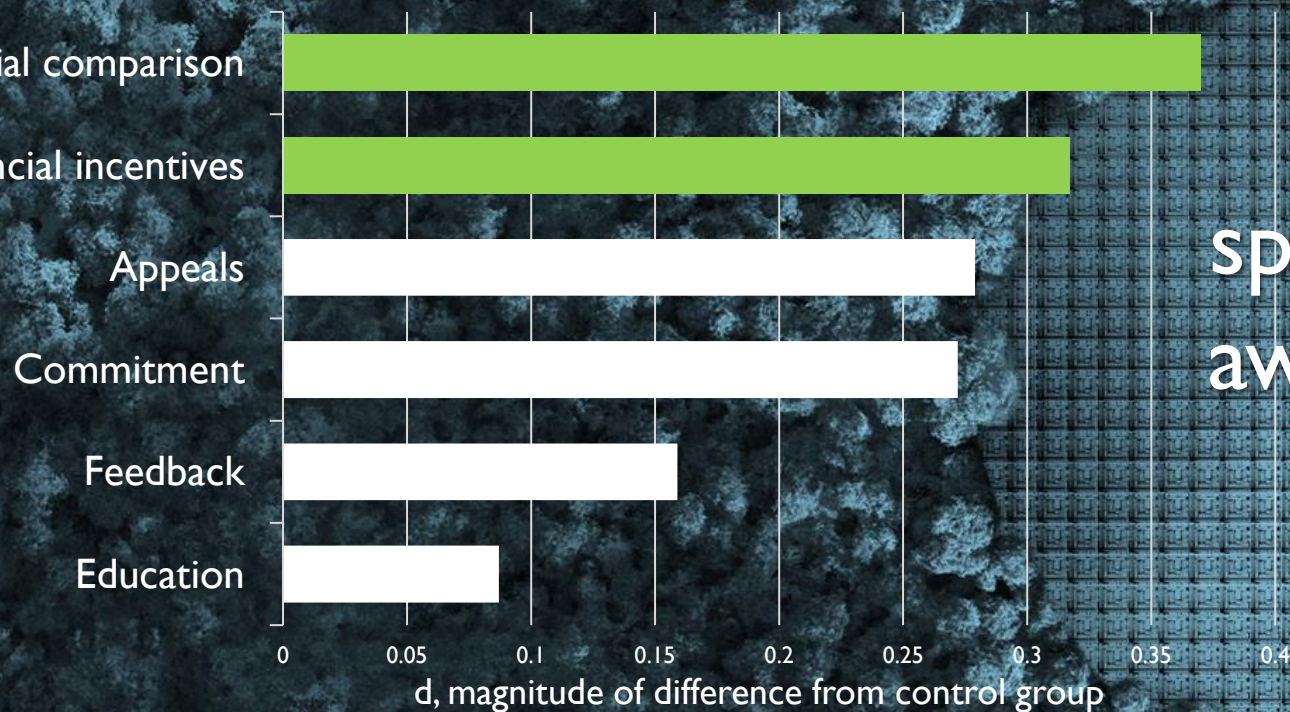
someone else's knowledge



spread climate
awareness: but
how?

"...ny facts don't change our minds", Elizabeth Kolbert, the New Yorker, February 2017.

Ways to induce climate-aware behaviors



spread climate
awareness: but
how?