Sustainable Processor Design

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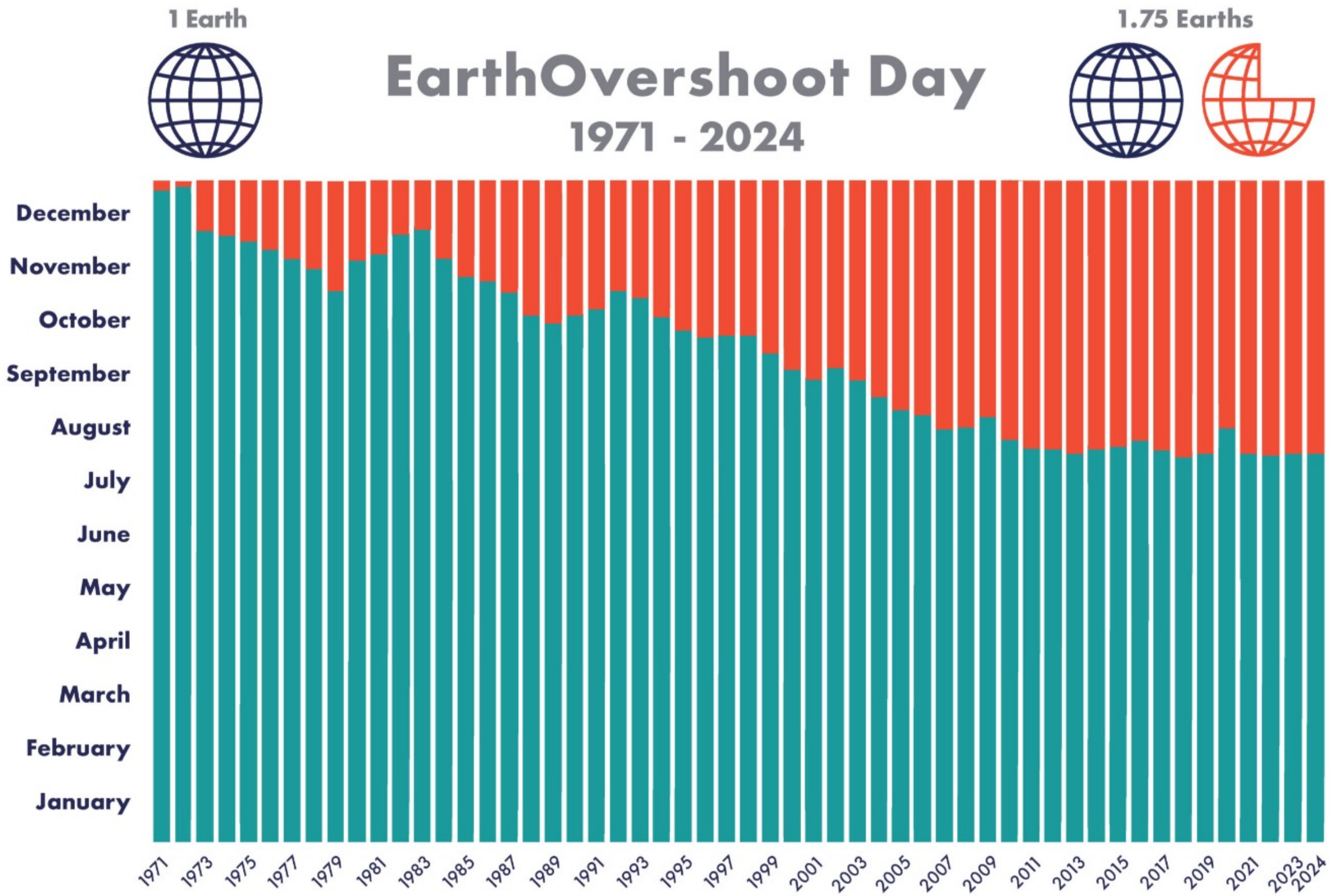
LOCOS -- January 22, 2026

“***Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.***”

[The Brundtland Report of the World Council on Economic Development, 1987]

How Are We Doing?



EARTH OVERSHOOT DAY · FODAFO FOOTPRINT DATA FOUNDATION · Global Footprint Network Advancing the Science of Sustainability

Based on National Footprint and Biocapacity Accounts 2023 Edition

[Global Footprint Network]

U.N. Report Says World Could See 3.1°C Warming by 2100 Without Urgent Action on Climate

HEADLINE OCT 25, 2024

GHG Emissions Lead to Global Warming

bush fire

drought

biodiversity loss

hurricanes

flooding

Contribution of ICT to global greenhouse gas (GHG) emissions estimated to be around 2.1–3.9%, and it is rising

…on par with aviation industry…

[Freitag et al., 2020]

Sustainability is a Multi-Faceted Challenge

Sustainability is much more than combating global warming

It is also about

- **Raw material extraction**

  World Bank projects that demand for metals and minerals will increase rapidly with climate ambition

  - Electric storage batteries: 10x more metals (aluminum, cobalt, iron, lead, lithium, manganese and nickel) needed by 2050 under a 2℃ scenario

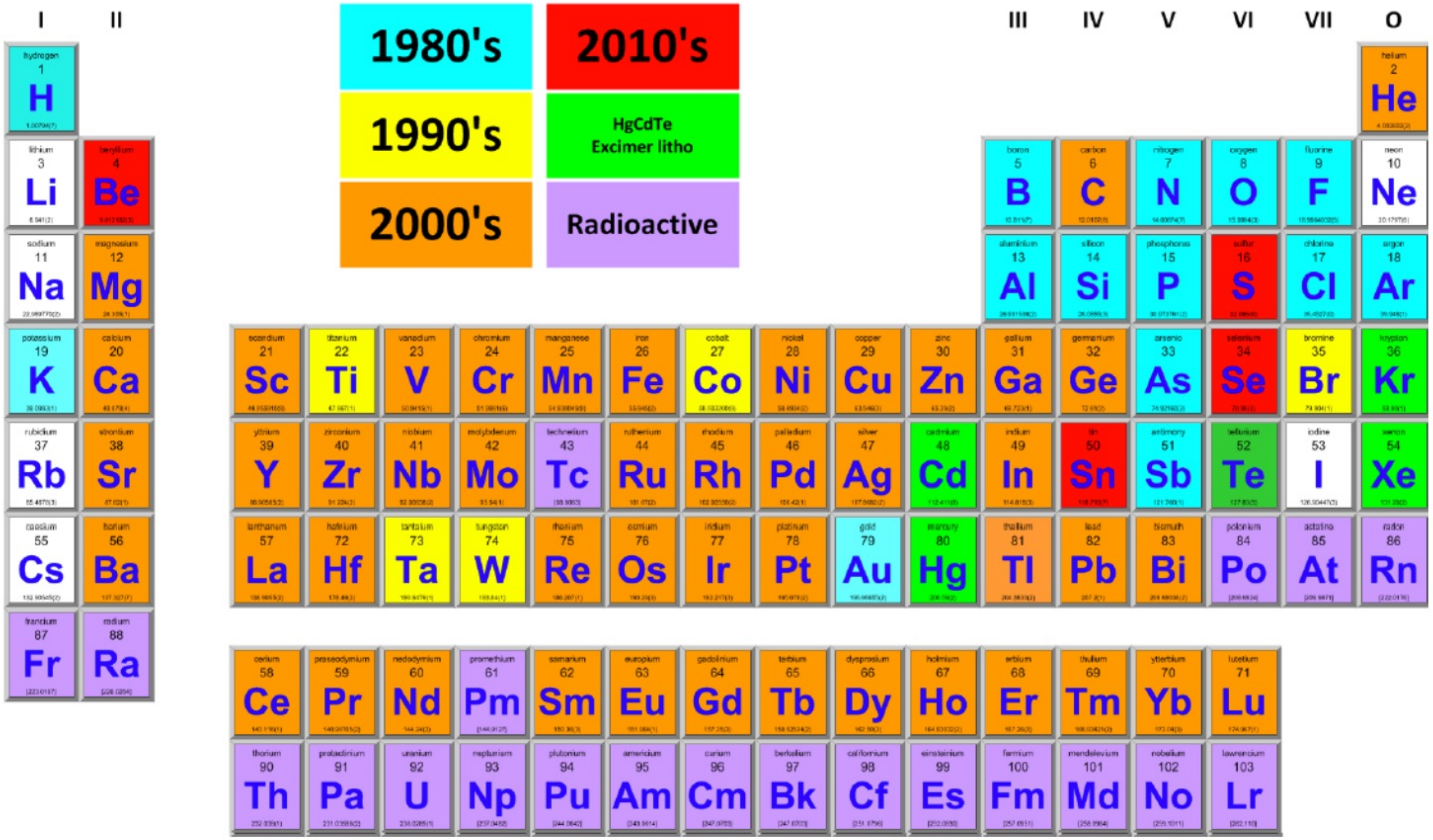
  Under EU's climate-neutrality scenarios for 2050, the EU needs

  - 18x more lithium in 2030, and almost 60x more in 2050
  - 5x more cobalt in 2030, and almost 15x more in 2050
  - 10x more **Rare Earth Elements (REEs)** in 2050
    - REEs for permanent magnets: Dysprosium, Neodymium, Praseodymium, Samarium; The remaining rare earths are Yttrium, Lanthanum, Cerium, Promethium, Europium, Gadolinium, Terbium, Holmium, Erbium, Thulium, Ytterbium, Lutetium

[World Bank (2017): The Growing Role of Minerals and Metals for a Low Carbon Future]

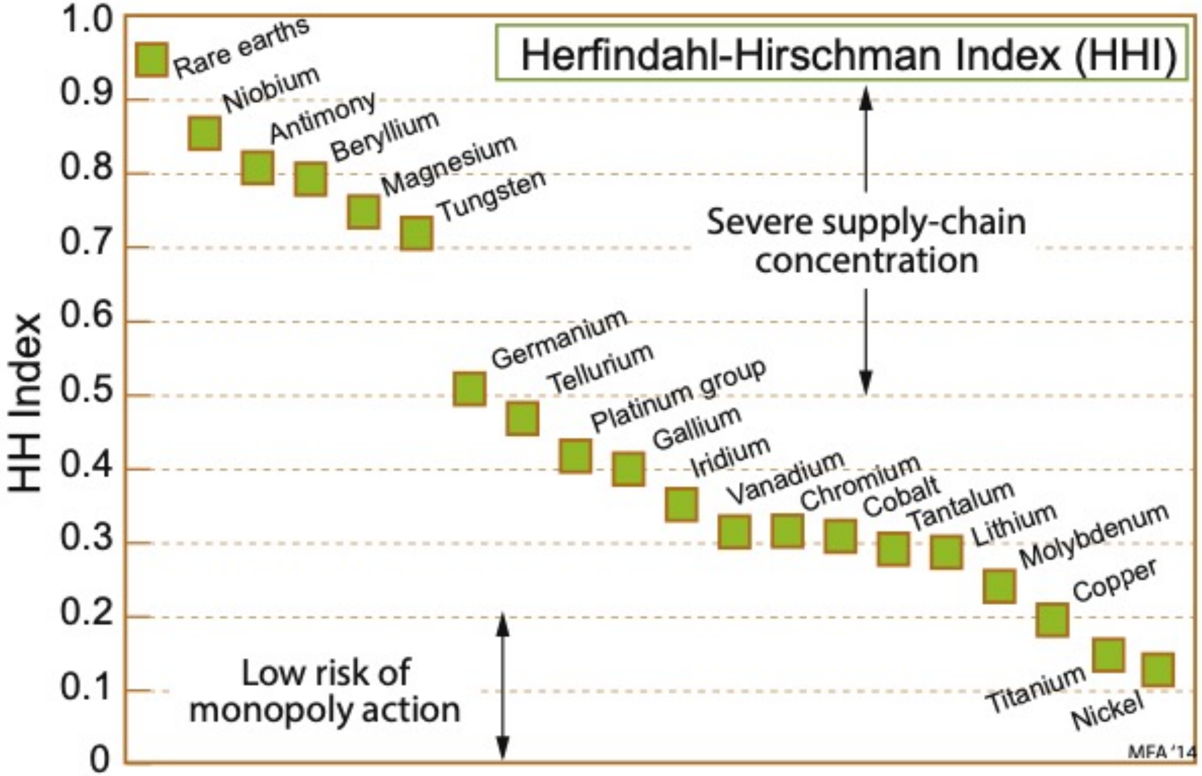
[European Commission 2020: Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability]

What Materials Are Needed to Produce Microelectronic Devices?



[Ernst et al., HiPEAC Vision 2024]

Supply Chain Risk



Herfindahl-Hirschman Index (HHI):

$$HHI = \sum_{i=1}^{n} f_i^2$$

f_i is fraction of market sourced by nation *i*, and *n* is total number of source-nations.

One nation is monopoly: HHI = 1

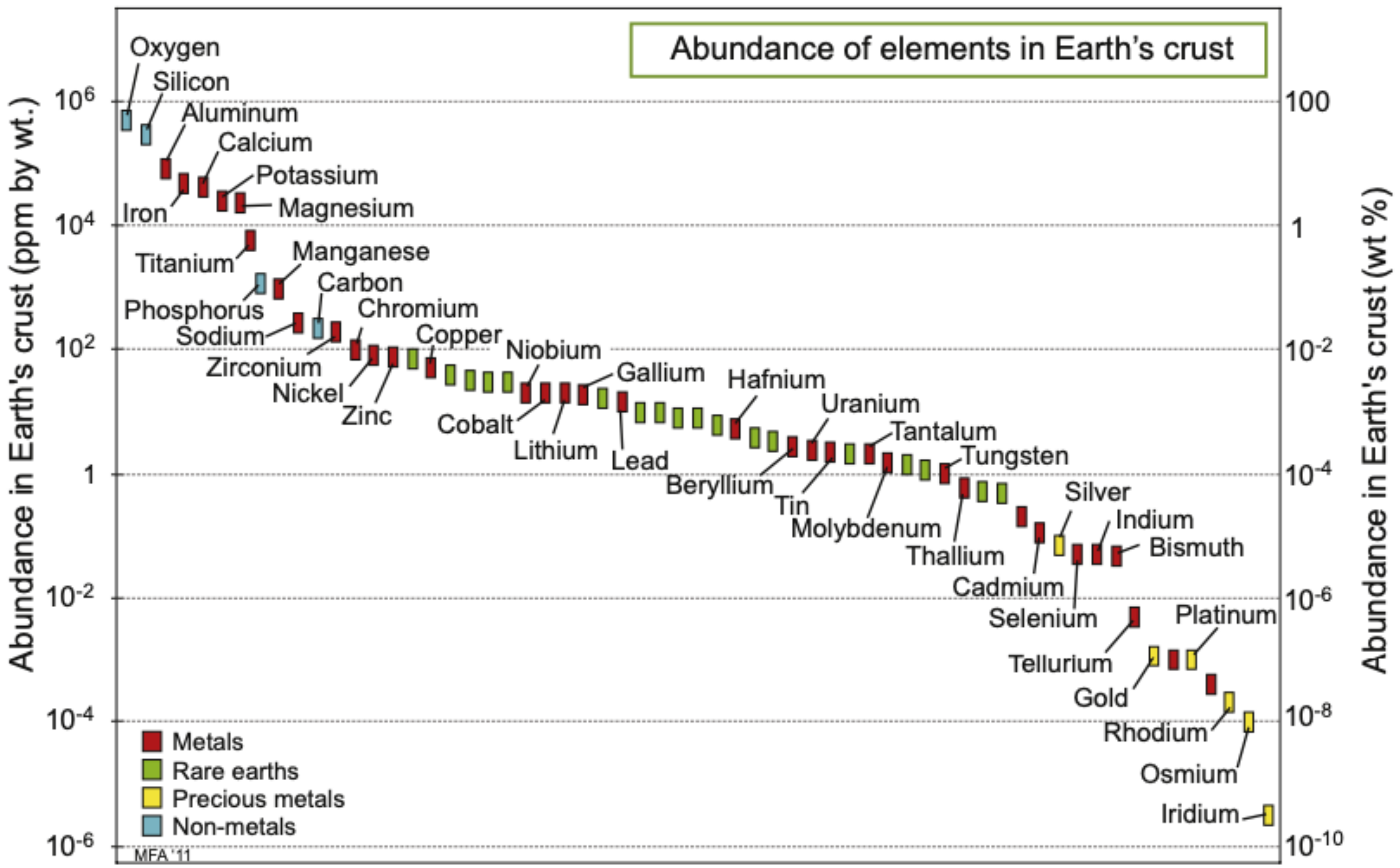
Two nations with equal share: HHI = $0.5^2 + 0.5^2 = 0.5$

Many source-nations: HHI → 0

Esp. problematic if HHI is high and materials come from politically unstable region(s)

[M. F. Ashby, Materials and Sustainable Development, 2016]

Some Materials are Rare



[M. F. Ashby, Materials and Sustainable Development, 2016]

How much of everything have we got?

Enormous range: some elements are abundant, others are rare

Mining rare elements can become extremely expensive and challenging

Raw Material Mining

- Energy/carbon-intensive industry
- Has significant impact on the environment

For example: copper (Cu)

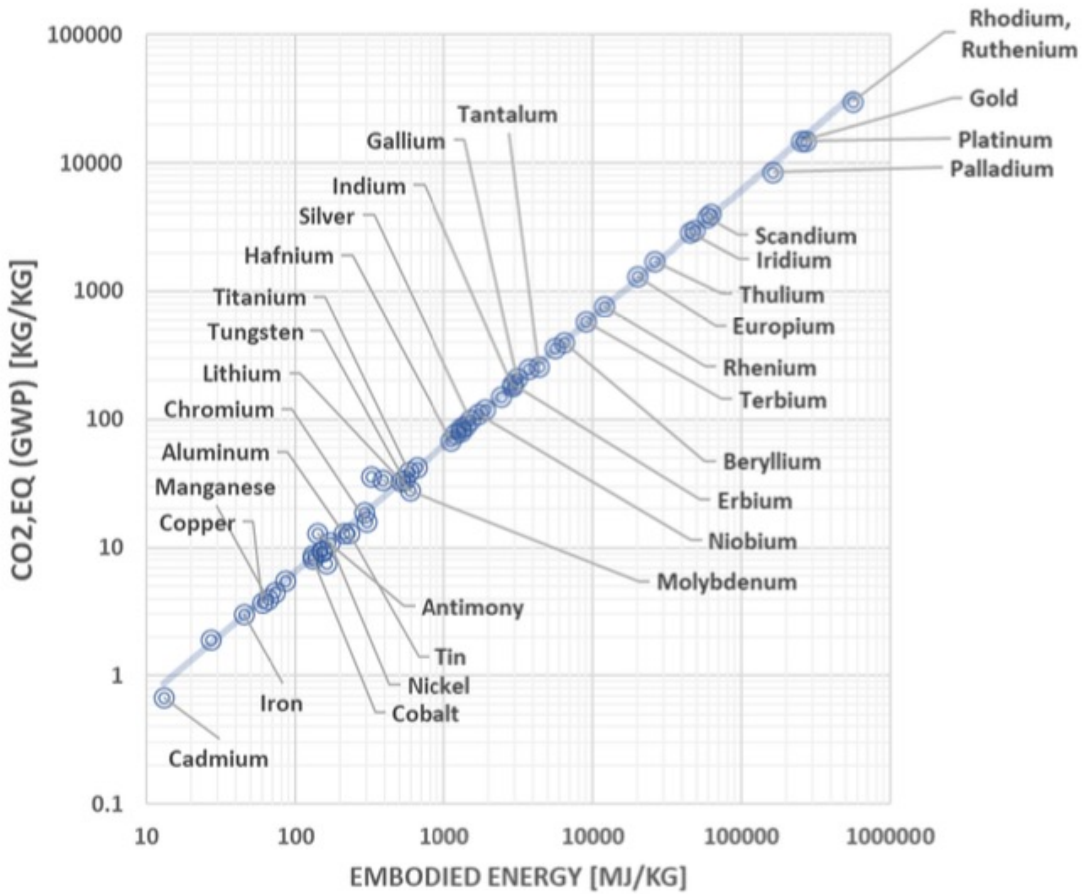
~50 MJ energy for 1 kg of Cu

~4 kg of CO2 for 1 kg of Cu

For example: gold (Au)

~200 BJ energy for 1kg of Au

~15 tons of CO2 for 1kg of Au



[M. Ashby (2016): Materials and Sustainable Development]

Sustainability is a Multi-Faceted Challenge

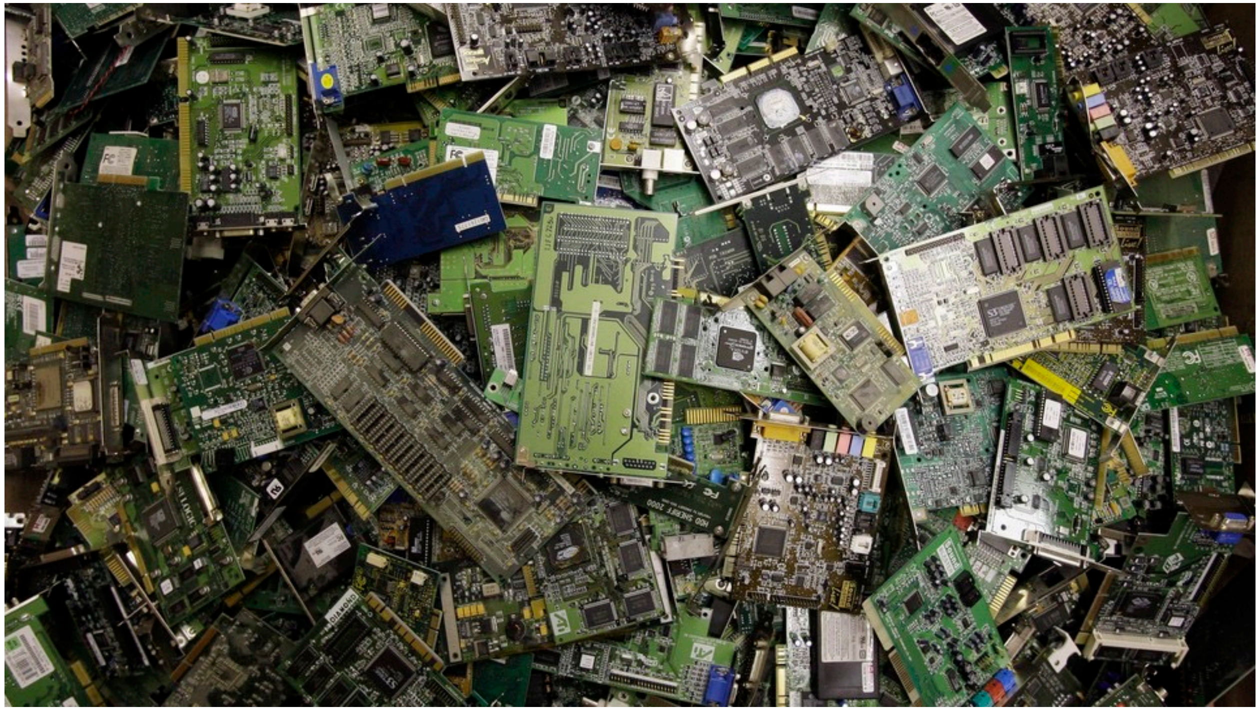
Sustainability is much more than combating global warming

It is also about

- **Raw material extraction**
- **E-waste**

due to linear economy

[Credit: Michael Conroy, AP]



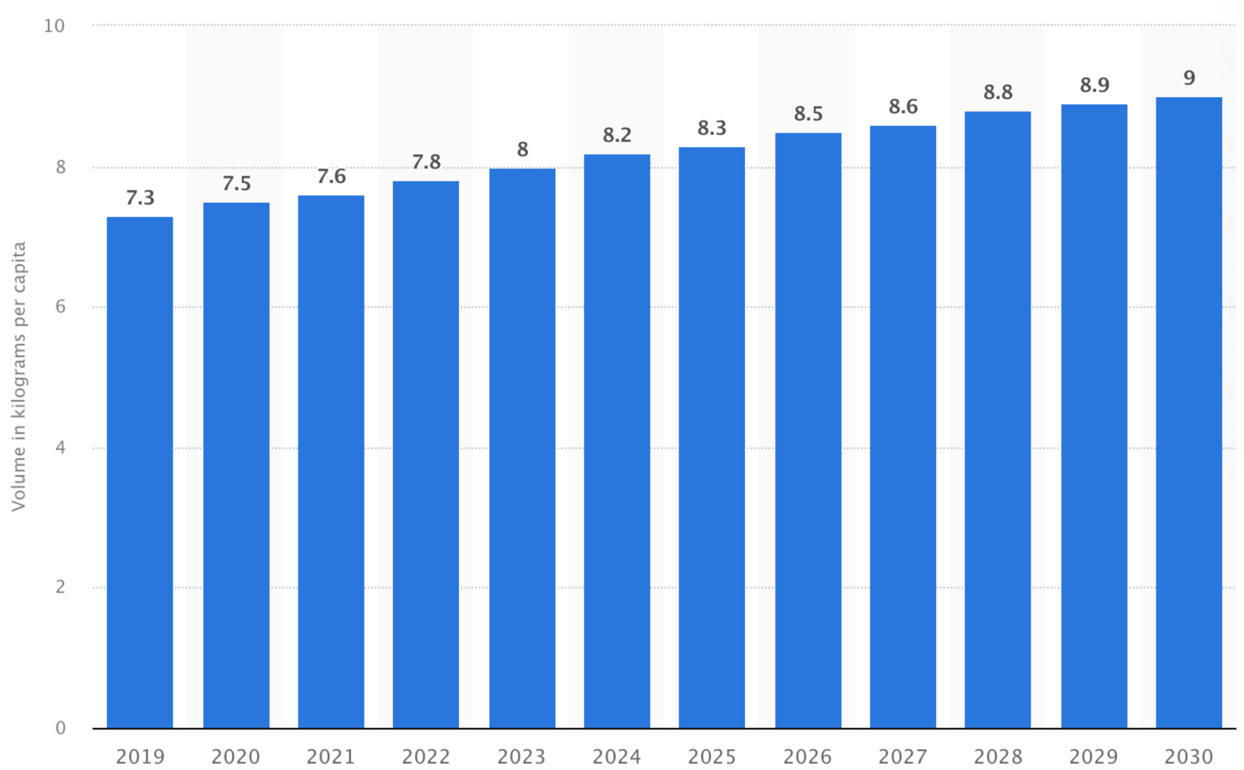
Sustainability is a Multi-Faceted Challenge

Sustainability is much more than combating global warming

It is also about

- **Raw material extraction**
- **E-waste**

- 8 kg per capita per annum
  - this includes small to large appliances
- only 17% gets recycled



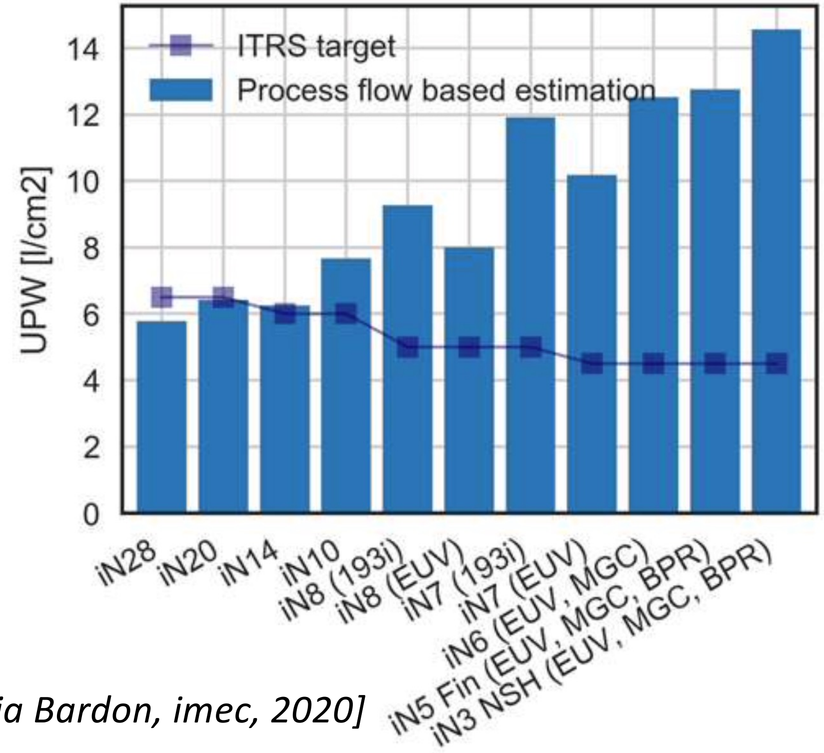
[Statista 2023]

Sustainability is a Multi-Faceted Challenge

Sustainability is much more than combating global warming

It is also about

- Raw material extraction
- E-waste
- **Ultra pure water**



[M. Garcia Bardon, imec, 2020]

Sustainability is a Multi-Faceted Challenge

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- Raw material extraction
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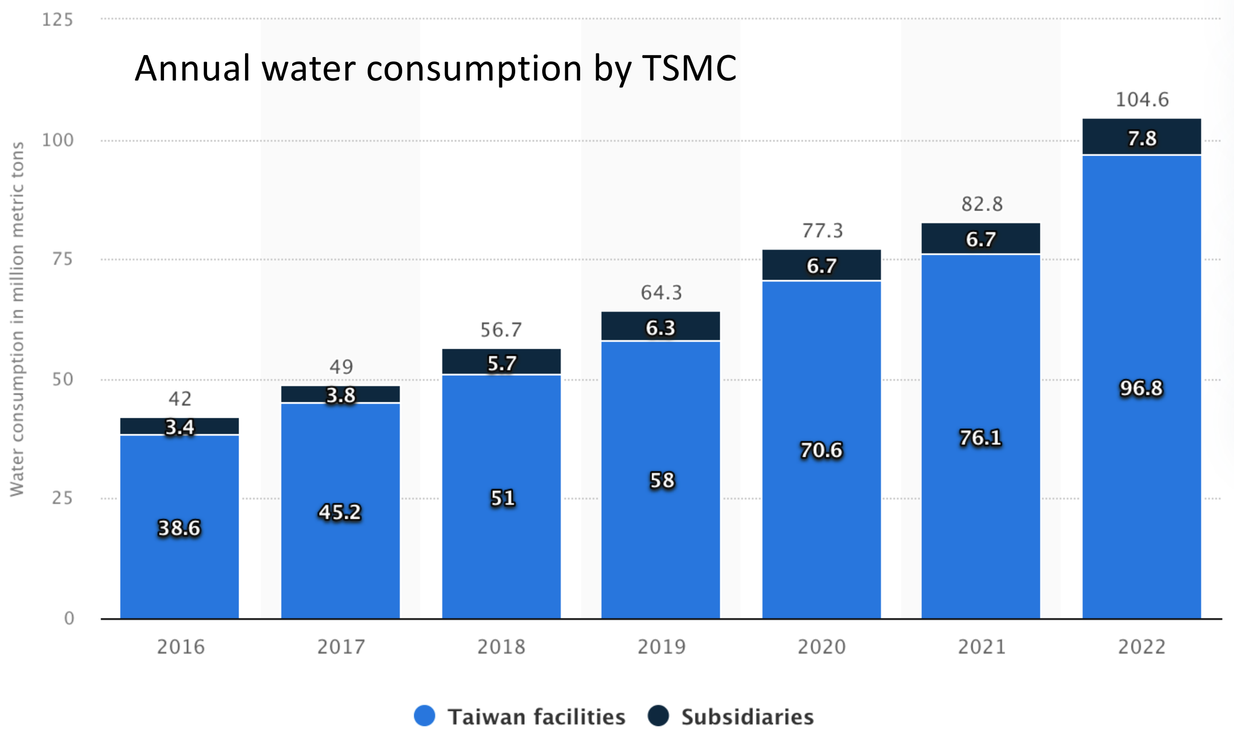
- **Water usage**



[Statista, 2024]

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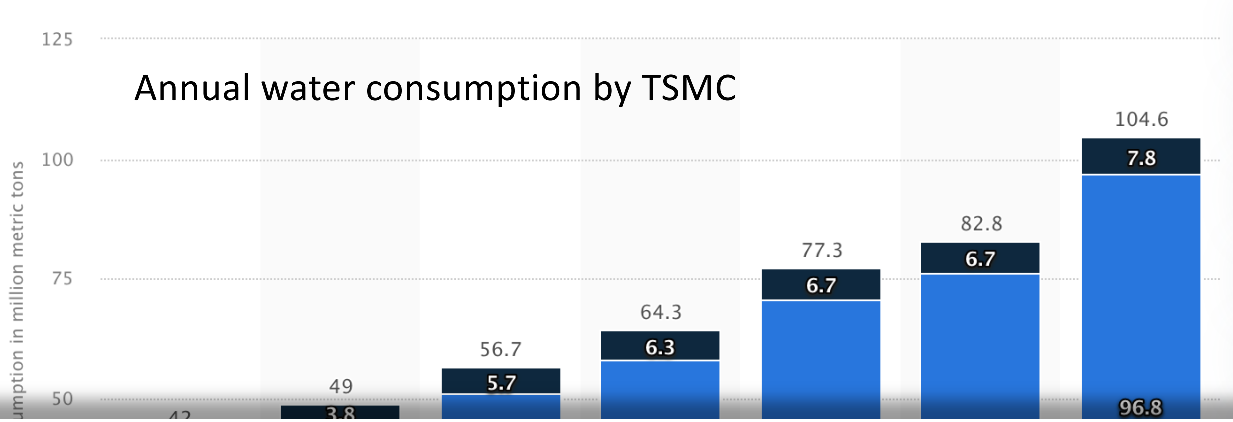


CLIMATE

Epic drought in Taiwan pits farmers against high-tech factories for water

The island is facing one of its worst dry spells in a century, and both the agricultural and high-tech sectors are competing for scarce water resources.

April 19, 2023 | By: Emily Feng

[NPR, 2023]

Sustainability is a Multi-Faceted Challenge

Sustainability is much more than combating global warming

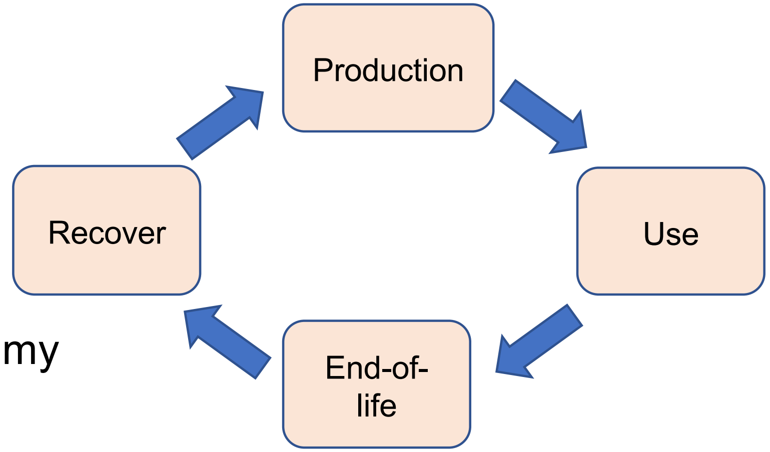
It is also about

- **Raw material extraction**
- **E-waste**
- **Water usage**
- **New business models & legislation**

Key motivation for circular (rather than linear) economy

Keep materials in the economy longer

- Fewer raw materials are needed
- Less impact on climate
- Avoid (e-)waste
- Improved security of material supply
  - Be less depending on third-party countries
- Design for repairability



Selling services instead of goods

Consumer wants (societal needs)

Light, not lamps

Mobility, not cars

Connectivity, not smartphone

Kaya Identity

Contributing factors to carbon emissions *[by energy economist Yoichi Kaya, 1997]*

F = P × G/P × E/G × F/E, with

F = global CO_2 emissions

P = global population

G/P = GDP per capita

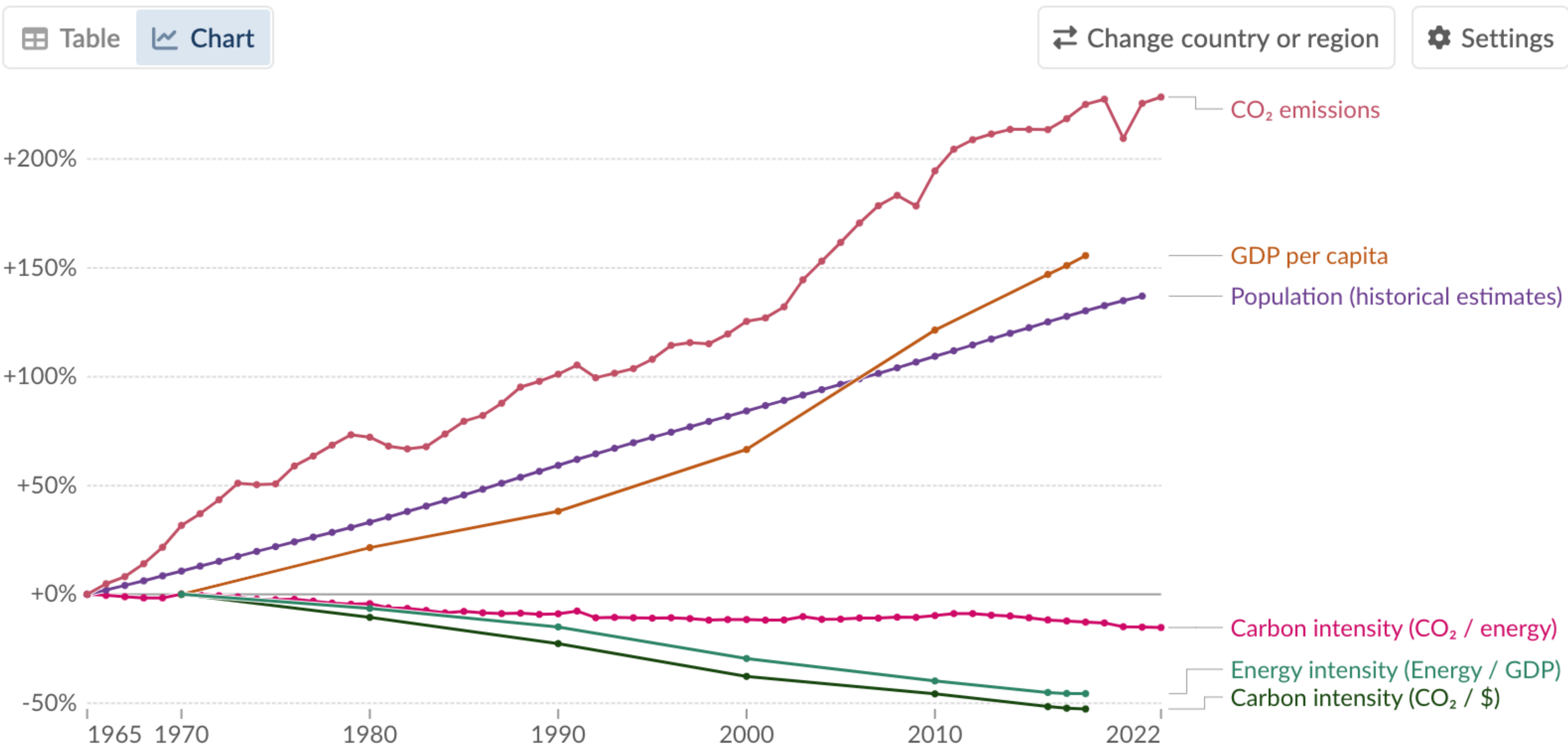
E/G = energy intensity (energy / GDP)

F/E = carbon intensity (CO_2 / energy)

Kaya identity is used by the Intergovernmental Panel on Climate Change (IPCC) to predict world CO_2 emission scenarios and impact on global warming

Kaya identity: drivers of CO_2 emissions, World

Percentage change in the four parameters of the Kaya Identity, which determine total CO_2 emissions. Emissions from fossil fuels and industry are included. Land-use change emissions are not included.



Despite improvements in energy intensity and carbon intensity, we witness an overall increase in CO_2 emissions

Kaya Applied to ICT Devices

F = P × D/P × F/D, with

F = global CO_2 emissions

P = global population → CAGR = +0.9% per year *[World Bank]*

D/P = ICT devices per capita → CAGR = +8.4% per year

F/D = carbon intensity per device

[CISCO, 2020]

Region	2018	2023	CAGR
Global	2.4	3.6	+8.4%
Asia Pacific	2.1	3.1	+8.1%
Central and Eastern Europe	2.5	4.0	+9.9%
Latin America	2.2	3.1	+7.1%
Middle East and Africa	1.1	1.5	+6.4%
North America	8.2	13.4	+10.3%
Western Europe	5.6	9.4	+10.9%

[L. Eeckhout, "The Sustainability Gap for Computing: Quo Vadis?", Communications of the ACM, March 2025]

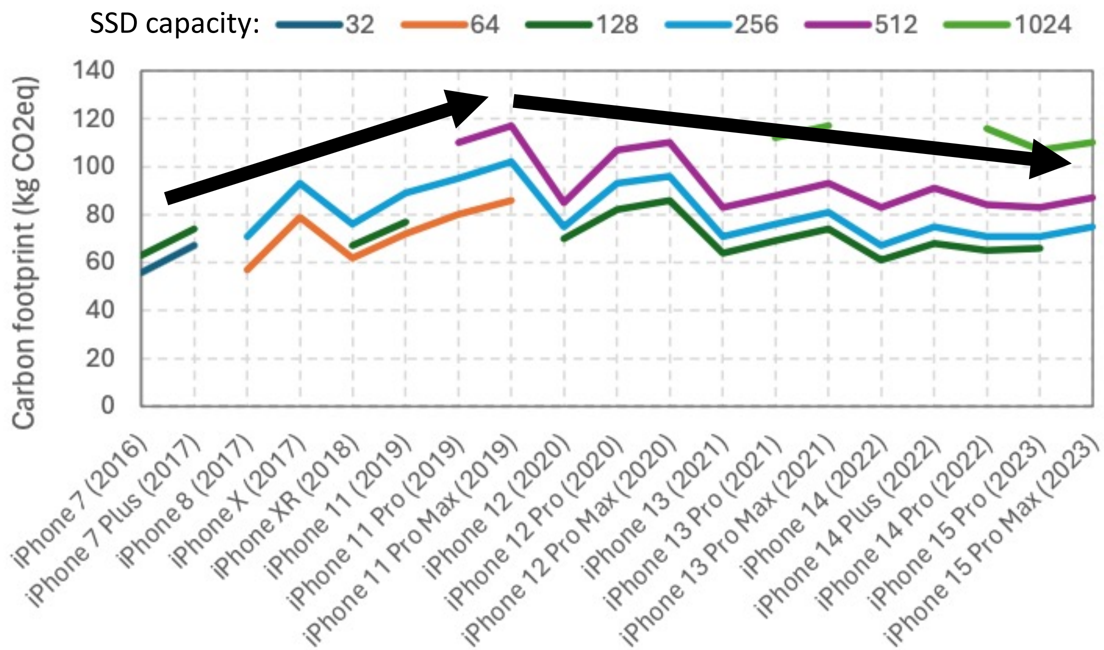
Kaya Applied to ICT Devices

F = P × D/P × F/D, with

F/D = carbon intensity per device

iPhone 8 (2017) →
iPhone 11 Pro Max (2019)
CAGR = +19.8%

iPhone 11 Pro Max (2019) →
iPhone 15 Pro Max (2023)
CAGR = -7.1%



[L. Eeckhout, "The Sustainability Gap for Computing: Quo Vadis?", Communications of the ACM, March 2025]

Kaya Applied to ICT Devices

F = P × D/P × F/D, with

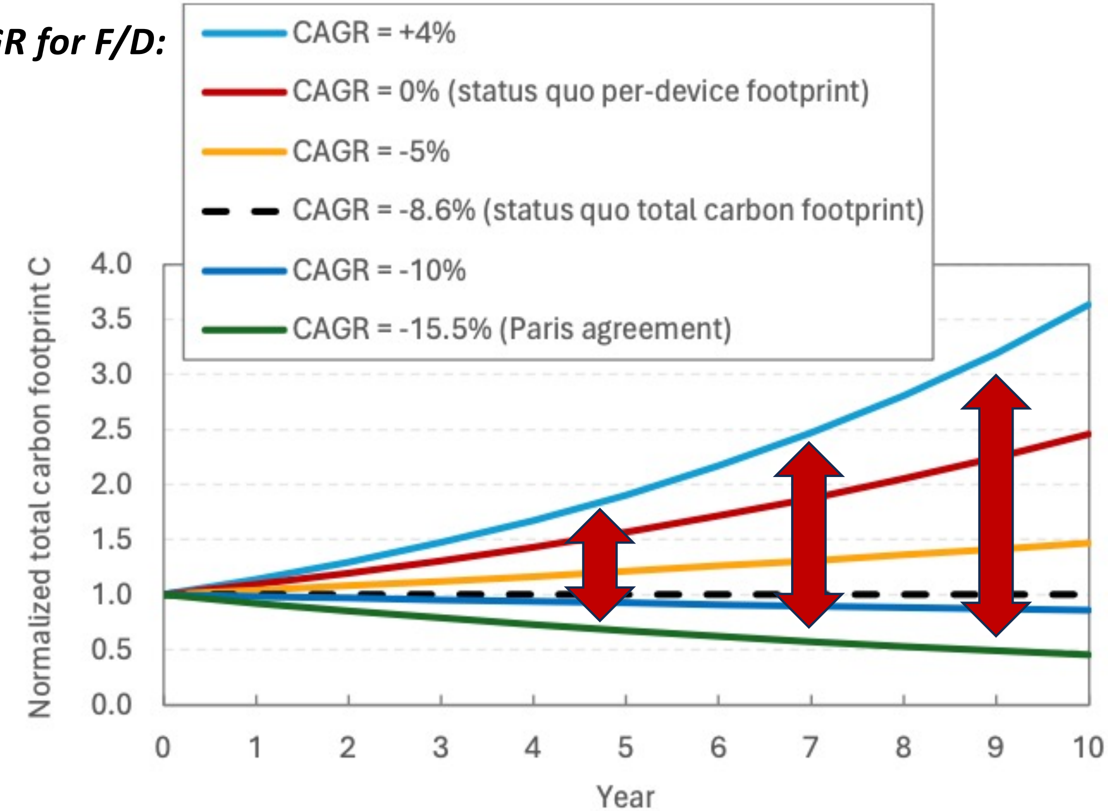
F/D = carbon intensity per device varies between -10% and +4%

Device	Model	Period	CAGR
Smartwatch	Apple Watch	2019–2023	-7.7%
Smartphone	Apple iPhone Pro Max	2019–2023	-7.1%
	Apple iPhone Pro Max	2021–2023	-3.3%
	Google Pixel	2021–2023	-10.5%
Laptop	Apple MacBook Pro 16-inch	2019–2023	-6.9%
	Apple MacBook Air 13-inch	2018–2024	-5.1%
	Dell Precision 7000	2018–2023	+3.8%
Desktop	Dell OptiPlex 700	2019–2022	-8.1%
	Dell Workstations 5000&7000	2018–2023	+4.0%
Server	Dell PowerEdge rackmount	2014–2024	+1.8%

[L. Eeckhout, "The Sustainability Gap for Computing: Quo Vadis?", Communications of the ACM, March 2025]

Are We On Track?
How to Close the Sustainability Gap?

CAGR for F/D:

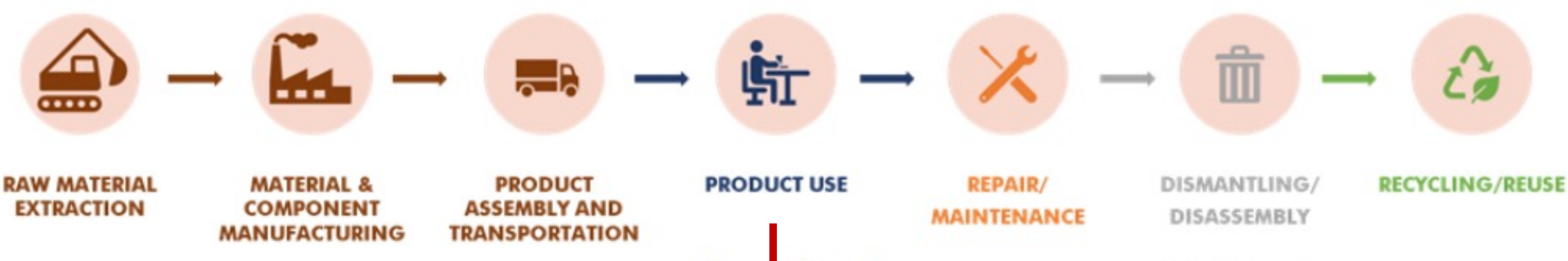


To close the sustainability gap, we need to reduce device carbon intensity by 15.5% <u>per annum</u> to meet the Paris agreement, to compensate for population and affluence growth…

[L. Eeckhout, "The Sustainability Gap for Computing: Quo Vadis?", Communications of the ACM, March 2025]

The Life of a Computer Device

Power/energy-efficient computing ignores embodied footprint



(upstream) embodied footprint

operational footprint

(downstream) embodied footprint

[Global Economic Council, 2021: State of Sustainability Research -- Climate Change Mitigation]

Rebound Effect due to Improved Efficiency

Counter-intuitive finding: making an *individual* system more carbon-efficient may lead to an *overall* increase in footprint a.k.a. Jevons' paradox

more efficient system → cheaper/easier to use → increased usage and deployment → increased (embodied and operational) footprint

Making systems more carbon-efficient is a necessary condition, not a sufficient condition

William Stanley Jevons (1865) first describes this rebound effect

- James Watt improved the efficiency of coal-fired steam engine
  - Each steam engine uses less coal, so coal became a more cost-effective fuel
- This led to an increased use of steam engines in a variety of industries
- The result was increased overall coal consumption

Reformulating Kaya for Architects

Can we reformulate the Kaya identity to something we, computer architects, gain insight from?

… so we can understand how to reduce environmental impact of computing?

We focus on carbon footprint

- But representative for other sustainability issues
- Using recently published numbers, yet to be taken with grain of salt…

Distinction between

- **Embodied emissions**: GHG emissions during manufacturing process
  - **Scope-1:** chemicals and gases emitted
  - **Scope-2:** carbon emissions from energy usage
  - **Scope-3:** due to material extraction *[not considered here – follows same trend as Scope-1]*
- **Operational emissions**: GHG emissions during product lifetime

Total Carbon Footprint

Embodied Scope-2 (energy usage during production)

$\mathbf{CO2e_{embodied,\ scope\text{-}2} = \#chips \times \#wafer/chips \times kWh/wafer \times CO2e/kWh}$

Embodied Scope-1 (chemicals and gases during production)

$\mathbf{CO2e_{embodied,\ scope\text{-}1} = \#chips \times \#wafer/chips \times CO2e/wafer}$

Operational (energy usage during lifetime)

$\mathbf{CO2e_{operational} = \#chips \times kWh/chip \times CO2e/kWh}$

How do these factors scale over time?

[L. Eeckhout, "Kaya for Architects: Towards Sustainable Computer Systems", IEEE Micro, 2023]

Demand for Chips is Increasing

Embodied Scope 2 (energy usage during production)

$CO2e_{embodied,\ scope\text{-}2} = \#chips \times wafer/chips \times kWh/wafer \times CO2e/kWh$

Embodied Scope 1 (chemicals and gases during production)

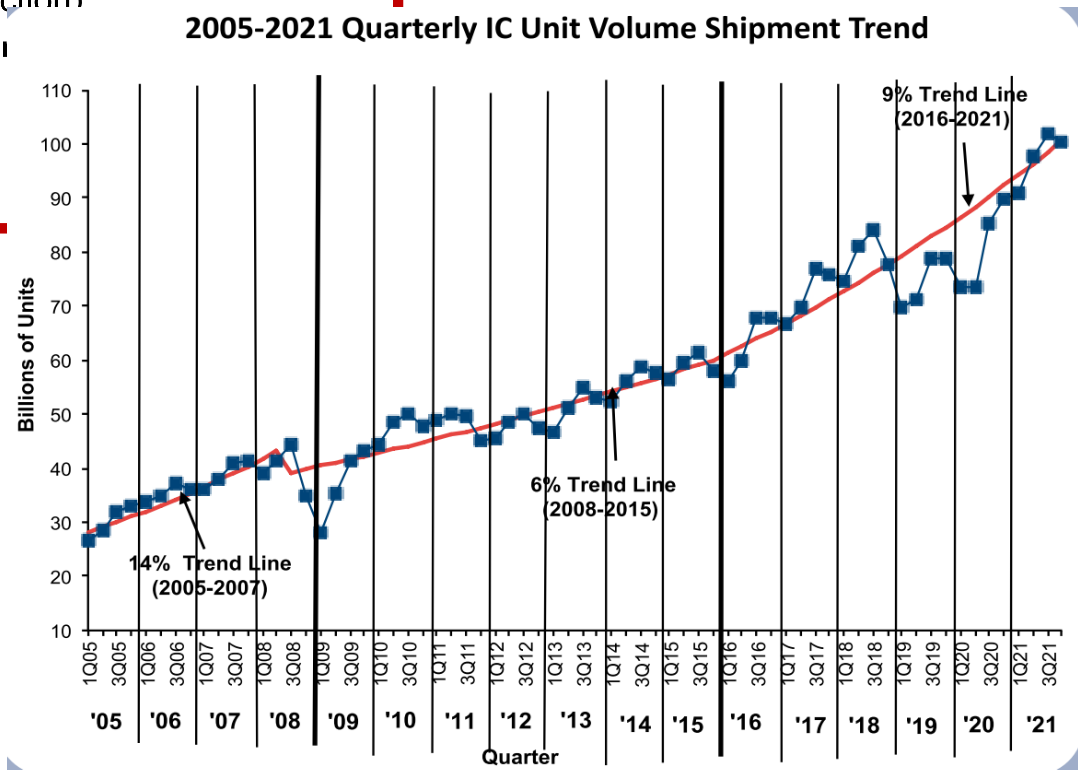
$CO2e_{embodied,\ scope\text{-}1} = \#chips \times wafer/chips \times CO2e/wafer$

Operational (energy usage during lifetime)

$CO2e_{operational} = \#chips \times kWh/chip \times CO2e/kWh$

Increasing number of chips:

CAGR = +9%



[IC Insight, 2022]

Die Size Seems to Have Stagnated

Embodied Scope 2 (energy usage during production)

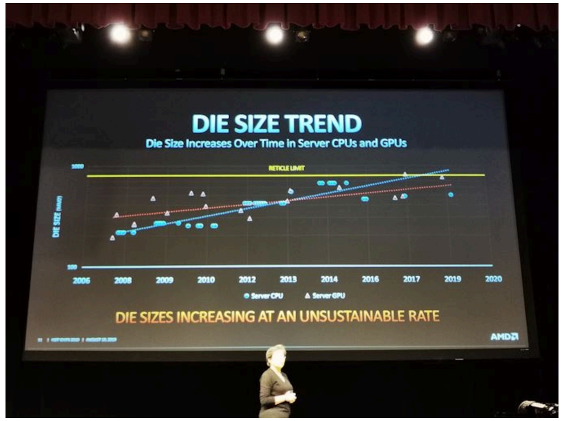
$CO2e_{\text{embodied, scope-2}}$ = #chips × #wafer/chips × kWh/wafer × CO2e/kWh

Embodied Scope 1 (chemicals and gases during production)

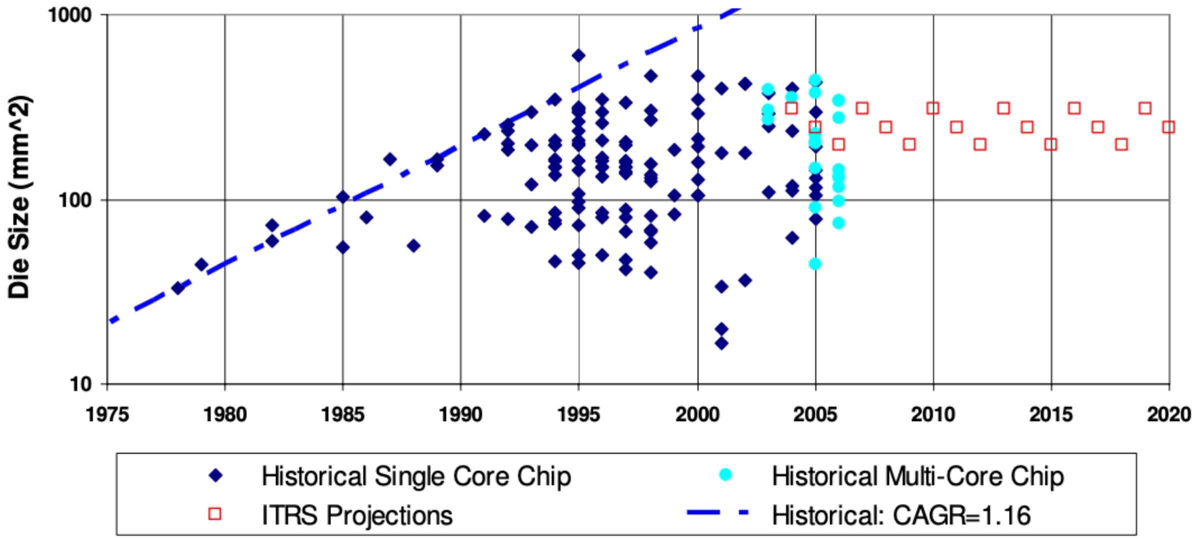
$CO2e_{\text{embodied, scope-1}}$ = #chips × #wafer/chips × CO2e/wafer

Operational (energy usage during lifetime)

$CO2e_{\text{operational}}$ = #chips × kWh/chip × CO2e/kWh



Number of chips per wafer: CAGR ≃ +0%



[Kogge et al., 2008]

Increasing Energy Demand per Wafer

Embodied Scope 2 (energy usage during production)

$CO2e_{embodied, scope-2}$ **= chips × wafer/chips × kWh/wafer × CO2e/kWh**

Embodied Scope 1 (chemicals and gases during production)

$CO2e_{embodied, scope-1}$ **= chips × wafer/chips × CO2e/wafer**

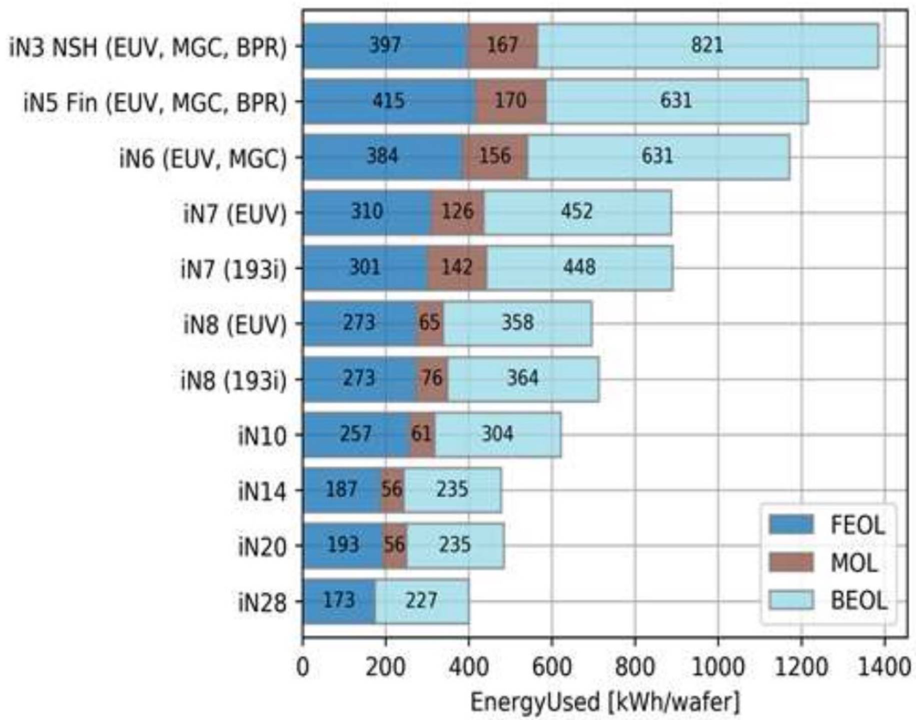
Operational (energy usage during lifetime)

$CO2e_{operational}$ **= chips × kWh/chip × CO2e/kWh**

Increasing energy demand for new tech nodes

- increasing no. processing steps
- CAGR kWh/wafer = +11.9%

[M. Garcia Bardon, imec, 2020]



Increasing Chemicals/Gases per Wafer

Embodied Scope 2 (energy usage during production)

$$CO2e_{embodied,\ scope\text{-}2} = \#chips \times \#wafer/chips \times kWh/wafer \times CO2e/kWh$$

Embodied Scope 1 (chemicals and gases during production)

$$CO2e_{embodied,\ scope\text{-}1} = \#chips \times \#wafer/chips \times CO2e/wafer$$

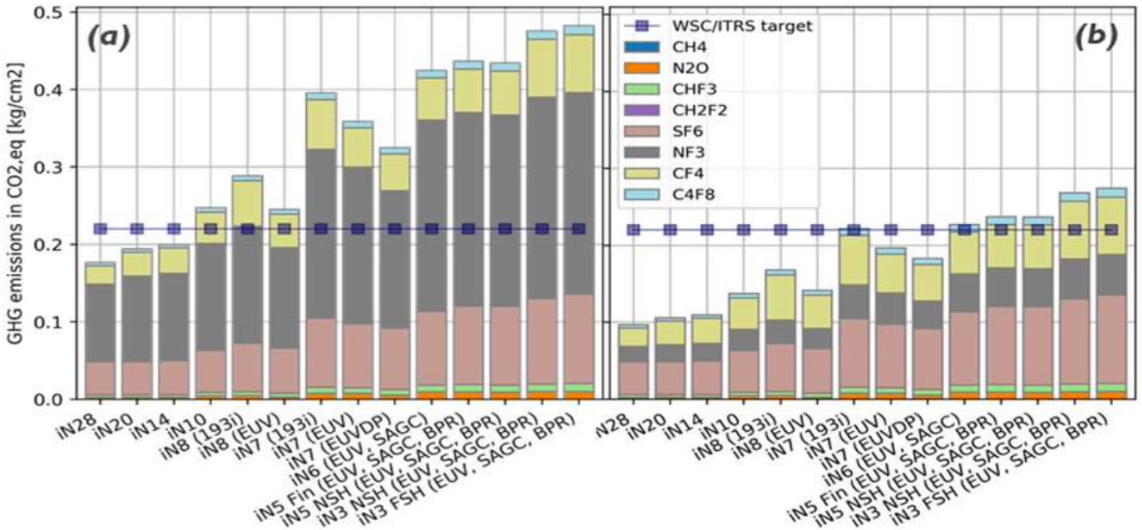
Operational (energy usage during lifetime)

$$CO2e_{operational} = \#chips \times kWh/chip \times CO2e/kWh$$

[M. Garcia Bardon, imec, 2020]

Increasing chemical/gas emissions for new tech nodes

CAGR CO2e/wafer = +9.4%



Carbon Intensity Slowly Decreasing

Embodied Scope 2 (energy usage during production)

$$CO2e_{embodied,\ scope\text{-}2} = \#chips \times \#wafer/chips \times kWh/wafer \times CO2e/kWh$$

Embodied Scope 1 (chemicals and gases during production)

$$CO2e_{embodied,\ scope\text{-}1} = \#chips \times \#wafer/chips \times CO2e/wafer$$

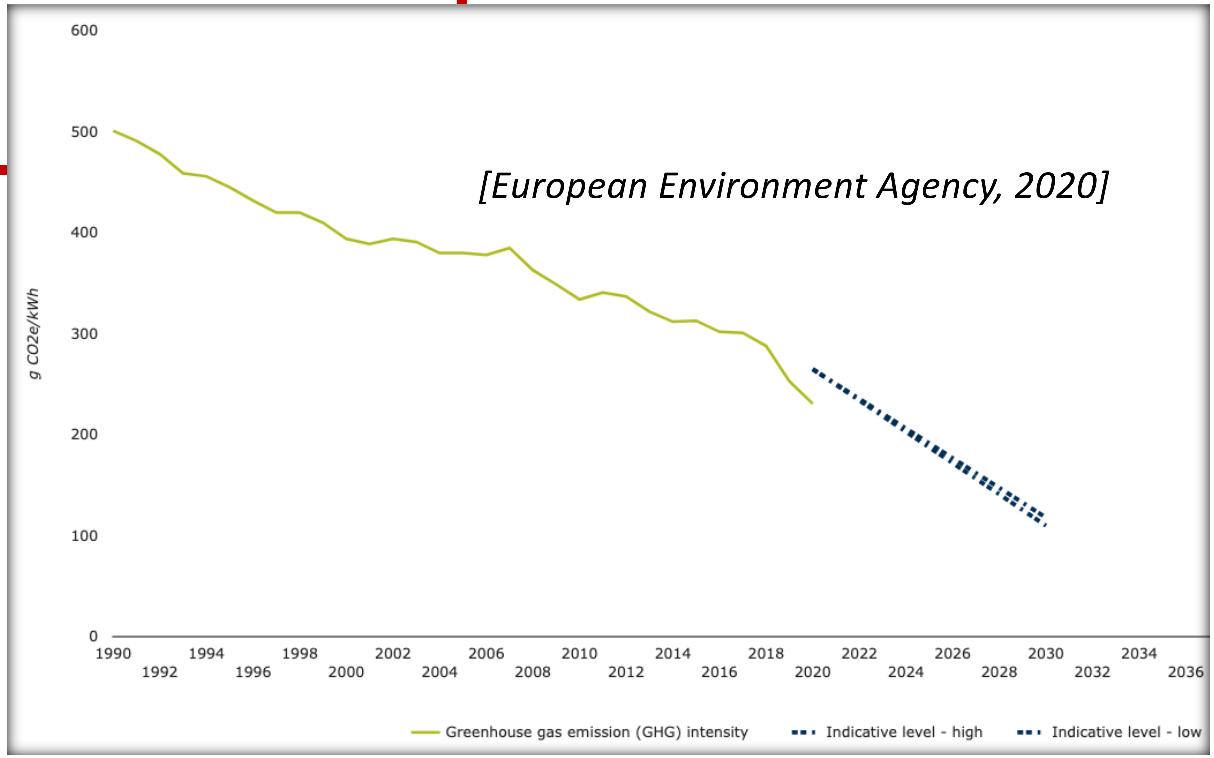
Operational (energy usage during lifetime)

$$CO2e_{operational} = \#chips \times kWh/chip \times CO2e/kWh$$

Transition towards green energy sources

CO2e/kWh (Europe): CAGR = -2.5%

Only addresses embodied scope-2 and operational footprint, not embodied scope-1 nor scope-3



Decreasing Operational Energy

Embodied Scope 2 (energy usage during production)

$CO2e_{embodied, scope\text{-}2}$ = #chips × #wafer/chips × kWh/wafer × CO2e/kWh

Embodied Scope 1 (chemicals and gases during production)

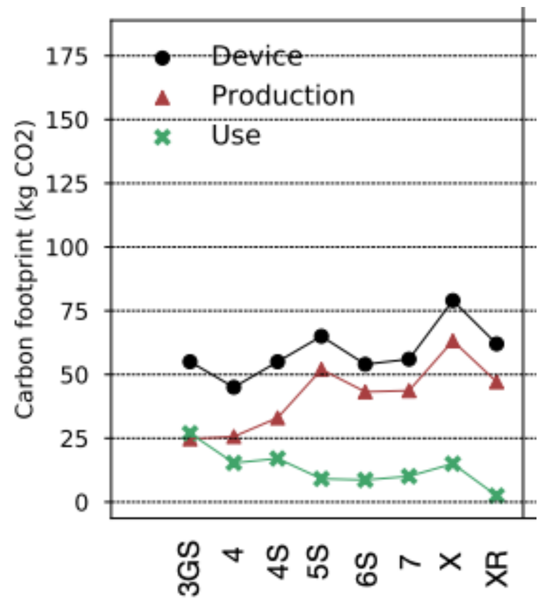
$CO2e_{embodied, scope\text{-}1}$ = #chips × #wafer/chips × CO2e/wafer

Operational (energy usage during lifetime)

$CO2e_{operational}$ = #chips × kWh/chip × CO2e/kWh

Operational energy consumption is decreasing

kudos to ourselves! ☺



iPhone

[U. Gupta et al. , HPCA 2021]

How Does Total Carbon Footprint Scale?

Embodied Scope-2 (energy usage during production)

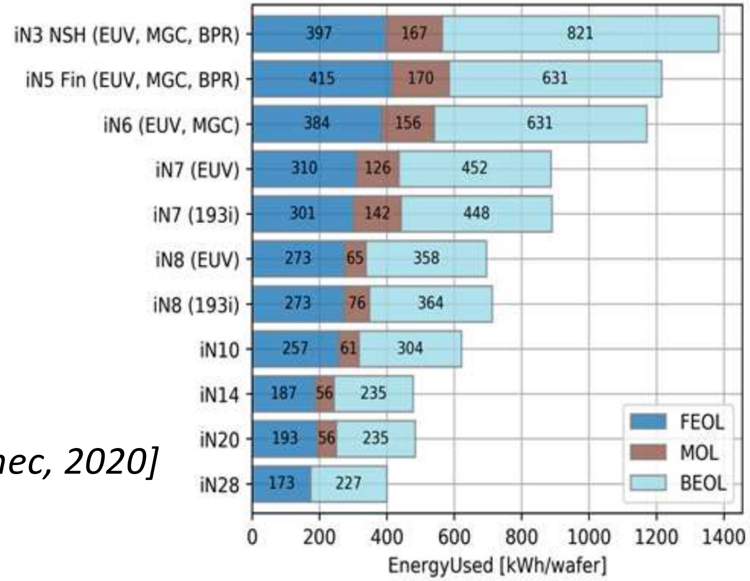
$CO2e_{\text{embodied, scope-2}}$ = #chips × wafer/chips × kWh/wafer × CO2e/kWh

Embodied Scope-1 (chemicals and gases during production)

$CO2e_{\text{embodied, scope-1}}$ = #chips × wafer/chips × CO2e/wafer

Operational (energy usage during lifetime)

$CO2e_{\text{operational}}$ = #chips × kWh/chip × CO2e/kWh



[M. Garcia Bardon, imec, 2020]

Key take-aways:

- Demand for chips keeps increasing by ~9% per year
- GHG emissions (both scope-1 and 2) per wafer increase by ~9% to ~12% per year due to increased manufacturing complexity in new technology nodes
- Devices become more energy-efficient, so operational emissions decrease
- Transition to green energy not moving fast enough ***and*** it doesn't impact scope-1 nor scope-3 emissions (and other sustainability issues like raw material need, e-waste, water usage, etc.)
- End result: **embodied emissions dominate or will soon dominate**

How to design sustainable processors considering inherent data uncertainty?

Embrace it!

FOCAL: First-Order CArbon ModeL

FOCAL is a top-down, parameterized model that

- is deliberately simple,
- is built upon first principles, and
- provides insight

Key idea:

- use proxies for embodied and operational footprint,
- parameterize relative importance of embodied versus operational footprint,
- while considering different use case scenarios, incl. rebound effects

FOCAL enables powerful analyses despite inherent data uncertainty:
- *similar conclusions across a range of scenarios → confident conclusions*
- *otherwise → need to be careful when reaching conclusions*

[L. Eeckhout, "FOCAL: A First-Order Model to Assess Processor Sustainability", ASPLOS 2024 & IEEE Micro Top Picks 2025]

Proxy for Embodied Footprint?

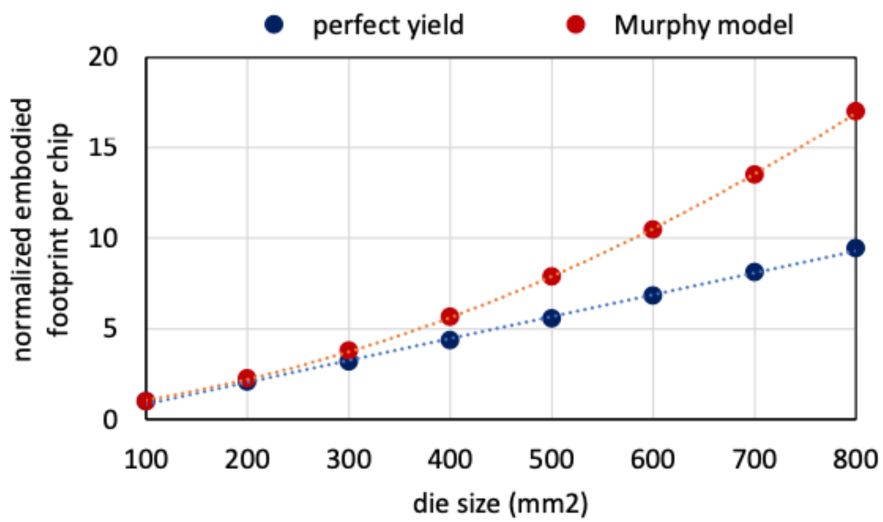
Wafer = production unit in semiconductor fab

- Environmental impact for producing a wafer: energy consumed, chemicals and gases emitted, ultra pure water used, materials used

The bigger the size of a chip, the higher its embodied footprint

- Accounting for lost silicon wafer area
  [de Vries, 2005]
- Accounting for yield issues
  [Murphy model,
  TSMC: 0.09 defect density per cm^2]

Proxy = chip area (A)



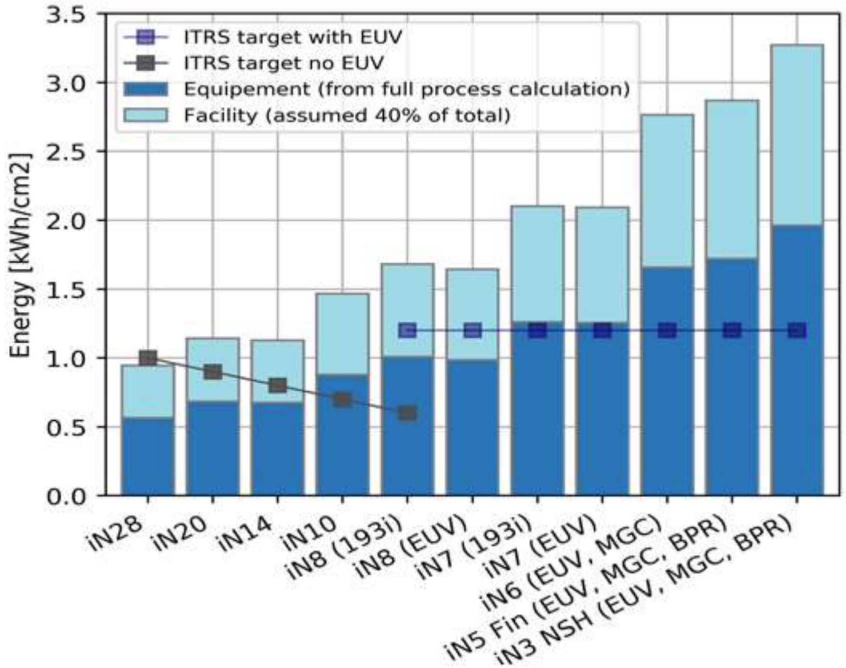
Proxy for Embodied Footprint?

Embodied footprint of an IC is proportional to its area

Amount of energy needed (and chemicals/gases emitted) to produce a wafer increases with newer chip technologies

From imec: iN28 (~2011) to iN3 (~2022)

CAGR = +11.9%



[M. Garcia Bardon, imec, 2020]

Proxy = chip area (A)

Embodied footprint =

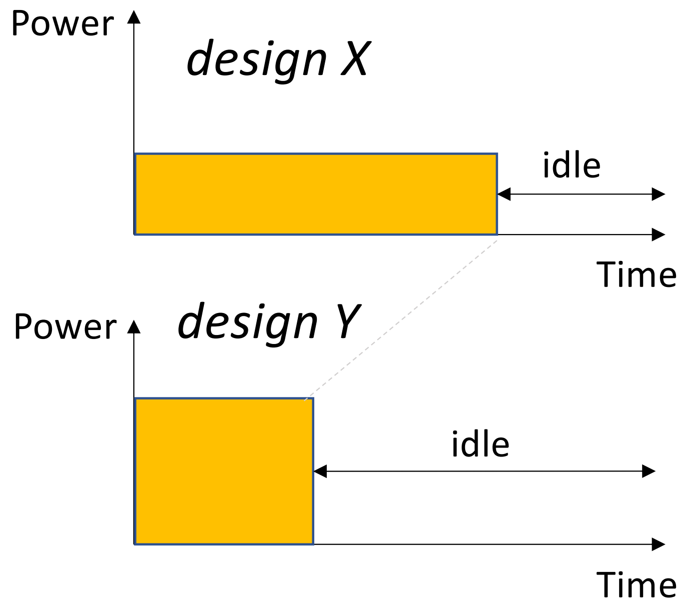
$$\mathbf{A}\ [cm^2] \times \mathbf{E_I}\ [kWh / cm^2] \times \mathbf{C_I}\ [CO2e / kWh]$$

Proxy for Operational Footprint? (1/2)

(1) Fixed-work scenario

- Assumption: a device performs fixed amount of work over its entire lifetime

The higher energy consumption, the higher its operational footprint



Proxy = energy consumption (E)

Operational footprint =

$$E\,[kWh] \times C_I\,[CO2e / kWh]$$

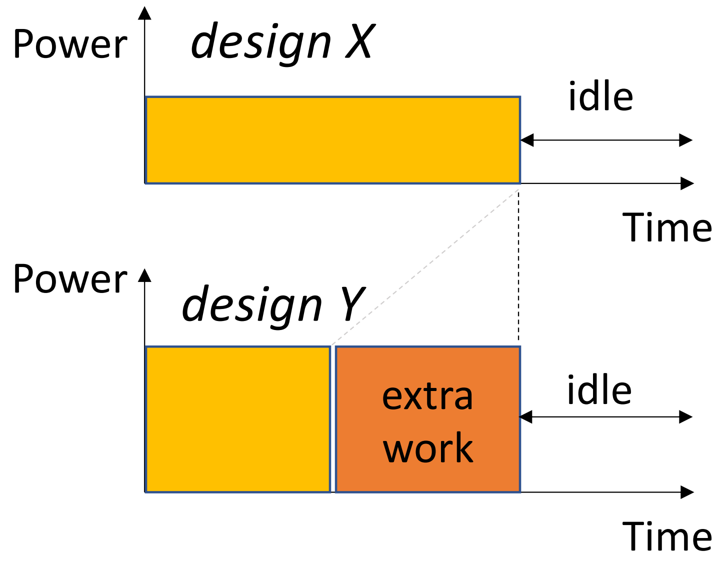
Proxy for Operational Footprint? (2/2)

(2) Fixed-time scenario – *more realistic scenario(?)*

- We do more work because it is more efficient, cf. Jevons' paradox
- Assumption: we use the device for the same amount of time

The higher power consumption, the higher its operational footprint

Proxy = power consumption (P)



How to Weigh Embodied versus Operational Footprint?

Ratio of embodied vs operational footprint depends on

Device type

Battery-operated vs always-on devices

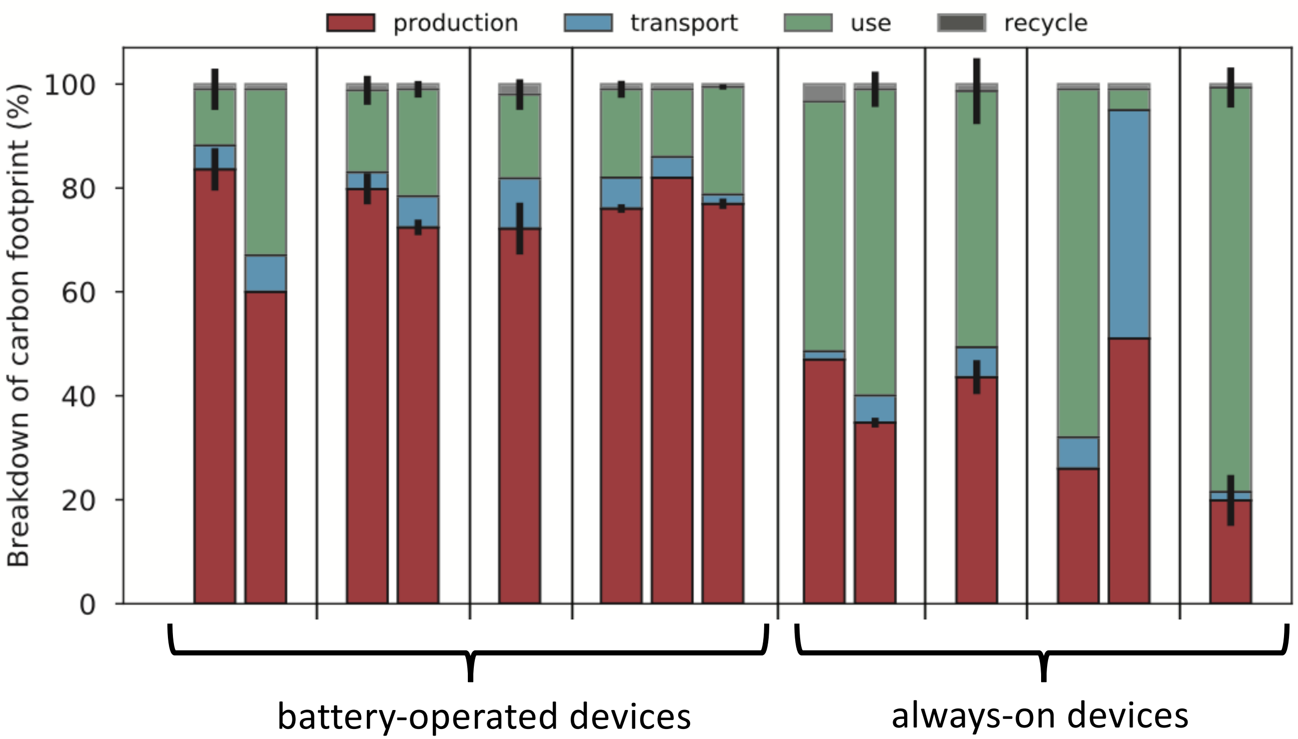
Lifetime

The longer the lifetime, the higher the relative weight of operational footprint

Energy mix

The greener the energy mix during lifetime, the higher the relative weight of embodied footprint

Answer: we parameterize the embodied-vs-operational footprint



[Gupta et al., HPCA 2021]

FOCAL Computes the Normalized Carbon Footprint (NCF)

fixed-work:

$$NCF_{fw,\alpha_{E2O}}(X,Y) = \alpha_{E2O}\frac{A_X}{A_Y} + (1-\alpha_{E2O})\frac{E_X}{E_Y}$$

fixed-time:

$$NCF_{ft,\alpha_{E2O}}(X,Y) = \alpha_{E2O}\frac{A_X}{A_Y} + (1-\alpha_{E2O})\frac{P_X}{P_Y}$$

α_{E2O} parameter is a function of device type/usage, lifetime of device, rebound effect, energy source during manufacturing vs lifetime

Parameterization allows for considering different scenarios w/ confidence intervals:

- Embodied emissions dominate (assume $\alpha_{E2O} = 0.8 \pm 0.1$) versus
- Operational emissions dominate (assume $\alpha_{E2O} = 0.2 \pm 0.1$)
- Fixed-work versus fixed-time

[L. Eeckhout, "FOCAL: A First-Order Model to Assess Processor Sustainability", ASPLOS 2024 & IEEE Micro Top Picks 2025]

Evaluating Archetypal Processor Design Choices using FOCAL

A design choice is

- **strongly sustainable** if it reduces carbon footprint under both the fixed-work and fixed-time scenarios

  → ***no (limited) risk for rebound effect***

  e.g., **die shrink**, **multicore (vs single-core w/ same chip area)**, pipeline gating, DVFS

- **weakly sustainable** if it reduces carbon footprint only under a fixed-work scenario

  → ***(substantial) risk for rebound effect***

  e.g., **speculation (branch prediction, runahead)**, heterogeneity, acceleration, caching

- **less sustainable** if it increases carbon footprint under both the fixed-work and fixed-time scenarios

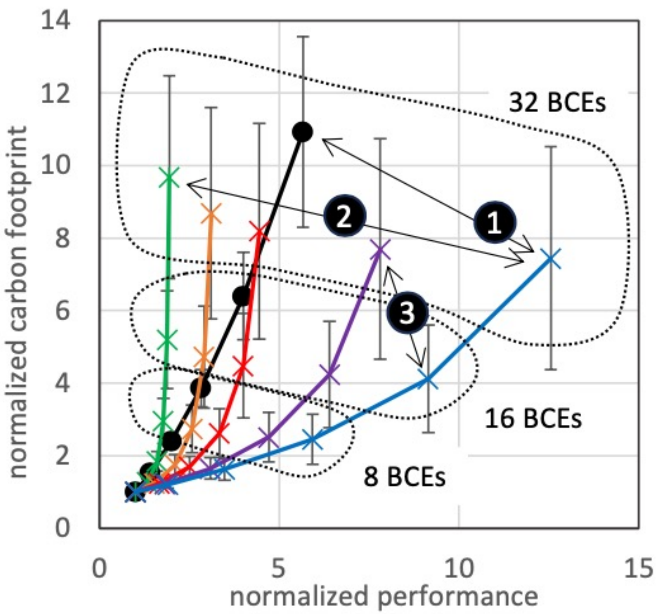
  e.g., high-complexity microarchitecture (out-of-order vs. in-order), **dark silicon**, turboboosting

#1: Multi-core is Strongly Sustainable

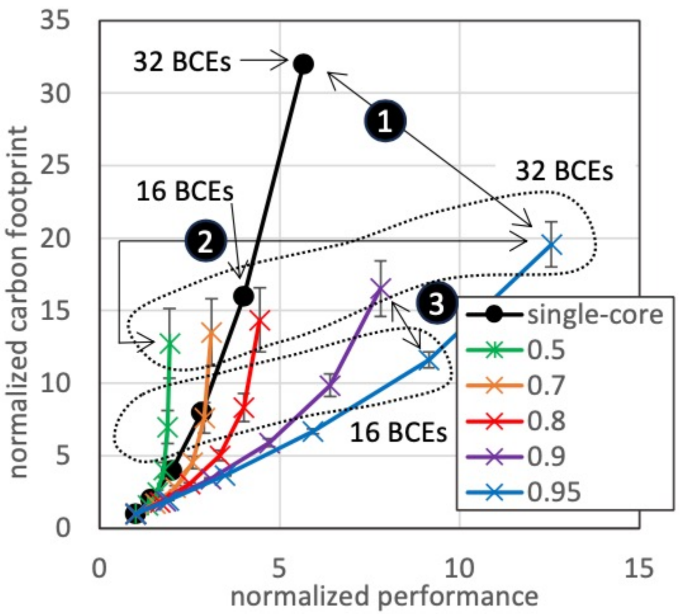
Key insights:

1. Multicore is strongly sustainable compared to single core
2. Parallelizing software is weakly sustainable
3. Parallelizing software is more sustainable than adding cores

fixed-work



fixed-time



Using Amdahl's Law and Pollack's rule
[Hill & Marty, 2008]
[Woo & Lee, 2008]

f = degree of parallelism
[see legend]

BCE = Base Core Equivalent
= number of cores
= unit of chip area

assuming $\boldsymbol{\alpha}_{E2O}$ *= 0.2 ±0.1*

#2: CPU Speculation is Weakly Sustainable

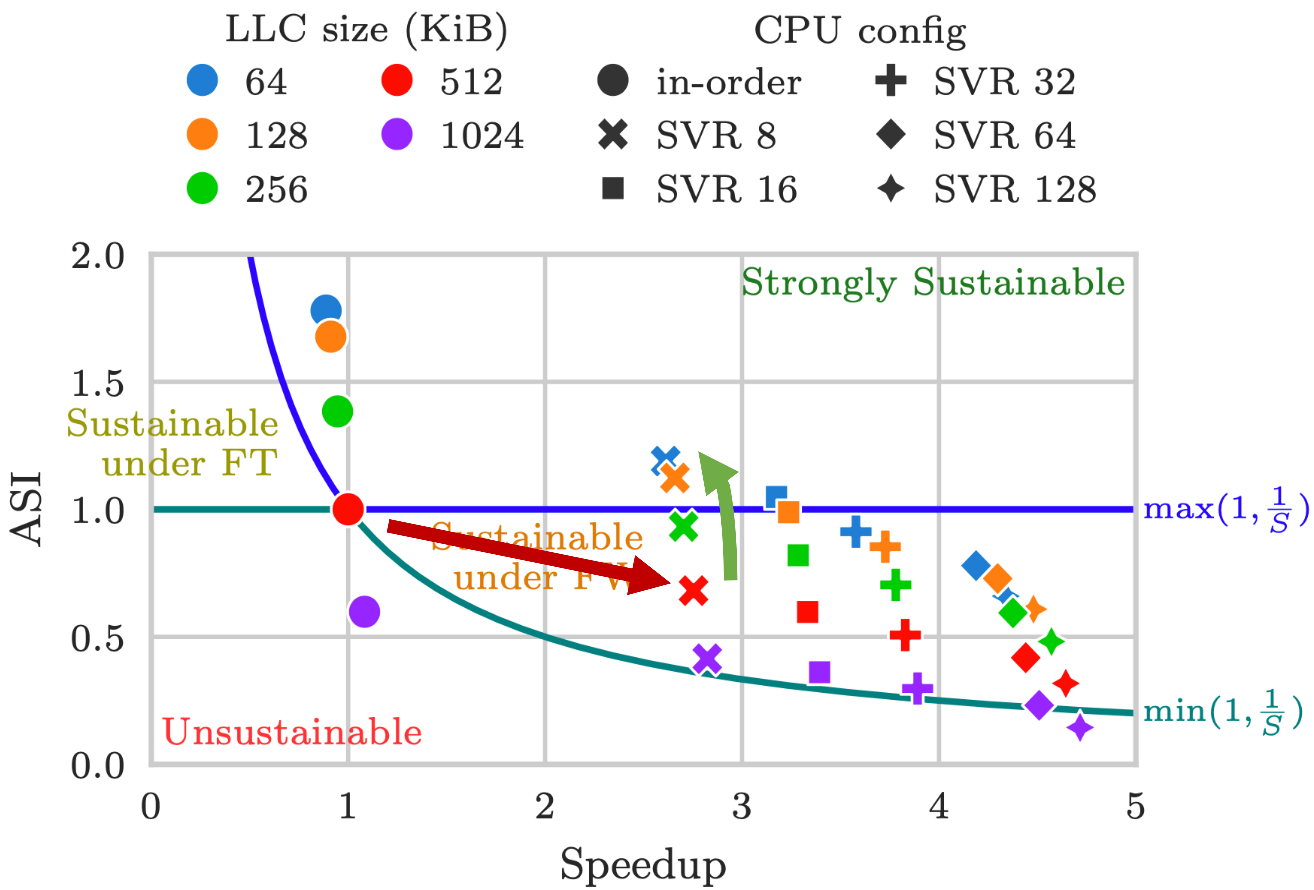
Scalar Vector Runahead (SVR)*

In-core data prefetcher by speculatively vectorizing chains of dependent loads

Architectural Sustainability Index (ASI)** reports whether a design is weakly or strongly sustainable

SVR = Weakly sustainable

Compensate weak sustainability by reducing LLC size → illustrates how to design a strongly sustainable processor architecture



*[Roelandts et al., MICRO 2024, Top Picks 2025]

**[Roelandts et al., (Best of) IEEE CAL 2025]

#3: Dark Silicon is Unsustainable

Domain-Specific Accelerators (DSAs) powered on only when needed

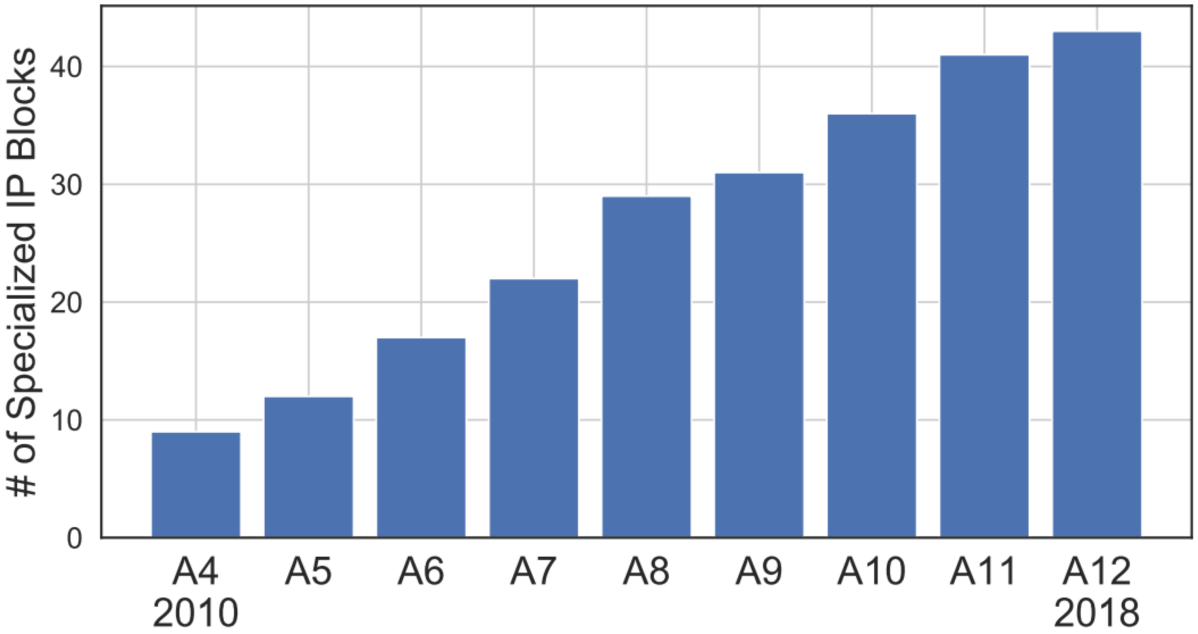
Sea of DSAs is widely deployed across modern-day SoCs:

- **Mobile**: e.g., Qualcomm Snapdragon
- **Laptop**: e.g., Apple M2
- **Server**: e.g., IBM Tellum

Dark silicon fundamentally trades off chip area for power/energy efficiency

Question: Does the increase in embodied footprint due to dark silicon offset the decrease in operational footprint? Answer: No!

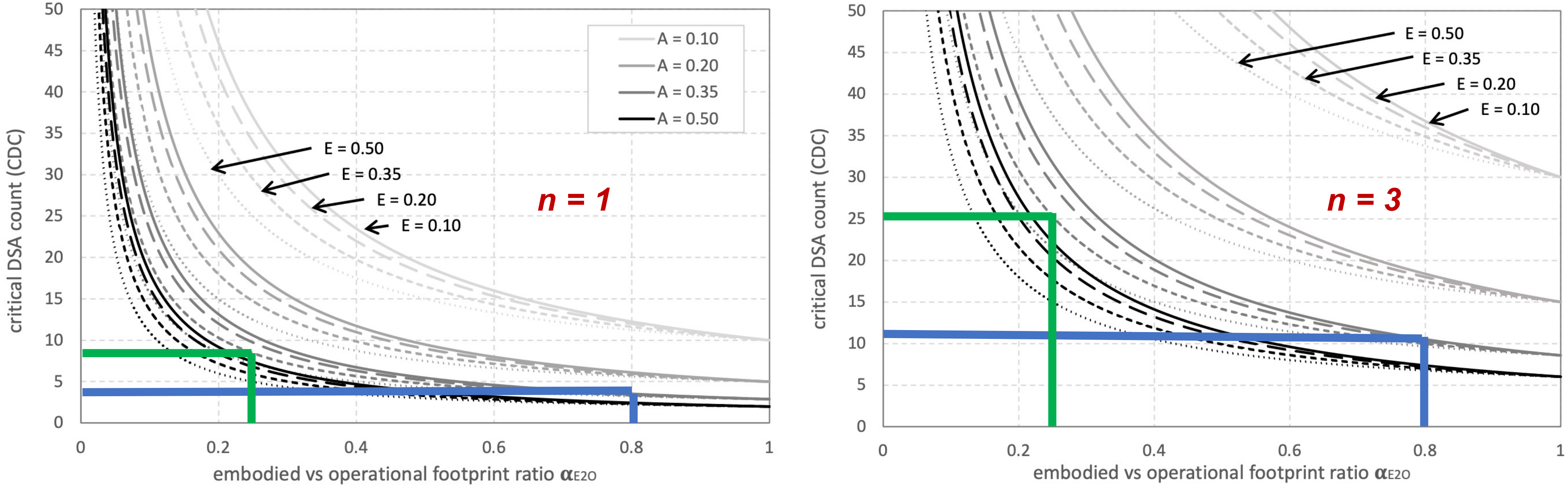
[Brunvand et al., IGSC, 2019]
[Eeckhout, ASPLOS, 2024]



[Shao et al., ISCA@50, 2023]

Reconfigurability to the Rescue?

Does reduced embodied footprint of CGRA compensate for increased operational footprint?



for embodied-footprint dominated systems → if it replaces ~4 to ~12 DSAs

for operational-footprint dominated systems → if it replaces ~8 to ~25 DSAs

[assuming A = E = 0.35]

This is (way) fewer than the number of (~40) DSAs in modern-day SoCs

[P. Dangi et al., ICCAD 2024]

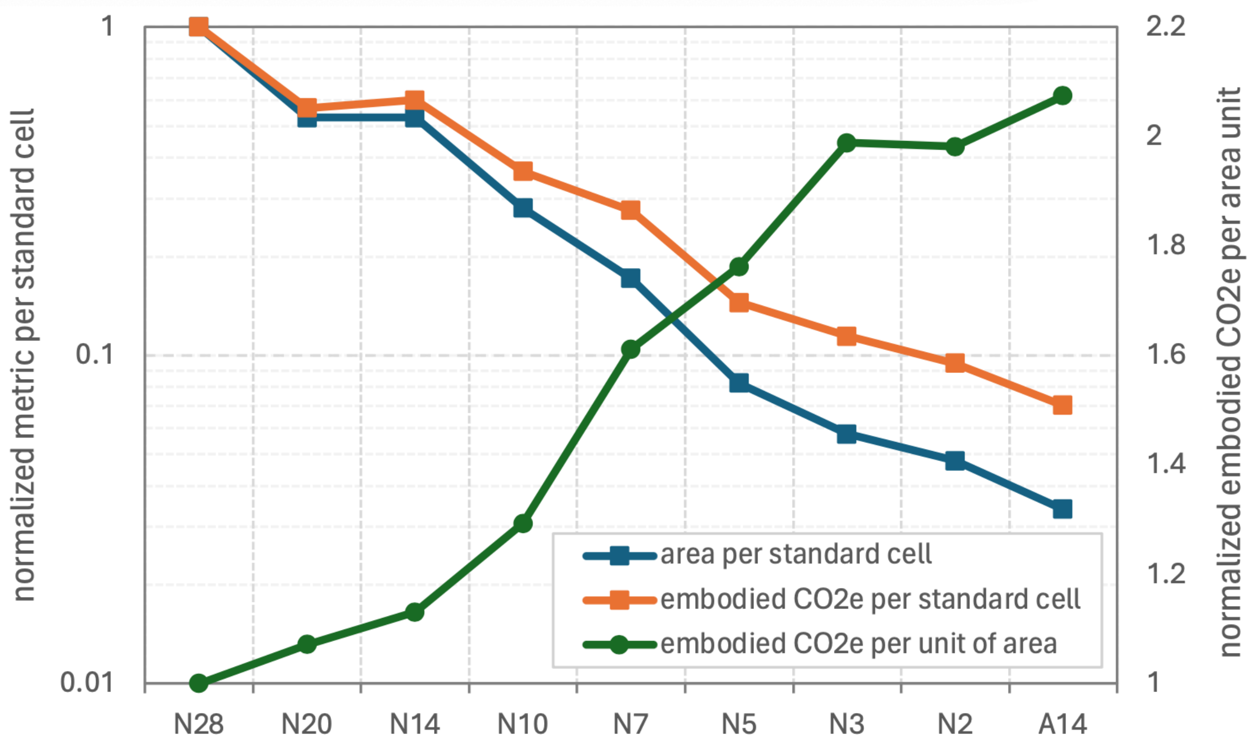
Towards Sustainable Processor Design: Questioning Current Design Paradigm

Area per transistor and embodied footprint per transistor scale exponentially

Pure die shrink = strongly sustainable

This is not what we've done – we've used additional transistors to add more functionality (cores, caches, accelerators)

Overall insight: *use increasing available transistor count in a sober way and leverage reduced carbon footprint per transistor to design more sustainable processors*



[Boakes et al., IEDM, 2023]

Wrap-Up

ICT's contribution to global warming is significant, and rising

Assessing computer architecture sustainability is challenging

- Multi-faceted problem, inherent data uncertainty, need to take whole lifecycle into account

Total carbon emissions continue to grow under current scaling trends

Embodied emissions are, or will soon be, most dominant contributor to the total carbon footprint

Computer architects can (and should) **reduce total carbon footprint by reducing die size** (primarily) ***and*** **operational emissions** (secondarily)

FOCAL: First-order model using proxies for embodied/operational footprint and parameterized embodied/operational ratio to holistically reason about sustainability

- Deliberately simple, yet accounts for Jevons' paradox
- Provides insight and intuition
- Framework to reason about computer architecture sustainability trade-offs for a variety of scenarios
  - Multicore, heterogeneity, caching, speculation, specialization, parallelization, etc.

Exciting and important work ahead of us: call for action for computer scientists and engineers ☺

Sustainable Processor Design

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January 22, 2026

[J. Roelandts et al., "The Architectural Sustainability Index", (Best of) IEEE CAL 2025]
[J. Rogers et al., "Neoscope: How Resilient is my SoC to Workload Churn?", ISCA 2025]
[L. Eeckhout, "The Sustainability Gap for Computing: Qua Vadis?", Communications of the ACM 2025]
[P. Dangi et al., "Sustainable Hardware Specialization", ICCAD 2024]
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[L. Eeckhout, "FOCAL: A First-Order Model to Assess Processor Sustainability", ASPLOS 2024, IEEE Micro Top Picks 2025]
[L. Eeckhout, "A First-Order Model to Assess Computer Architecture Sustainability", (Best of) IEEE CAL 2022]
[L. Eeckhout, "Kaya for Architects: Towards Sustainable Computer Systems", IEEE Micro 2023]