Fraunhofer IZM

Fraunhofer Institute for Reliability and Microintegration IZM

Electronic Packaging Days 2025

Energy and Carbon Footprint of Advanced Computer Hardware for HPC and AI Systems

—

Dr. Lutz Stobbe,
Fraunhofer IZM, 2025 Electronic Packaging Days, November 6th 2025

Gigawatt data center area is in full swing

Massive demand in energy and hardware

xAI Colossus (Elon Musk)

- 1 Gigawatt power demand
- 550,000 to 1,000,000 high-end Nvidia GPUs
- Investment of 20 to 30 Billion USD on:
  - Silicon (Compute & Network) 57%
  - Power (Gas & Batteries) 20%
  - Cooling (Water Recycling) 15%
  - Real Estate (Facility) 10%

Stargate (OpenAI, Oracle, Softbank)

- 10 Gigawatt power demand (planned)
- Up to 10,000,000 high-end Nvidia GPUs
- Investment of 500 Billion USD announced:

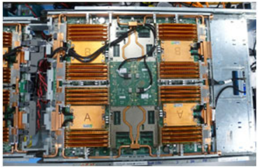
https://www.youtube.com/watch?v=RxuSvyOwVCI

x 10

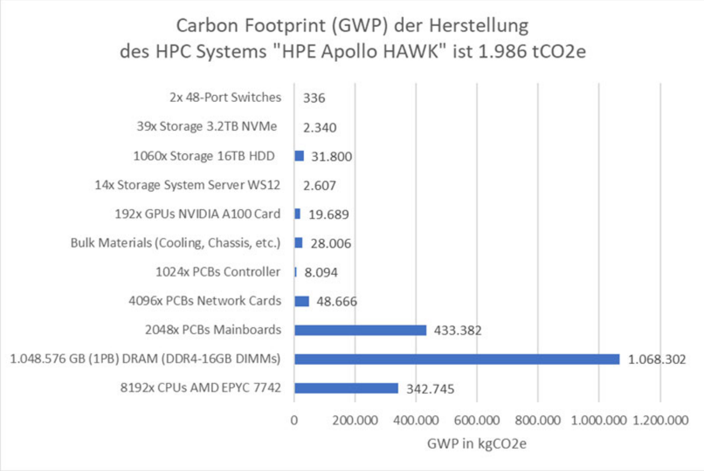
Simplified carbon footprint assessment of the HPE Apollo HAWK System

HRLS High Performance Computing Center Stuttgart (2020 – 2025)

- **26 Petaflops (theoretical)**
- **32 Racks / 4096 Compute Nodes**
- **~ 3000 kW power / ~ 115 kW/PFLOP (use)**
- **~ 76 tCO2e/PFLOP (manufacturing)**



DRAM



https://www.hlrs.de/de/loesungen/systeme/hpe-apollo-hawk

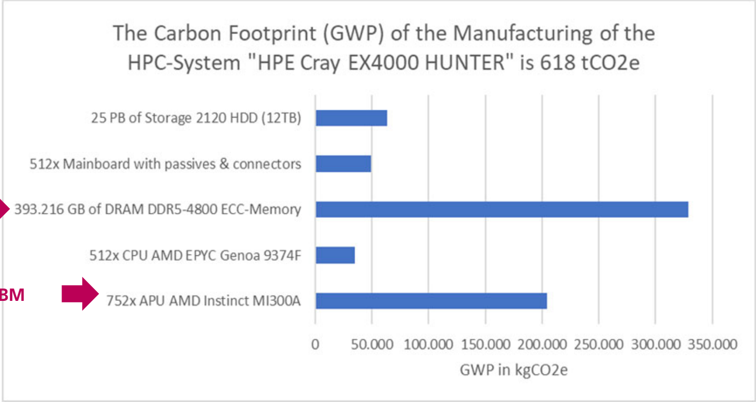
Simplified carbon footprint assessment of the HPE Cray EX4000 HUNTER

HRLS High Performance Computing Center Stuttgart (2025 -

- 48 Petaflops (theoretical)
- 8 Racks / 512 Compute Nodes
- ~ 560 kW power / ~ 12 kW/PFLOP (use)
- ~ 13 tCO2e/PFLOP (manufacturing)

DRAM

APU incl. HBM



Quelle: https://www.hlrs.de/de/loesungen/systeme/hunter

Increasing die area of advanced processor systems

Multiple compute chip-lets with an I/O orchestrator and high bandwidth memory (HBM) in a package

Intel Xeon 8180

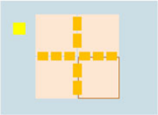
2017

Die-Area:

6,9 cm²

Intel Xeon 8468H

2023

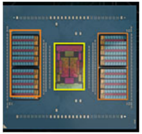


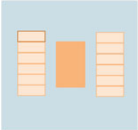
Die-Area:

21,8 cm²

AMD EPYC 9965

2024



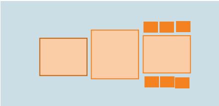


Die-Area:

14,6 cm²

NVIDIA GH200

2024

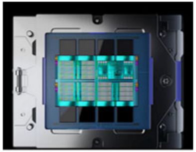


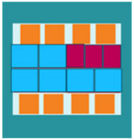
Die-Area:

45,2 cm²

AMD INSTINCT MI300

2023





Die-Area:

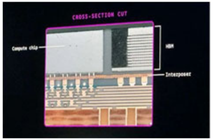
64,8 cm²

 11/7/2025 **Restricted**

Die-Area of application specific AI systems (ASIC) needs further analysis

Komplexe Chiplet Systeme

AWS Trainium 2 2024 (ASIC)



Total die area (est): 67,8 cm²

4x12 HBM dies: 52.8 cm²

2x ASIC dies: (15.0 cm²)

2x active Interposers: 24 cm²

Microsoft Maia 100 2024 (ASIC)

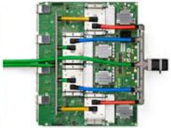
Total die area unknown yet

SoC size: 8.2 cm²

64 Tiles: 4 Tiles/cluster 16 Cluster/SoC

Assumption: @ 0,8cm²/tile = **51 cm²**

Google TPU v4 2024 (ASIC)



Total die area unknown yet

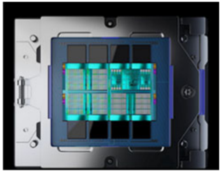
Hardware demand for advanced computer systems

Exemplary calculation of die area demand of an AI system

Average XPU die area:

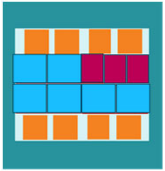
- 15 - 25 cm² Compute (APU, GPU, CPU)
- 40 – 60 cm² High Bandwidth Memory (HBM)
- 200 - 500 cm² Memory (DRAM)
- 25 - 40 cm² Silicon Interposer

- +++ NAND storage



AMD INSTINCT MI300

2023 (APU)

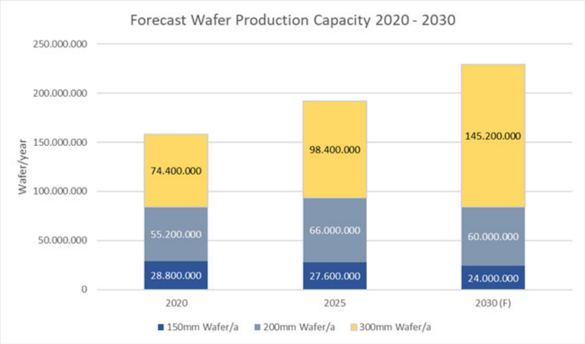


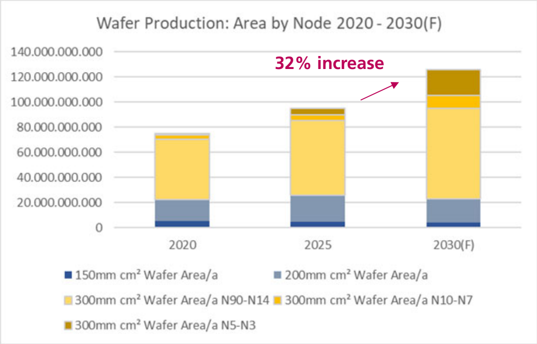
Total die-area (est.): 76.5 cm²
4x base layer dies: 14.8 cm²
8x4 HBM dies: 46.5 cm²
6x GPU dies: 11.5 cm²
3x CPU dies: 3.7 cm²
1x silicon Interposer: 30 cm²

.

Forecast wafer production capacity 2020 to 2030

Wafer area (in cm²) is expected to increase by 32% between 2025 and 2030





Calculation by IZM based on data from:

https://www.toolsresearch.com/12-inch-semiconductor-wafers-sell-well/

https://www.semi.org/en/news-media-press-releases/semi-press-releases/global-semiconductor-fab-capacity-projected-to-expand-6%25-in-2024-and-7%25-in-2025-semi-reports

https://www.kbvresearch.com/semiconductor-wafer-market/

Advanced Computing (HPC/AI) is dominated by the USA

Taiwan and South Korea are currently critical links in the advanced IC supply chain

Data Center (A/(HPC operation)

AI software application

- OpenAI ChatGPT
- Microsoft Copilot
- Google Gemini
- Meta AI (Whatsapp)
- Perplexity AI
- Anthropic Claude AI
- Deepseek

AI hardware design

- CPU + FPGA (Intel, AMD, Apple/ARM, Broadcom)
- GPU (NVIDIA)
- ASIC / APU
  - **Amazon** Trainium (T), Inferentia (A)
  - **Microsoft** Maia (Accelerator), Cobalt (CPU
  - **Google/**Broadcom TPU (T+I), Axion (CPU)
- DRAM / HBM
- NAND

AI hardware manufacturing

- Intel (USA)
- **Foundries:**
  - **TSMC (Taiwan) 62%**
  - UMC (Taiwan) 6%
  - Samsung Foundry (South Korea) 10%
  - Global Foundries (USA) 6%
  - SMIC (PR China) 5%
- Samsung (South Korea)
- SK Hynix ((South Korea),
- Micron (USA/JP)

https://www.youtube.com/watch?v=WqS3jhsGLvI

Semiconductor manufacturing Green House Gas Protocol

Breakdown of items according to studies from McKinsey & Company and Boston Consulting Group

Scope 2
- Electricity from the grid (consider type of energy mix)
- Heating
- Onside power plant / renewable

Average 50 - 55%

Scope 1
- Direct emissions from process gases (consider abatement)
- Direct emissions from onside power plant

Average 10 - 15%

Semiconductor Fab

Scope 3 (Upstream OPEX)
- Raw wafer (15%)* (9%)**
- Chemicals (22%)* (4%)**
- Process Gases (13%)* (16%)**
- Metals (8%)* (24%)**
- Transportation (6%)* (16%)**

Scope 3 (upstream CAPEX)
- Process equipment (16%)* (24%)**
- Fab & equipment maintenance (6%)*
- Fab construction (6%)*

Average 35 - 40%

*McKinsey & Company (2023): Semiconductors Practice: Beyond the fab: Decarbonizing Scope 3 upstream emissions

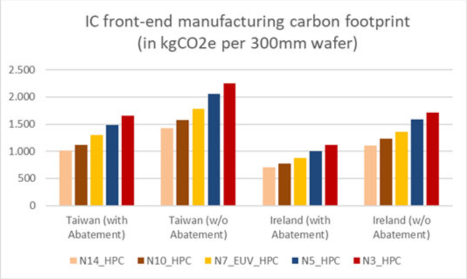
**https://www.bcg.com/publications/2023/why-chip-makers-need-to-focus-on-the-upcoming-decarbonization-challenges

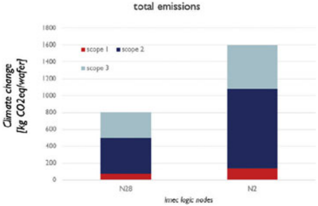
IMEC netzero: IC manufacturing carbon footprint datasets

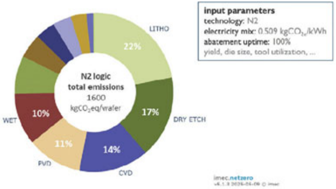
https://netzero.imec-int.com/

Aspects influencing the IC carbon footprint:

- IC type / functionality → materials & processes
- Die size / design → wafer utilization (yield)
- Tech. node → number & types of process steps
- Process yield → defects due to complexity, etc.
- Location → energy mix (fab / equipment age)
- Market demand → fab utilization



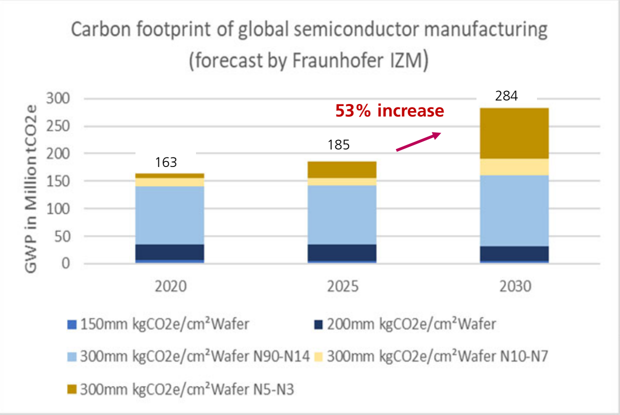


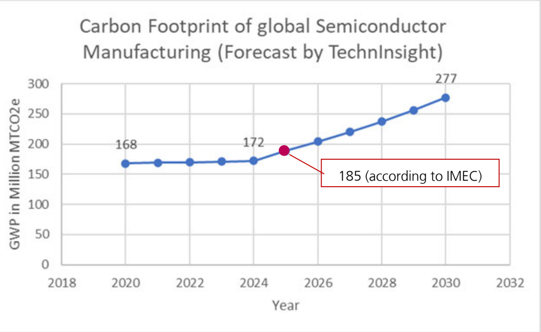


  Restricted

Carbon Footprint of Semiconductor Production (Forecast)

The carbon footprint of global semiconductor manufacturing is expected to increase by 53%





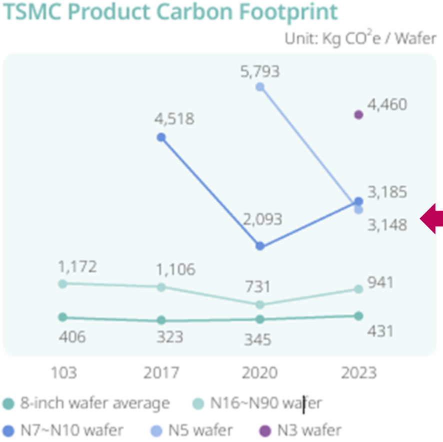
https://library.techinsights.com/public/hg-asset/1a965735-48b8-43a0-8ebd-7b5b8f048db5

https://www.semiconductor-digest.com/how-can-we-reduce-environmental-impact-in-chip-manufacturing/

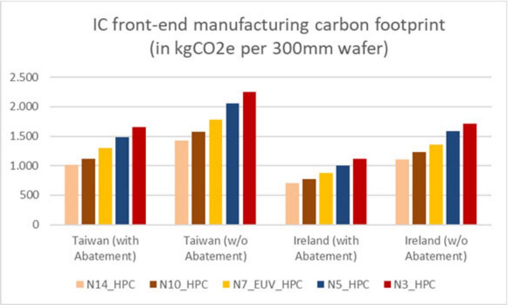
Calculation by IZM based on data from semiconductor industry environmental reports

TSMC reported IC manufacturing carbon footprint indicate reality

TSMC sustainability report 2024



Enterprise	item	unit	2021	*2021*	2022	*2022*	2023	*2023*	2024	*2024*
TSMC	wafer shipment	12" eq	14.178.630	*1,05*	15.252.882	*0,98*	12.002.177	*0,73*	12.910.000	*0,76*
TSMC	capacity	12" eq	13.500.000	*1,00*	15.500.000	*1,00*	16.500.000	*1,00*	17.000.000	*1,00*
UMC	wafer shipment	12" eq	4.391.111	*1,05*	4.484.000	*1,01*	3.202.000	0,69		
UMC	capacity	12" eq	4.201.333	*1,00*	4.458.000	*1,00*	4.674.000	*1,00*		*1,00*
GF	wafer shipment	12" eq	2.374.000	*1,06*	2.472.000	*1,01*	2.211.000	*0,81*		
GF	capacity	12" eq	2.239.623	*1,00*	2.447.525	*1,00*	2.729.630	*1,00*		*1,00*



https://esg.tsmc.com/en-US/file/public/2024-TSMC-Sustainability-Report-e.pdf

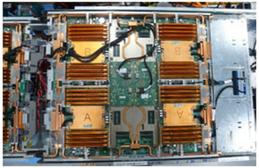
- Data from IMEC: https://netzero.imec-int.com/

  Restricted

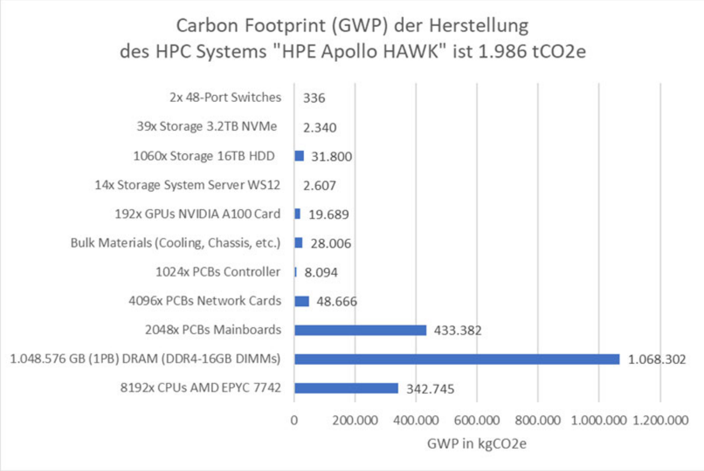
Simplified carbon footprint assessment of the HPE Apollo HAWK System

HRLS High Performance Computing Center Stuttgart (2020 – 2025)

- **26 Petaflops (theoretical)**
- **32 Racks / 4096 Compute Nodes**
- **~ 3000 kW power / ~ 115 kW/PFLOP (use)**
- **~ 76 tCO2e/PFLOP (manufacturing)**



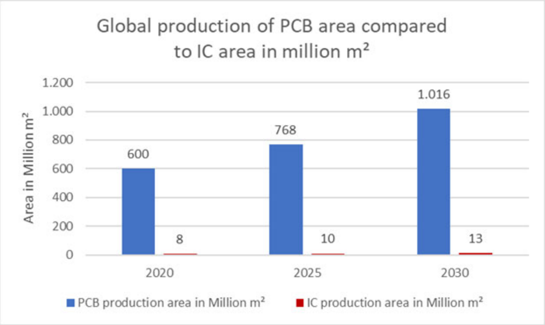
PCB →

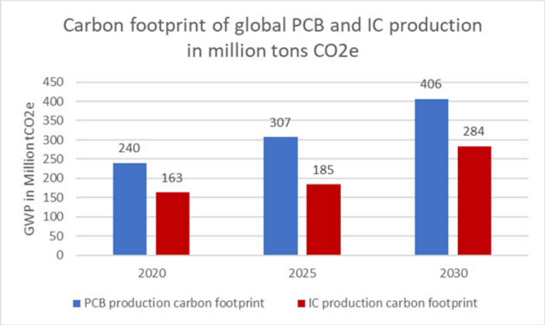


https://www.hlrs.de/de/loesungen/systeme/hpe-apollo-hawk

The environmental impact of PCB manufacturing in comparison to IC

PCB design & production should also become a stronger focus of environmental improvement





https://www.ugpcb.com/de/news/trade-news/pcb-industry-explosion-2025-global-100b-pcb-market-deep-dive-technology-breakthrough-paths/

https://www.precedenceresearch.com/printed-circuit-board-market

https://www.kingfordpcb.com/industry-news/5930.html

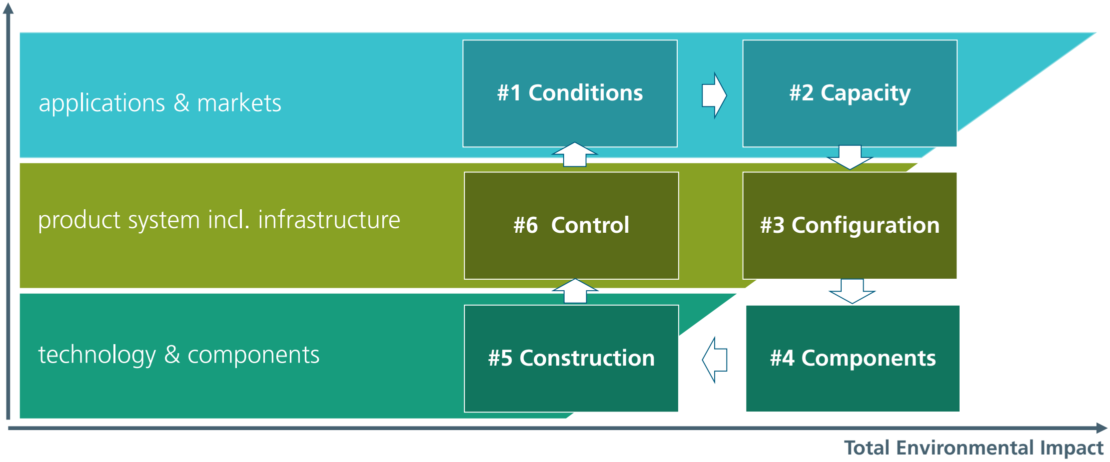
Ratio of manufacturing and use phase carbon footprint of AI compute system

Exemplary calculations based on averaged values

AI/HPC data center rate power:	1 Gigawatt
Power Usage Effectiveness:	1.3 PUE
Power per compute unit:	770 W
Number of compute units:	100.000 units (@15,000 Euro/unit = 1,500 Million Euro)
Manufacturing CFP:	150,000 tCO2eq (total compute units)
5 year use phase power consumption:	3.4 TWh (@ 0.25 Euro/kWh = 850 Million Euro)
• Average energy mix 380gCO2e/kWh:	1,300,000 tCO2e → 90% use and 10% manufacturing phase
• Green energy mix 120gCO2e/kWh:	405,000 tCO2e → 73% use and 27% manufacturing phase

The Six Cues (6C method)

A reference model for data acquisition in support of environmental assessments and ecodesign of ICT



ALU4CED: Aluminum based multifunctional housing for circular electronic devices

Laser direct structuring of a lacquer on aluminum carrier for creating antennas & touch buttons

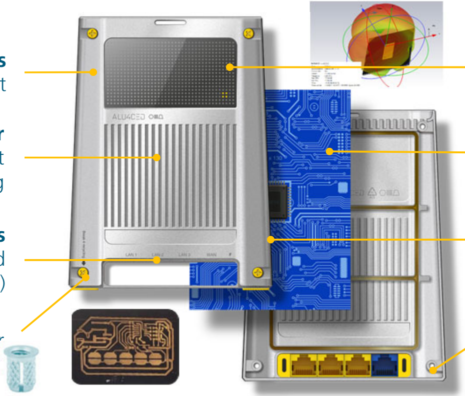
- **Polish-German R&D project funded by AiF CORNET program (2023 – 2025)**

Two identical AL housing shells
easy to recycle, low carbon footprint

Aluminum housing for
optimizing thermal management
and electromagnetic shielding

Capacitive touch buttons
with light indicators integrated
on outer surface (LDS techn.)

Break-out screws for
fastening and ease of recycling



Antennas integrated on outer
surface (LDS of lacquer technology)

High production yield design
of the printed circuit board (**PCB**)
with lower carbon footprint

Anodized surface treatment
for personalization and appeal

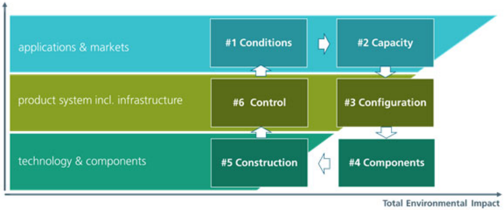
Compact connector area for
easy access

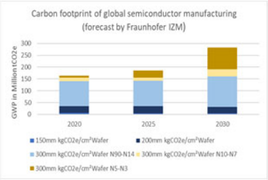
Fraunhofer IZM – Sustainable Electronics

Competencies, Methods, Tools

We are offering competence with respect to:

- the quantification of environmental impacts of advanced microelectronics and ICT systems (IC, package, PCB, etc.)
- the estimation of environmental impacts and costs with respect to new technologies and manufacturing options based on limited data
- the analysis of microelectronic system in order to identify eco-improvement options (development of eco-design strategy)
- the support of product eco-design with focus on energy and material efficiency including design for repair and recycling (circular economy)





Thank you for your attention

Fraunhofer IZM

Fraunhofer Institute for Reliability and Microintegration IZM