OAK RIDGE National Laboratory

Sustainability of semiconductor manufacturing

Manufacturing Energy Efficiency and Sustainability (MEES) Group

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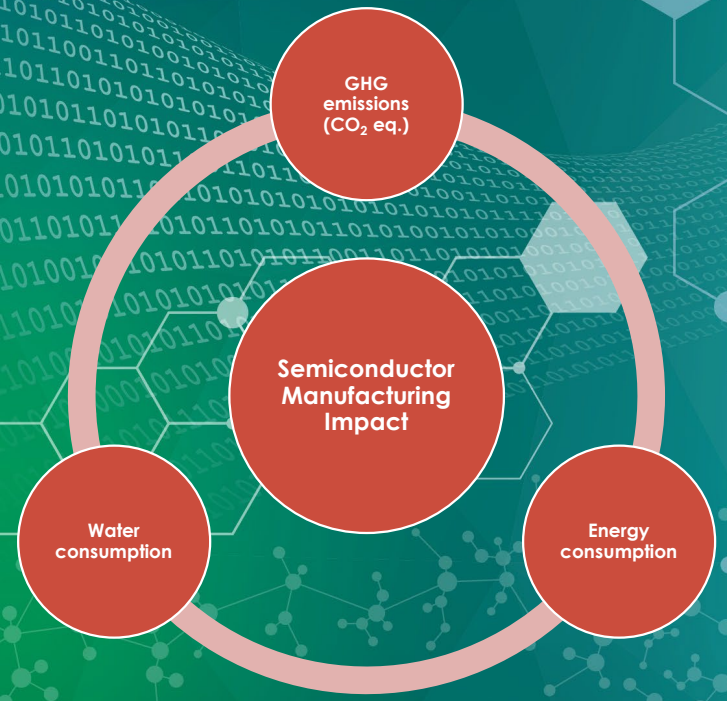


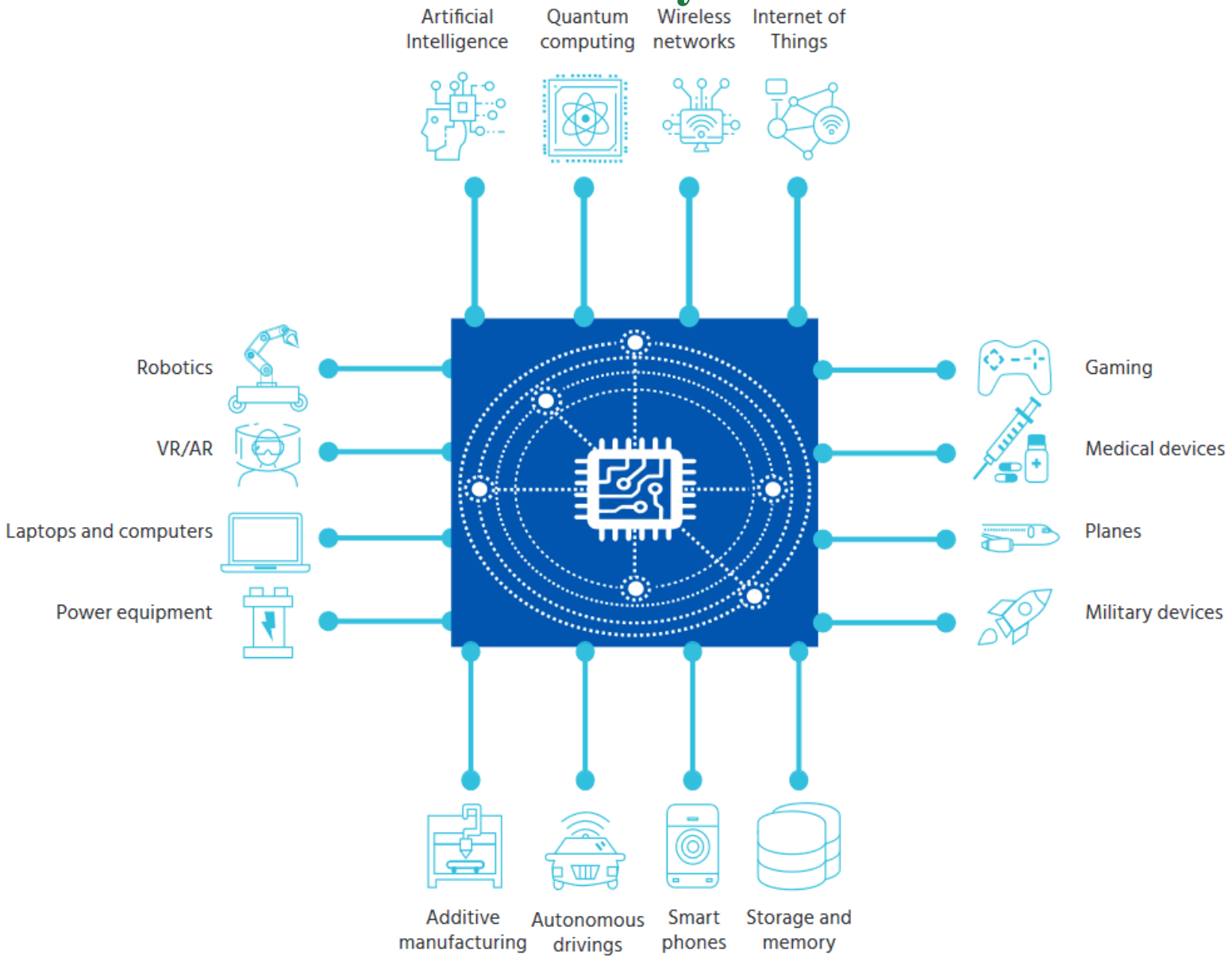
Semiconductor Industry Energy Efficiency Scaling (EES2) Roadmap Working Group Meeting #7

21 June 2023

ORNL is managed by UT-Battelle LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

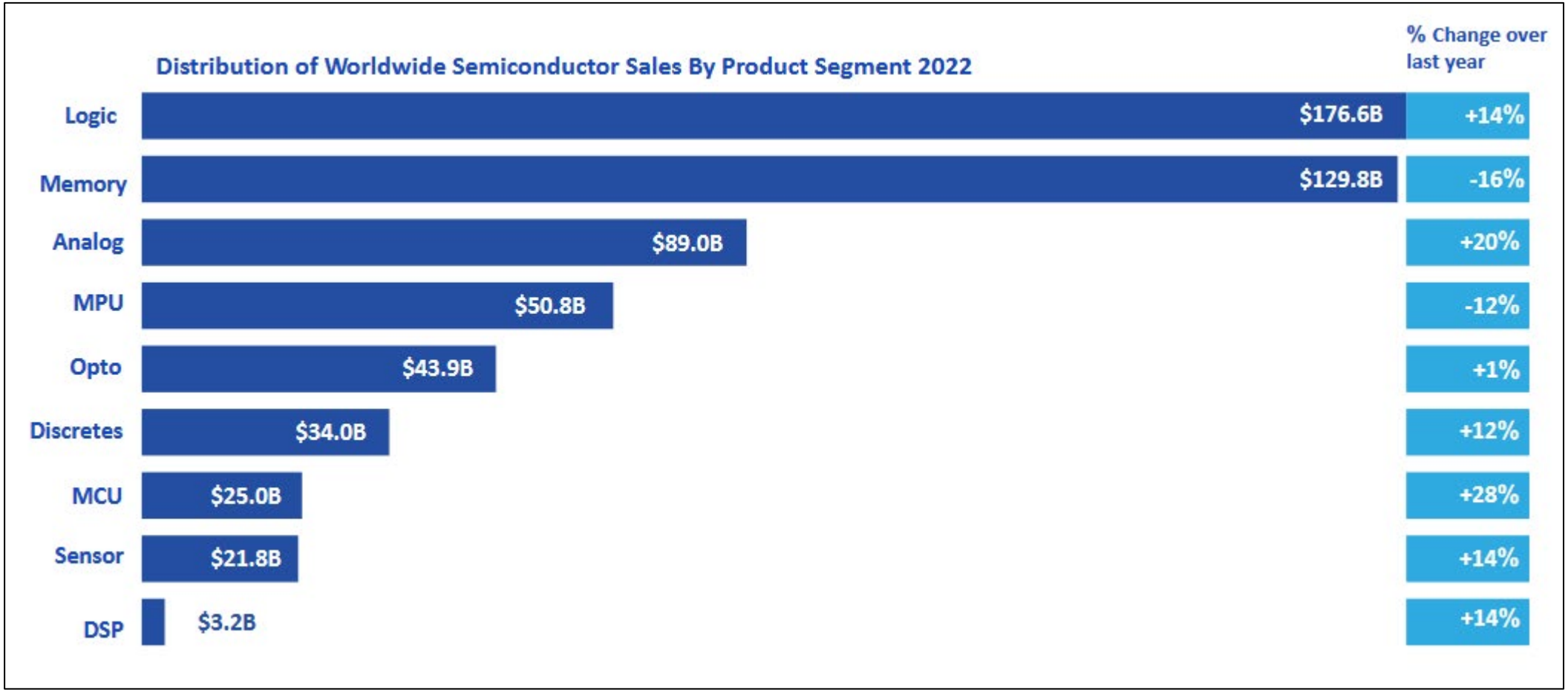
What are semiconductors & where are they used in?



Semiconductors are small integrated circuits (ICs) or microchips that used widely in many information and communication technology (ICT) devices that we use today

Image source: A. Capri, Hinrich foundation, Semiconductors at the heart of the US-China tech war, 2020.

Global semiconductor sales by type in 2022

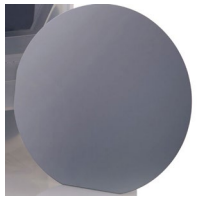


Semiconductor market is dominated by logic and memory ICs with their combined share exceeding >50%.

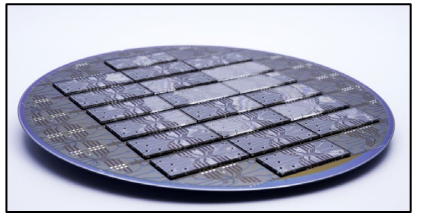
Source: SIA, 2023 factbook

Life cycle of an integrated chip (IC)

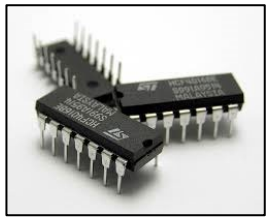
1. Silicon wafer manufacture

Polysilicon → Silicon ingot manufacture (Czochralski Process) →  Silicon ingots → Silicon wafer manufacturing →  Silicon wafer

2. IC Manufacture

IC Manufacture (DRAM, NAND, MPU, etc.) →  ICs on a silicon wafer

3. IC Assembly

 ← IC packaging and assembly

4. IC Use Phase

 ← Used in motherboards, cellphones, etc.

Product recycle (End of Life – EOL)

IC life cycle is complex - Four stages - Silicon wafer manufacture, IC manufacture, use, end of life

Nagapurkar, Prashant, and Das, Sujit. Economic and embodied energy analysis of integrated circuit manufacturing processes. United States: N. p., 2022. Web doi:10.1016/j.suscom.2022.100771.

Why focus on sustainability integrated circuits (IC) within devices?

Apple's carbon emission breakdown - 25 Mton CO_2 eq. in 2019

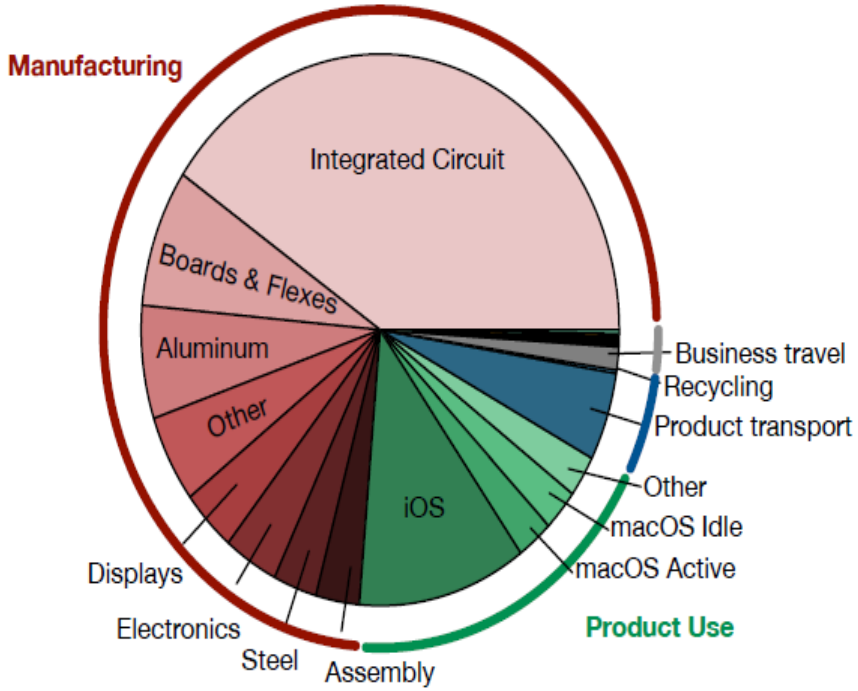
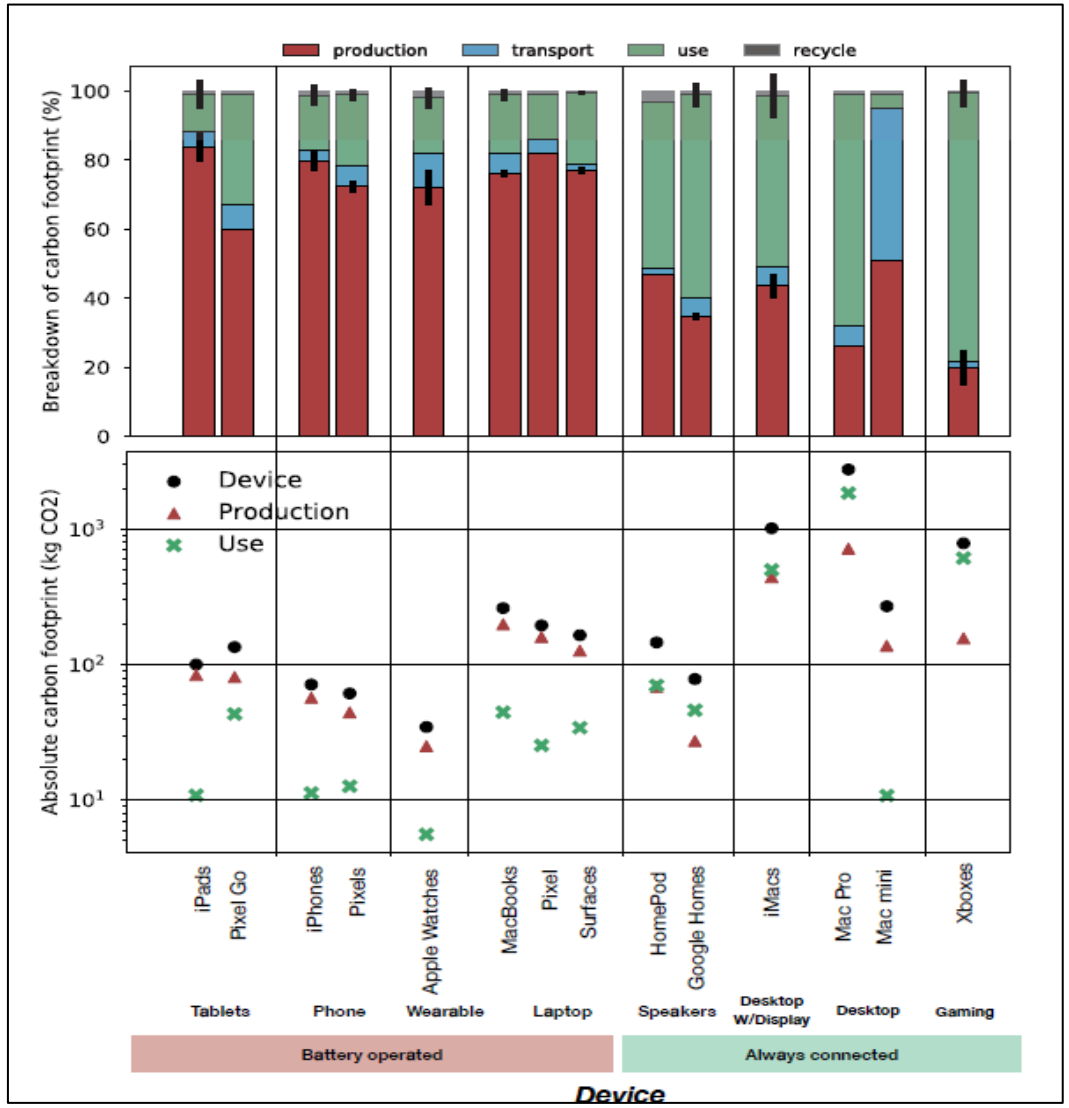


Fig. 5. Apple's carbon-emission breakdown. In aggregate, the hardware life cycle (i.e., manufacturing, transport, use, and recycling) comprises over 98% of Apple's total emissions. Manufacturing accounts for 74% of total emissions, and hardware use accounts for 19%. Carbon output from manufacturing integrated circuits (i.e., SoCs, DRAM, and NAND flash memory) is higher than that from hardware use.

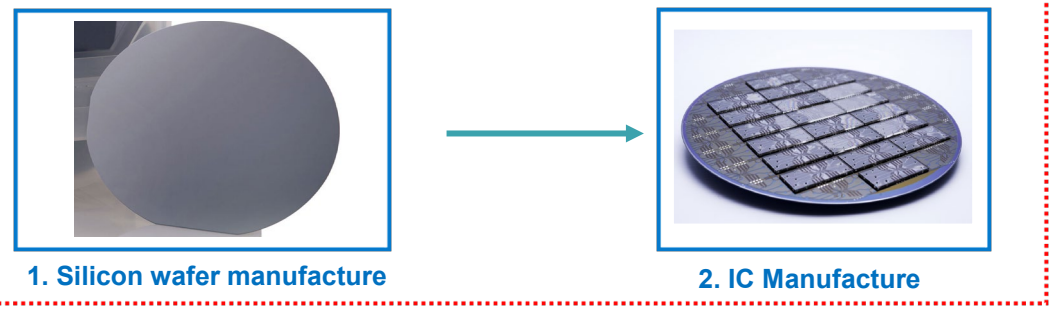


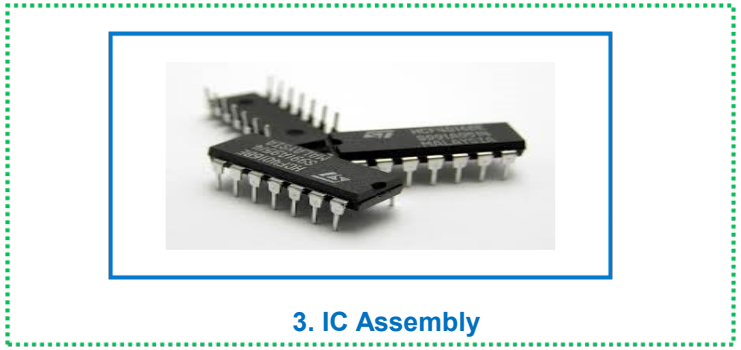
Manufacturing phase (typically for ICs) dominate emissions relative to use phase for battery operated devices. Reverse true for always ON devices.

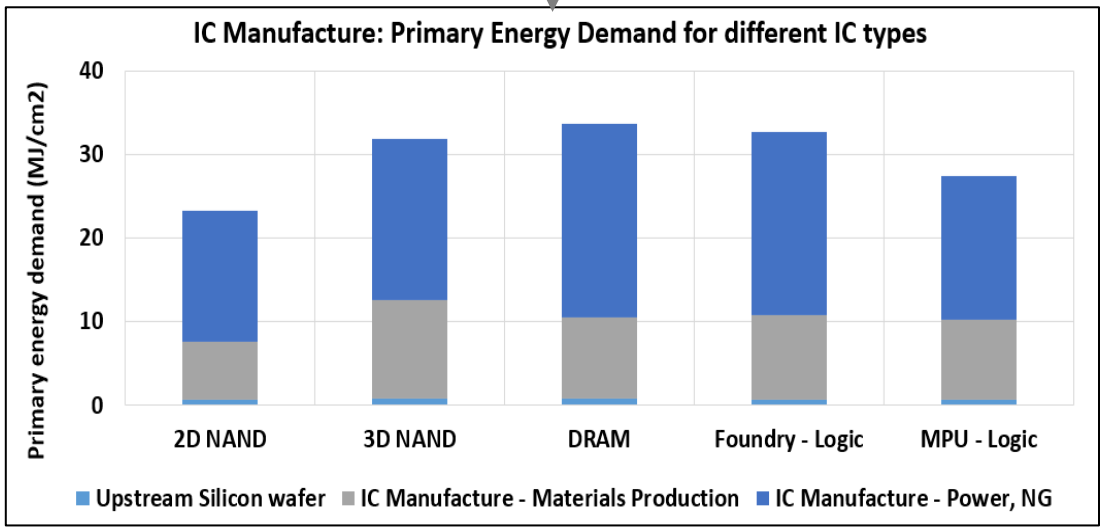
Source: U. Gupta, *et al.*, "Chasing Carbon: The Elusive Environmental Footprint of Computing," in *2021*

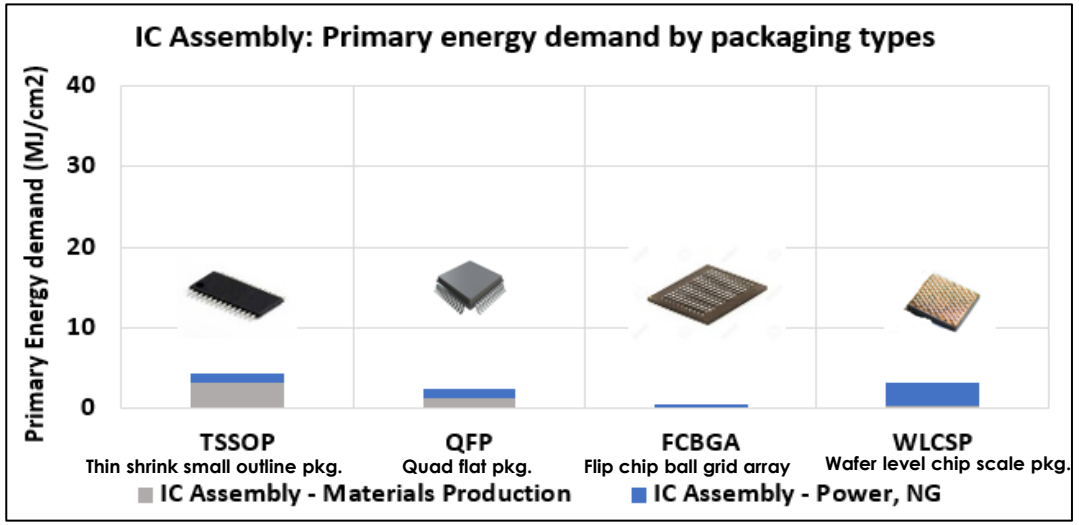
ORNL work - IC manufacture, Assembly Results: Primary energy demand by different types

- Using harmonization of studies, bill of materials for IC Manufacture, Assembly were inserted into OpenLCA software to compute primary energy demand.
- For ICs of similar technology node (~20 nm), Primary Energy Demand of IC manufacture phase is *six times* as IC assembly phase.
- Primary energy depended on IC manufacturing process, company (not all companies have identical IC manufacturing process) and final packaging type (QFP, TSSOP, etc.).









Work assumed 2019 US electricity grid
Analysis present for generic ICs as manufacturing technology & results may significantly differ with manufacturing company.

Primary energy demand of IC manufacture ~ 6X as that of IC assembly phase.

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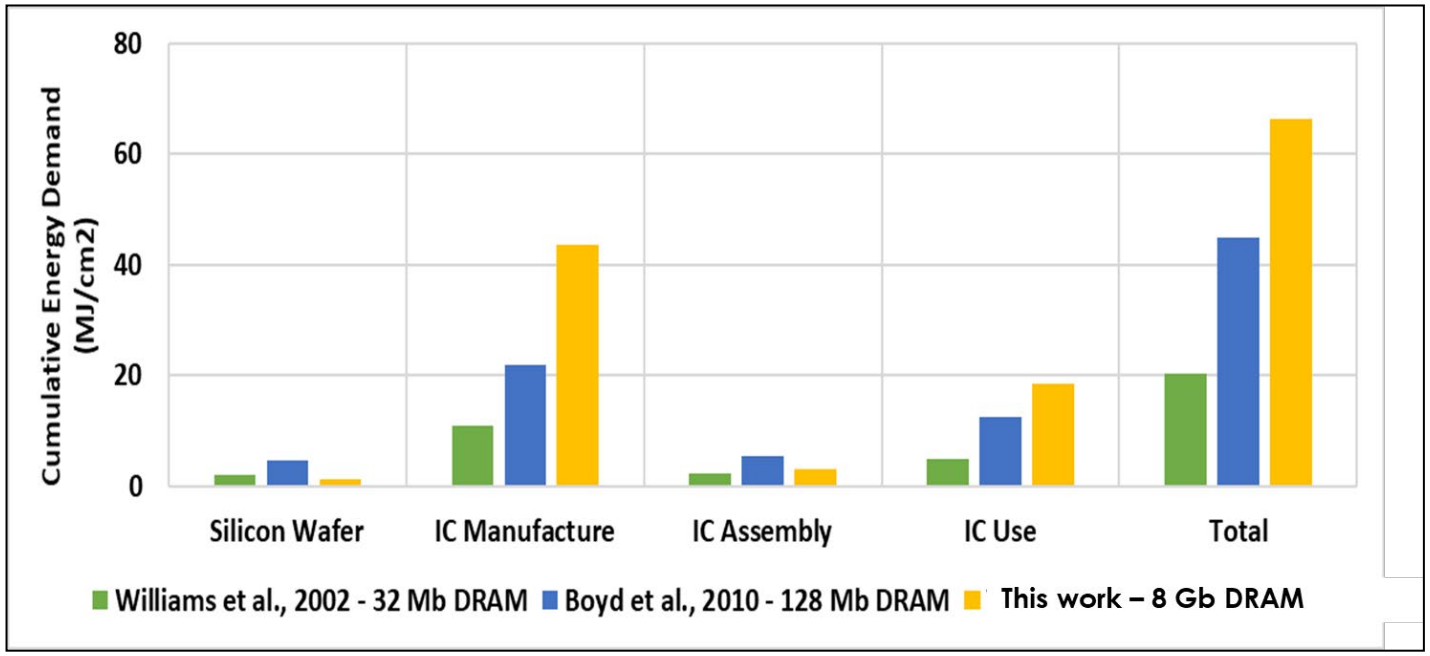
ORNL Work done by Prashant Nagapurkar, Sachin Nimbalkar, Sujit Das

ORNL work – Life cycle energy assessment via different DRAM IC stages

- For a representative DRAM IC, primary energy demand was computed over its entire life cycle (Silicon wafer, IC manufacture, assembly, use phase).
- IC Manufacture has the largest share of energy footprint 66% while use phase possessed small 28% share.



In entire life cycle of DRAM – IC manufacture phase has 2/3rd energy share; use phase has <1/3rd .

Nagapurkar, Prashant, and Das, Sujit. Economic and embodied energy analysis of integrated circuit manufacturing processes. United States: N. p., 2022. Web. doi:10.1016/j.suscom.2022.100771.

E. D. Williams, R. U. Ayres, and M. Heller, "The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices," *Environ. Sci. Technol.*, vol. 36, no. 24, pp. 5504–5510, Dec. 2002.

Boyd, Sarah B. "Life-Cycle Assessment of Dynamic Random Access Memory." Life-Cycle Assessment of Semiconductors. Springer, New York, NY, 2012. 97-107.

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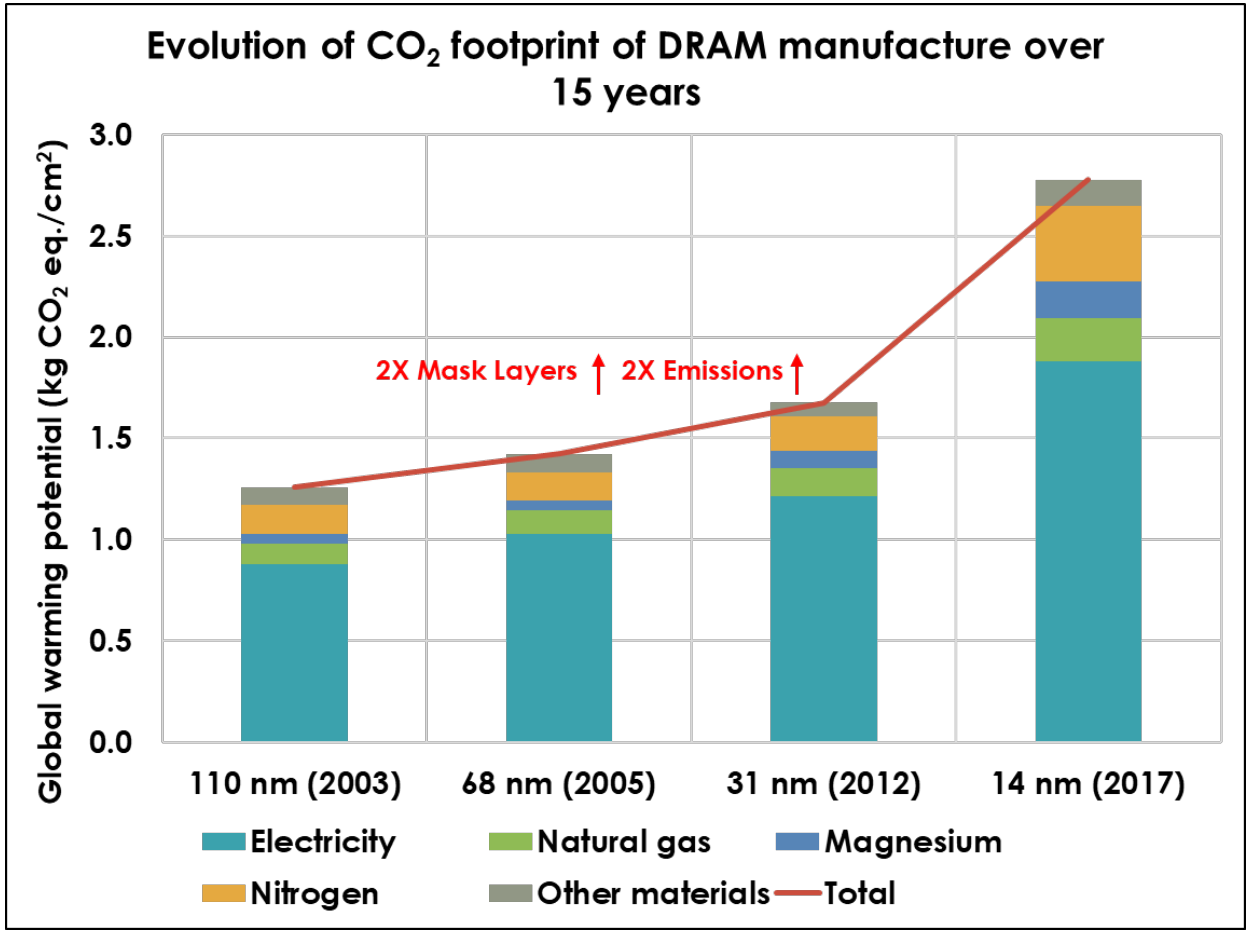
ORNL Work done by Prashant Nagapurkar, Sachin Nimbalkar, Sujit Das

ORNL work – IC manufacturing footprint increasing over time

- 2X increase in CO_2 emissions due to 2X increase in photomasks from years 2003 to 2017.
- Increase in # of photomasks increased the electricity consumption.
- Newer the manuf. technology (Higher the number of mask layers), larger is the CO2 footprint.



Work assumed 2019 US electricity grid
Analysis present for generic DRAM as DRAM's manufacturing technology may significantly differ by manufacturing company.

Region	Fossil Fuel Share in grid mix (Coal, natural gas, etc.)
Singapore	97%
Taiwan	85%
China	81%
Japan	79%
S. Korea	66%
USA	65%
Avg. Europe	44%

The manufacturing share of CO_2 eq. emissions have been increasing with the introduction of newer gen. DRAMs – Location of factory may play key role.

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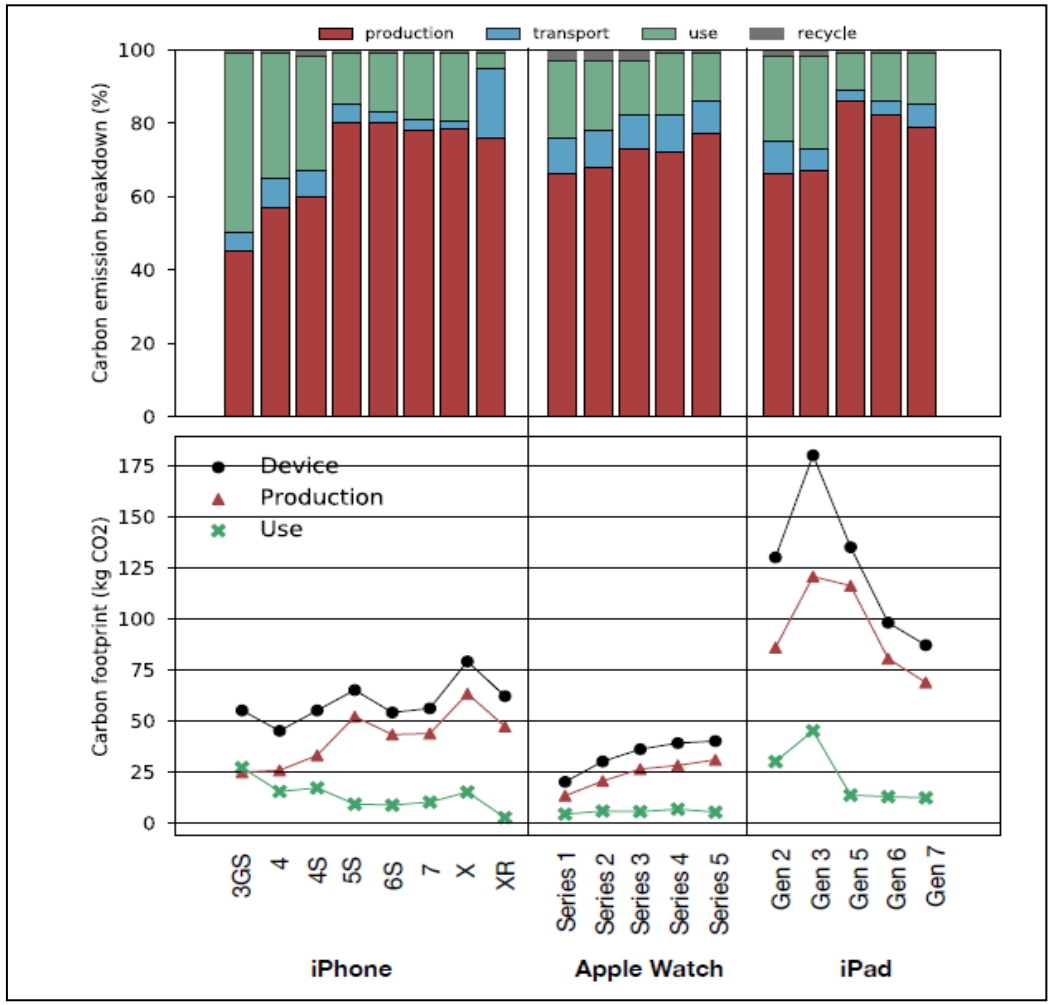
Do technology advancement really increase manufacturing carbon footprint? – What does literature say?

- Emissions share of production and manufacturing increased from generation to generation.
- For iPhones, manufacturing accounts for 45% of emissions in the 3GS and 75% in the XR;
  - For Apple Watches, 60% in Series 1 and 75% in Series 5;
  - For iPads, 60% in Gen2 and 75% in Gen 7.
- Hardware provides more flops, memory bandwidth, storage, application support, and sensors.

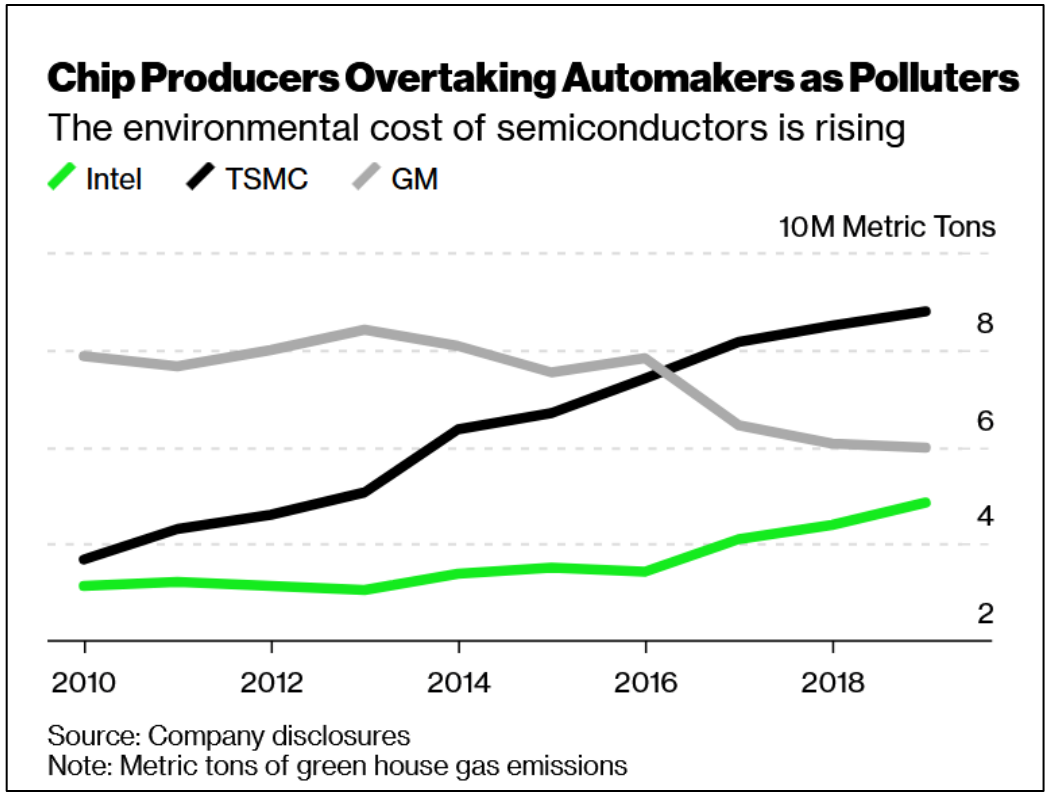


The manufacturing share of CO_2 eq. emissions have been increasing with the introduction of newer gen devices – Use phase share is same or decreasing.

Source: U. Gupta, *et al.*, "Chasing Carbon: The Elusive Environmental Footprint of Computing," in *2021*

Growing importance of environmental impacts of semiconductor manufacturing

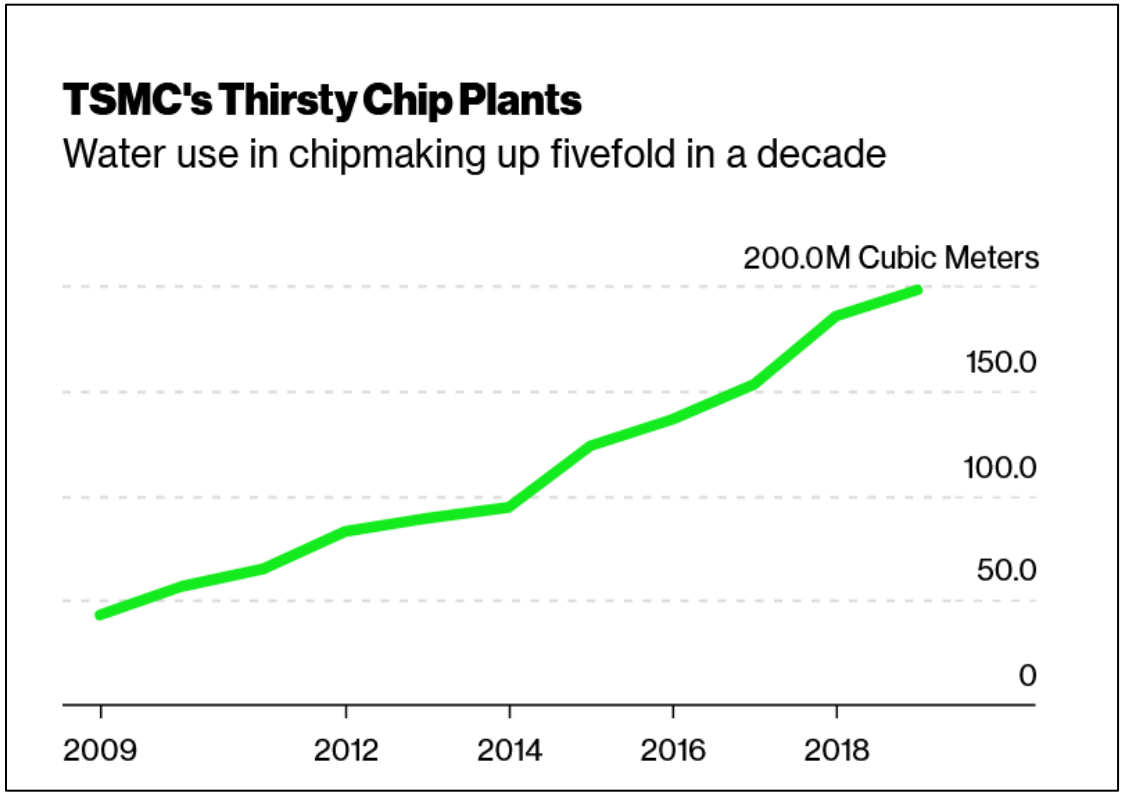
CO_2 footprint



Pollution & energy consumption could be correlated given high penetration of fossil sources (coal, natural gas) in electricity grid mix

Intel's share of renewable electricity was 82% in 2020 & is projected to be 100% by 2030. TSMC goal – 25% by 2030 & 100% by 2050.

Water footprint

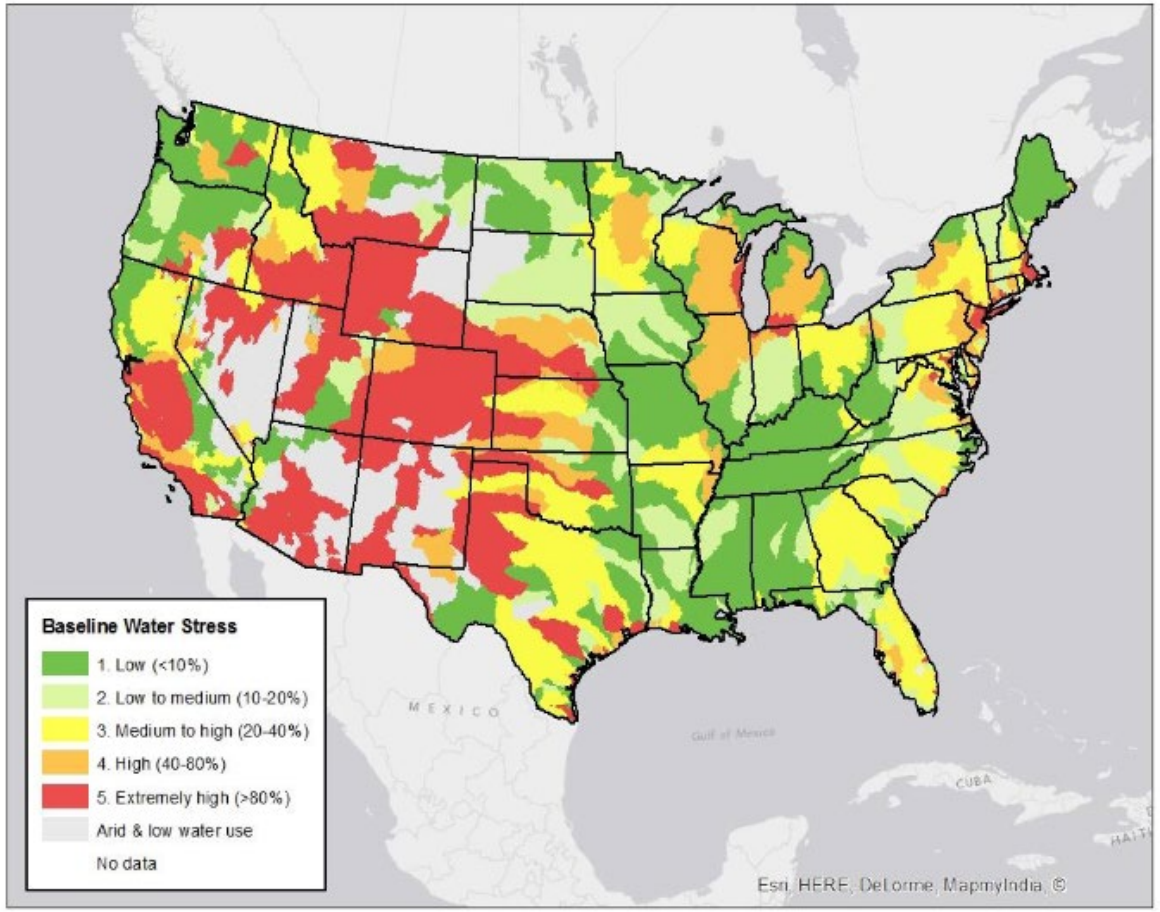


The water footprint and CO_2 eq. emissions of semiconductor manufacturing have been increasing over time.

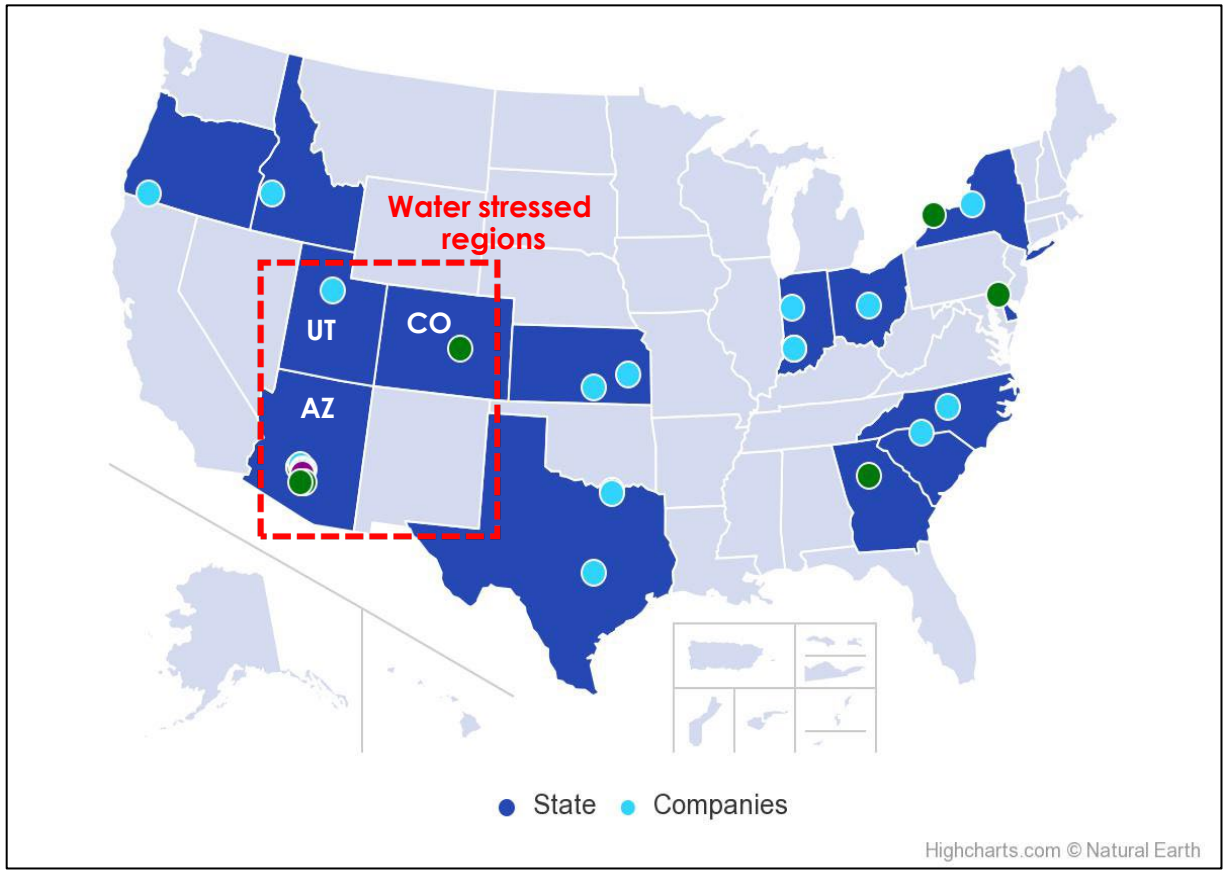
Source: https://www.bloomberg.com/news/articles/2021-04-08/the-chip-industry-has-a-problem-with-its-giant-carbon-footprint

Upcoming new facilities in water stressed US regions

Baseline water stress in the US



Upcoming manufacturing facilities coming up



A total of 13 manufacturing facilities (1 TSMC foundry in AZ) coming up in water stressed region of AZ & CO.

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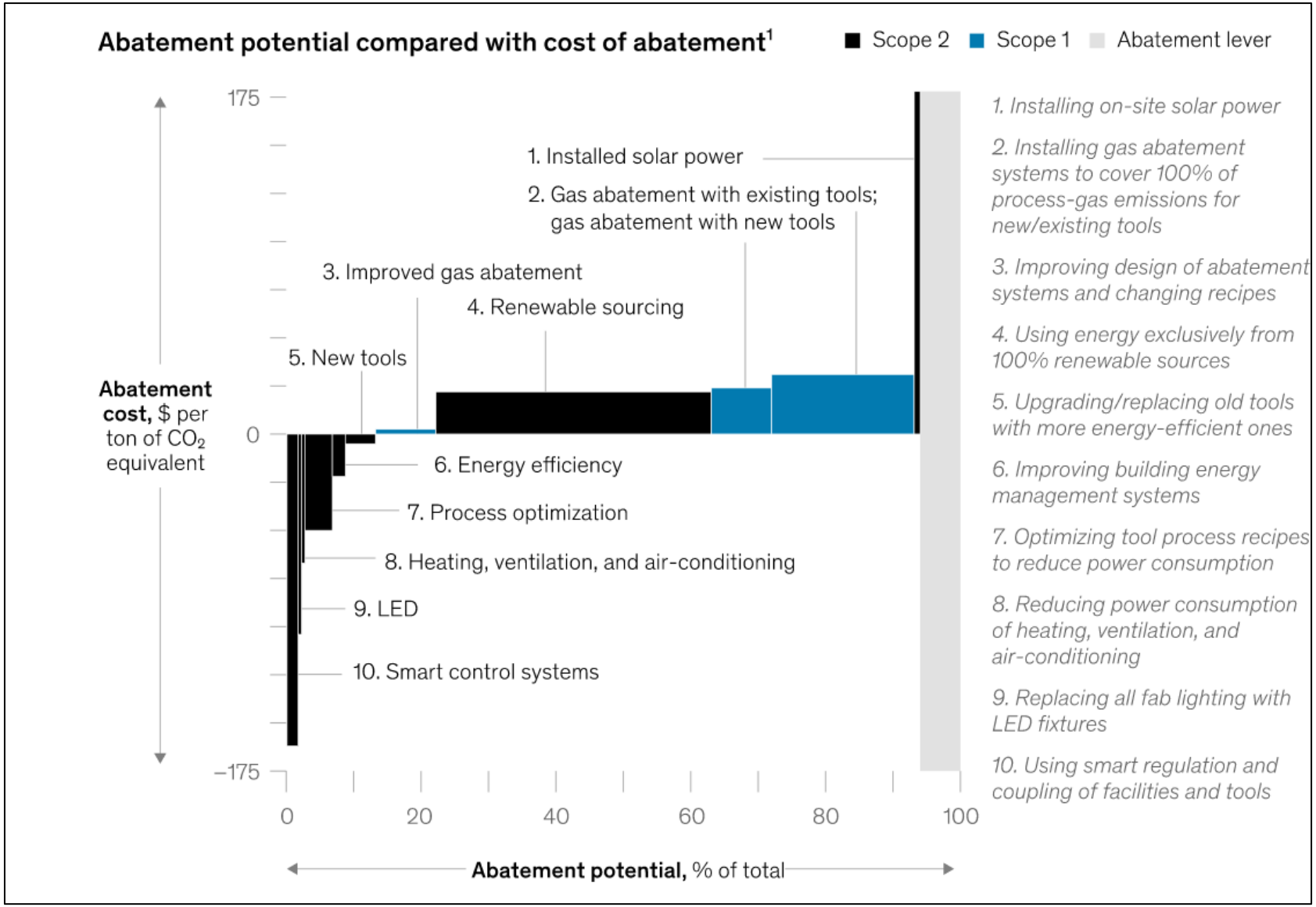
Kehl et al. 2020 DOI: https://doi.org/10.22158/ees.v3n2p1; https://www.semiconductors.org/u-s-semiconductor-ecosystem-map/

Cost effective solutions to decarbonize semiconductor manufacturing



ORNL has been developing similar cost curves – Manuscript written.

CO_2 abatement costs vary. Renewable electricity purchase most widely used option along with installation of PFC abatement tools

https://www.mckinsey.com/industries/semiconductors/our-insights/sustainability-in-semiconductor-operations-toward-net-zero-production

Conclusions & Future work

- Manufacturing energy of IC is an energy and environmental hotspot in the entire life cycle of the device.
- Manufacturing energy footprint and likely emissions of ICs have been increasing due to advancement in technology generations & complex manufacturing process.
- High water demand of fabs can be a concern particularly in water stressed states such as Colorado and Arizona.
- More analysis & data is needed for advanced generation of ICs (<5nm)
  - Lack of facility level data for emissions, energy, water footprint for advanced technology nodes (<5nm).
  - Data by process steps is unavailable.
  - EUV energy consumption.
- Facility level data is crucial to enhance & improve sustainability of semiconductor manufacturing.

Acknowledgements

- Grateful for funding from US Department of Energy's Advanced Manufacturing Office (Now, Industrial efficiency & industrial decarbonization office) – Joe Cresko
- Sachin Nimbalkar (ORNL), Sujit Das.

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