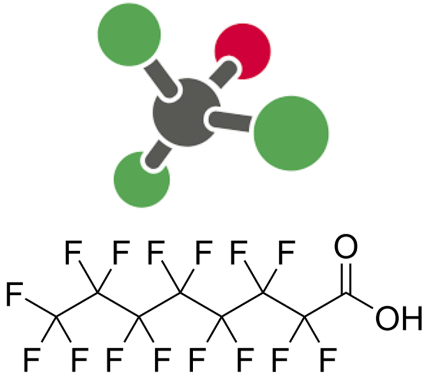
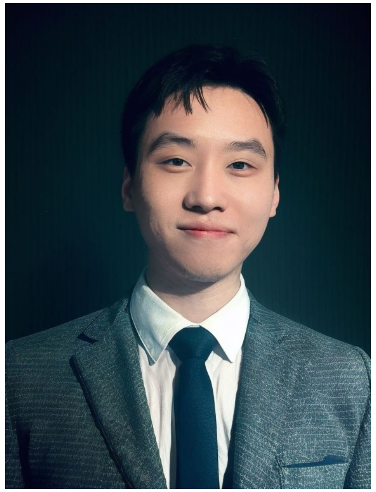


ForgetMeNot: Understanding and Modeling the Impact of Forever Chemicals Toward Sustainable Large-Scale Computing


Rohan Basu Roy


Raghavendra Kanakagiri


Yankai Jiang


Devesh Tiwari

THE UNIVERSITY OF UTAH

भारतीय प्रौद्योगिकी संस्थान तिरुपति IIT TIRUPATI

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What are forever chemicals and why are they harmful?

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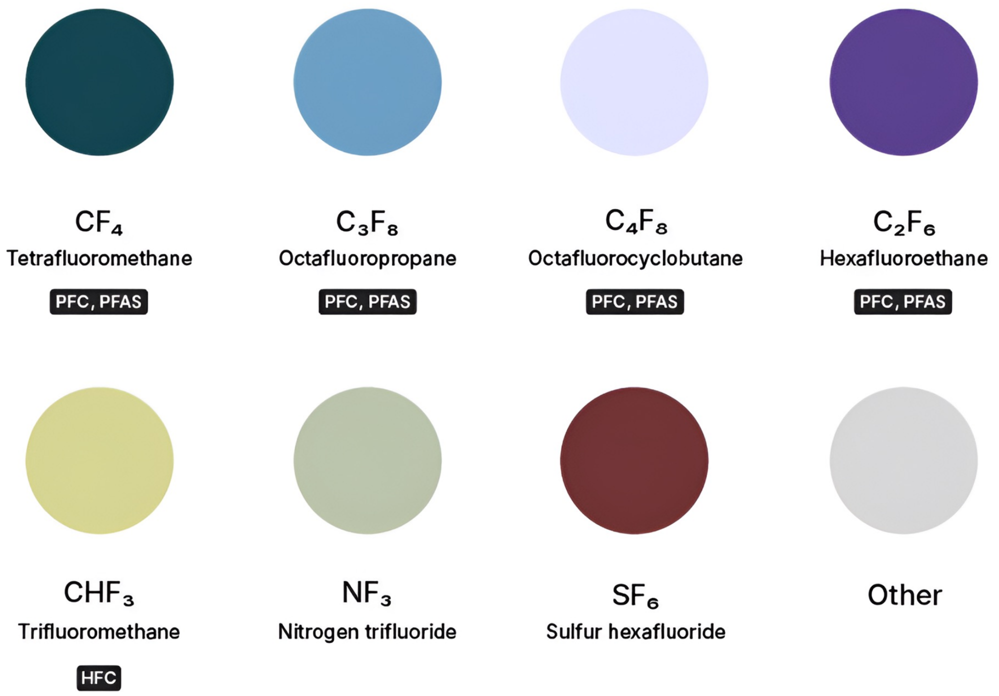
- CF_4 Tetrafluoromethane — PFC, PFAS
- C_3F_8 Octafluoropropane — PFC, PFAS
- C_4F_8 Octafluorocyclobutane — PFC, PFAS
- C_2F_6 Hexafluoroethane — PFC, PFAS
- CHF_3 Trifluoromethane — HFC
- NF_3 Nitrogen trifluoride
- SF_6 Sulfur hexafluoride
- Other

What are forever chemicals and why are they harmful?



Forever chemicals lasts in environment for thousands of years and have severely high global warming potential – much higher than that of carbon dioxide

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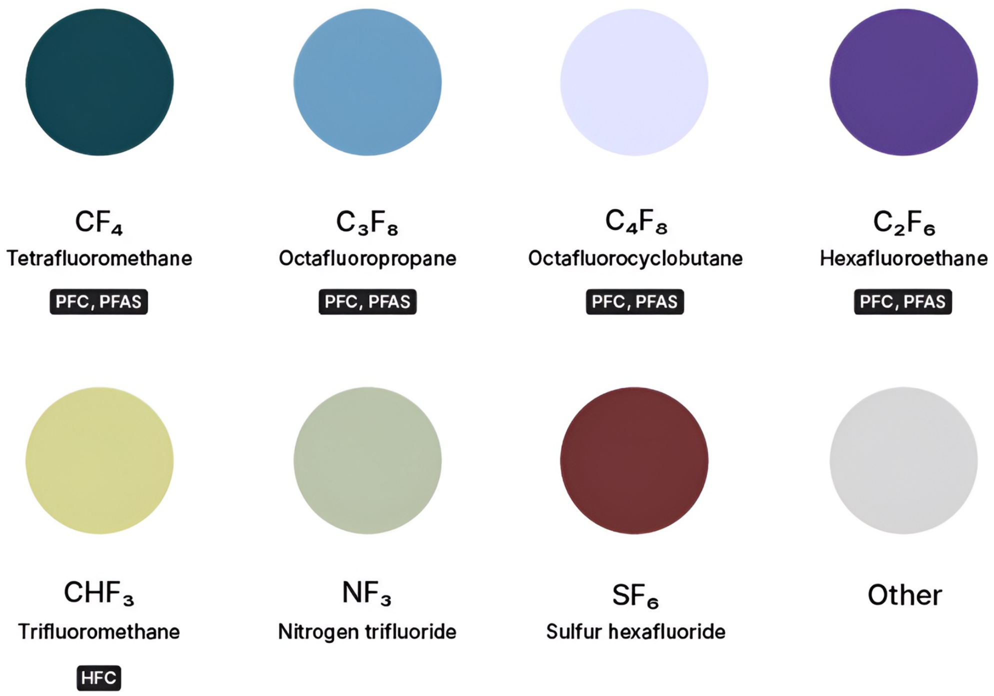

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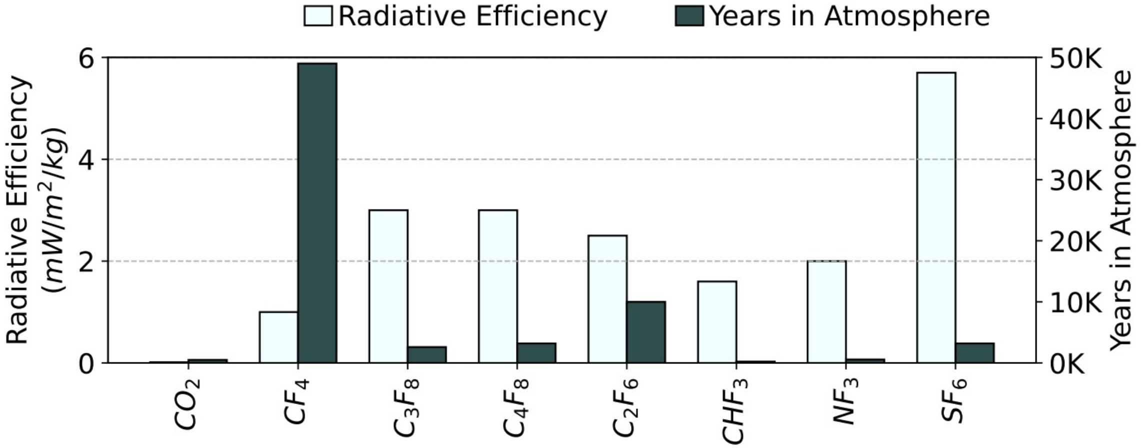

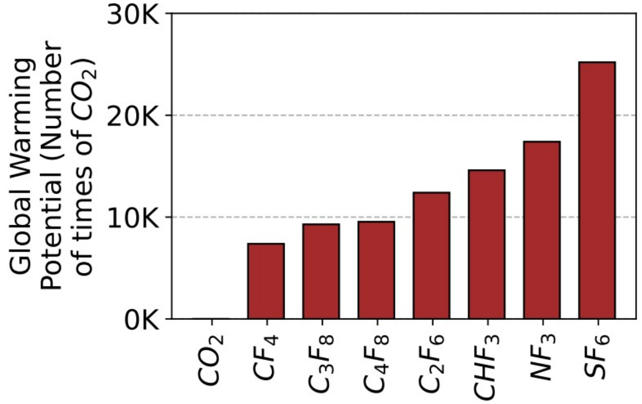

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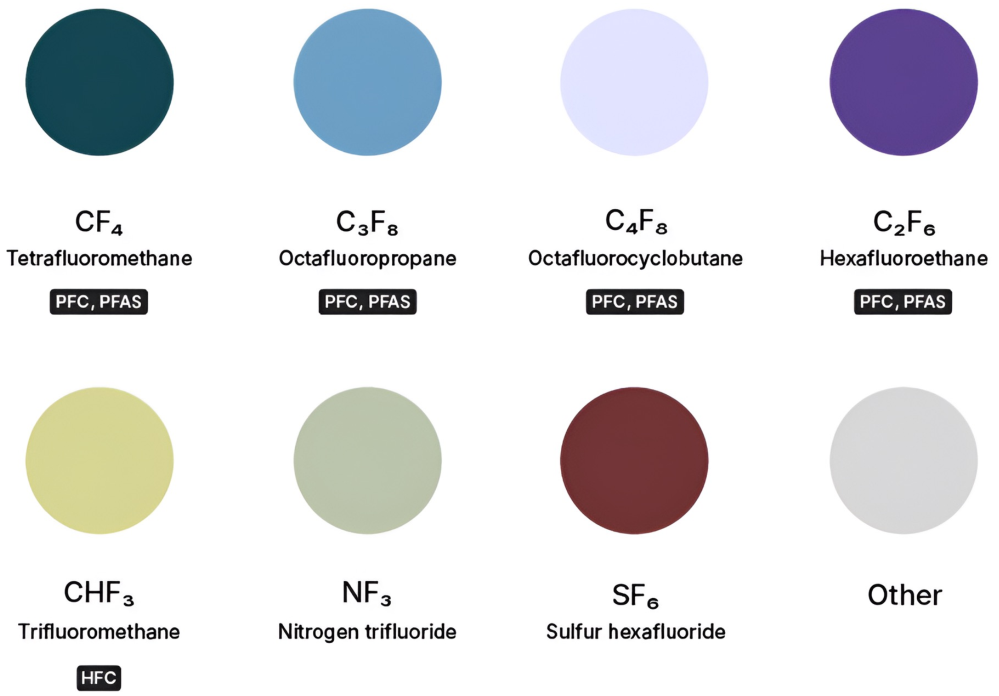
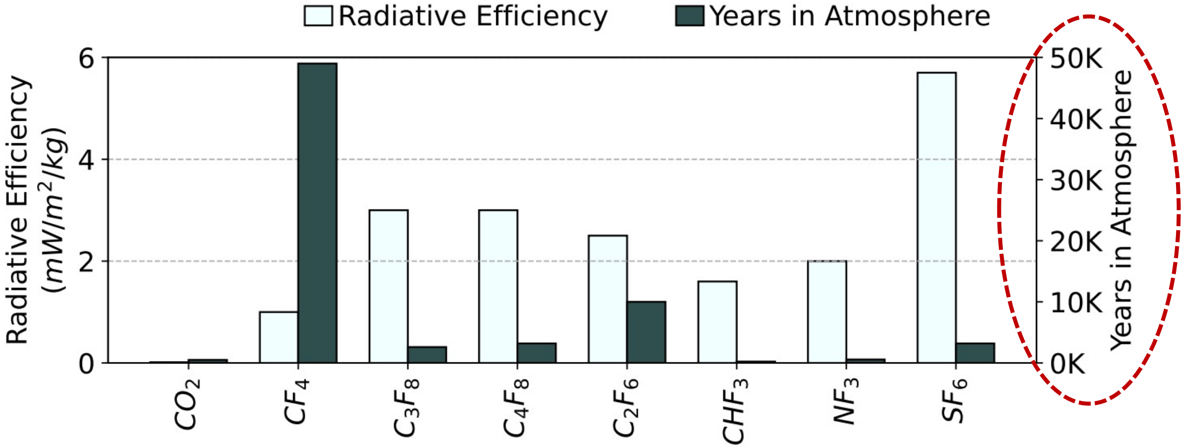
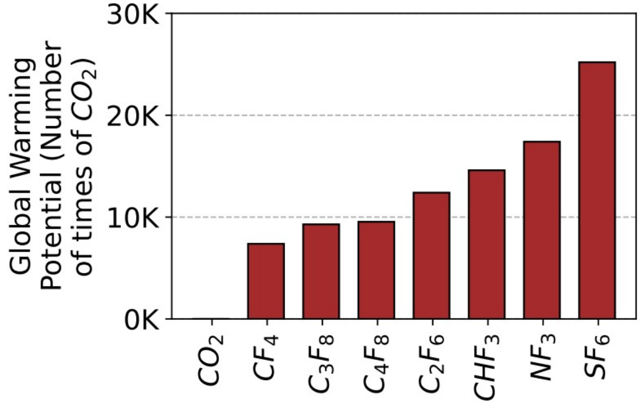


Forever chemicals lasts in environment for thousands of years and have severely high global warming potential – much higher than that of carbon dioxide

Lasts almost 'forever'!





Why should the computer systems community focus on forever chemicals?

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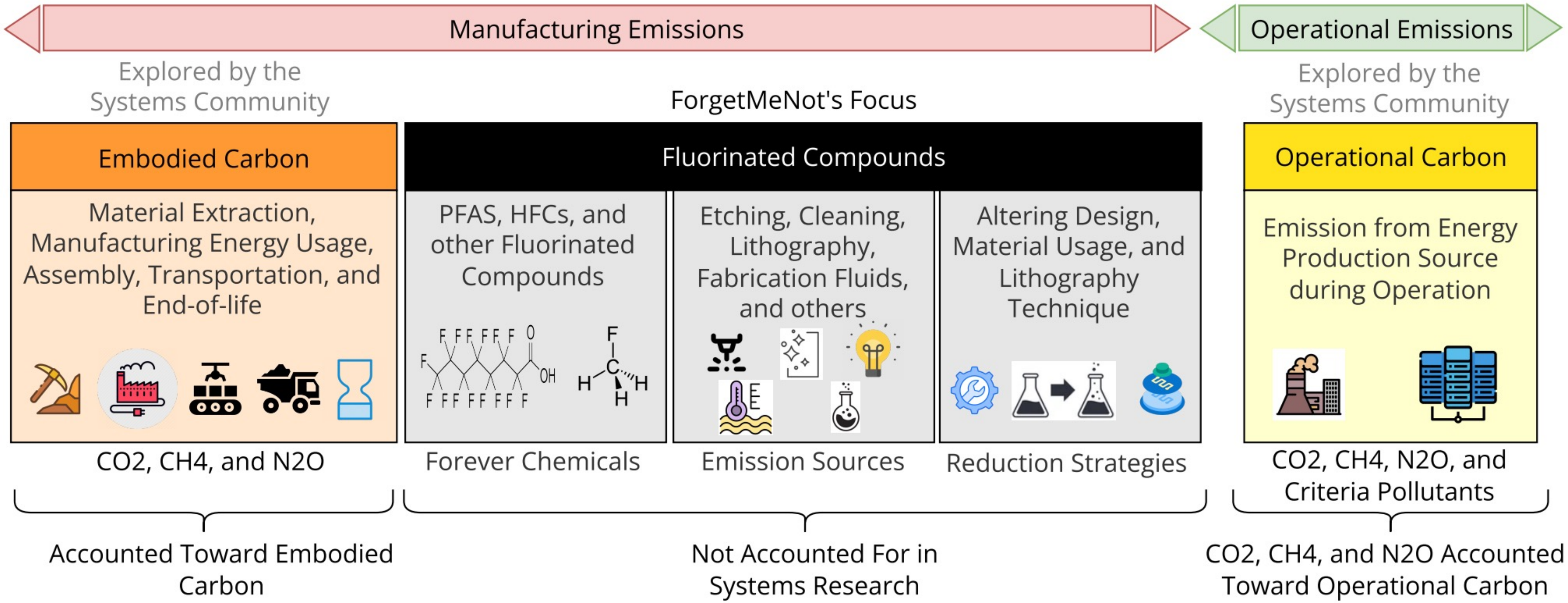
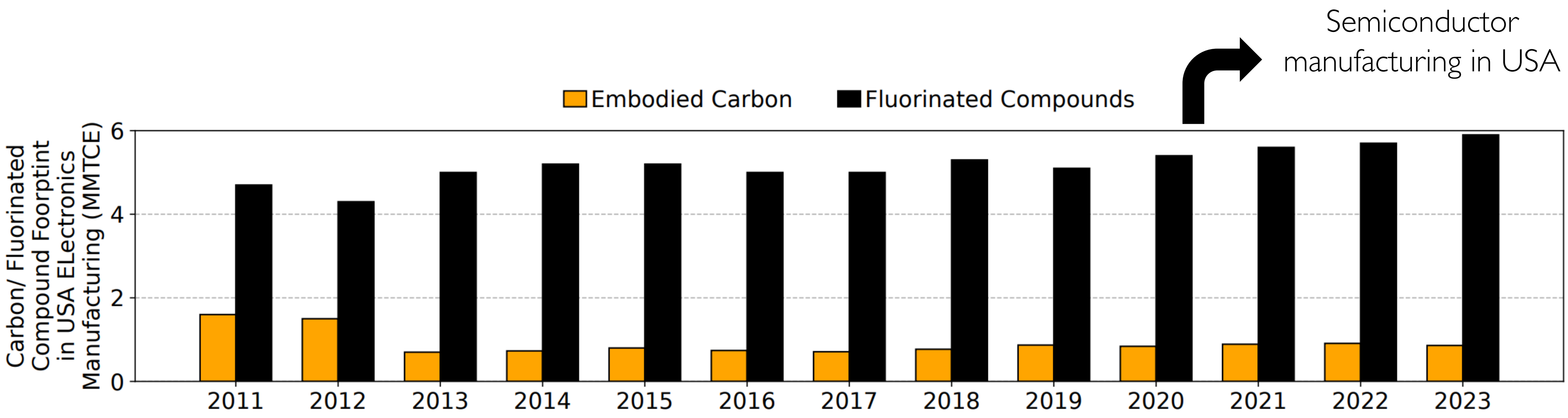


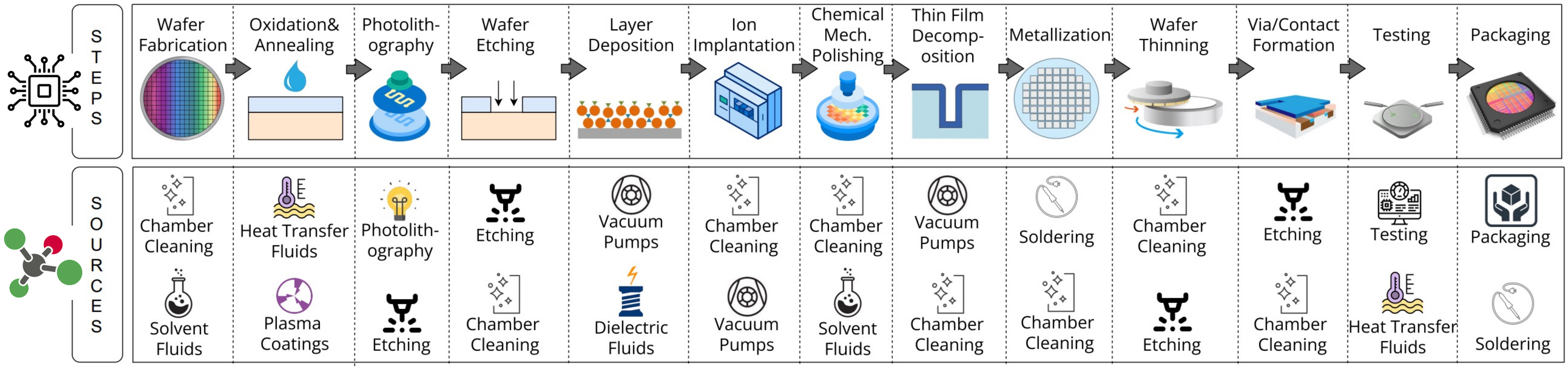
The forever chemicals are emitted in the atmosphere from fabrication facilities due to their use in various steps of semiconductor manufacturing; these emissions are not currently accounted for in systems research

We should actively try to reduce the emissions of fluorinated compounds (forever chemicals)



The global warming impact of forever chemical emissions from semiconductor manufacturing is much higher than that of embodied carbon and it is steadily rising over the years

Various steps of manufacturing contribute toward emissions of fluorinated compounds



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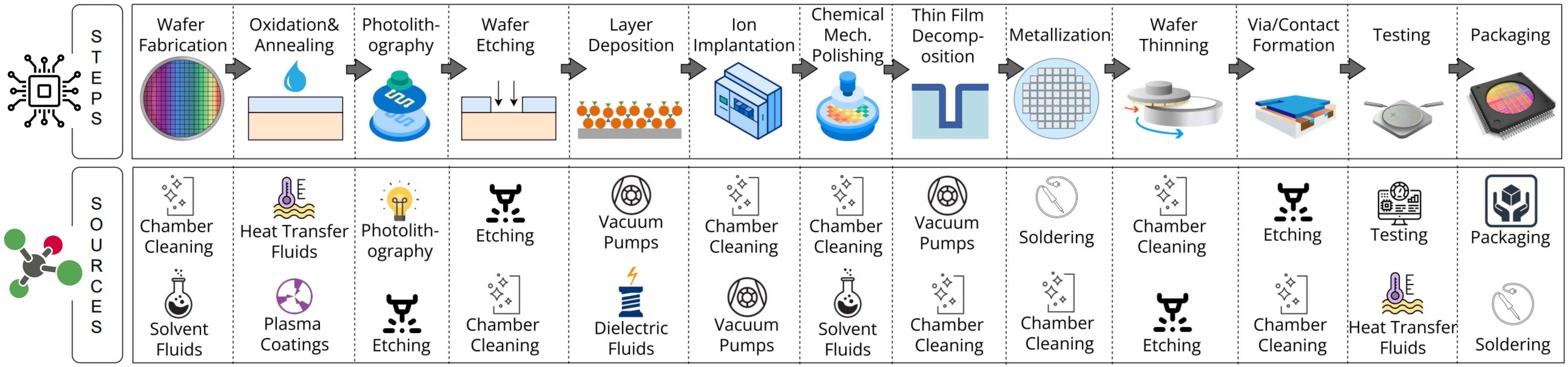
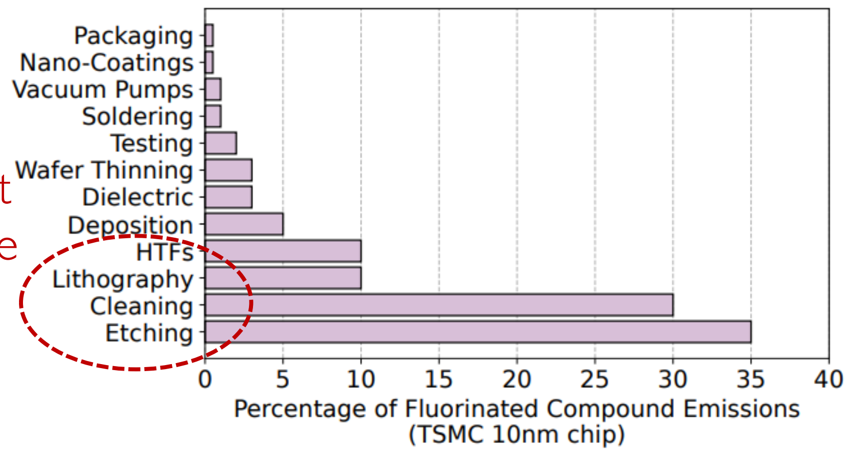


Etching, cleaning, lithography, and heat transfer fluids are the major emission sources



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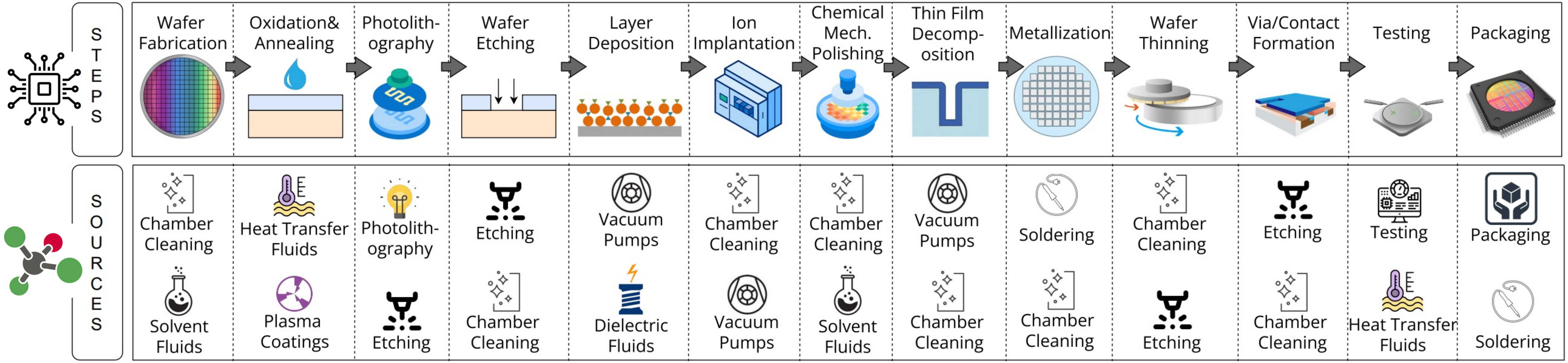

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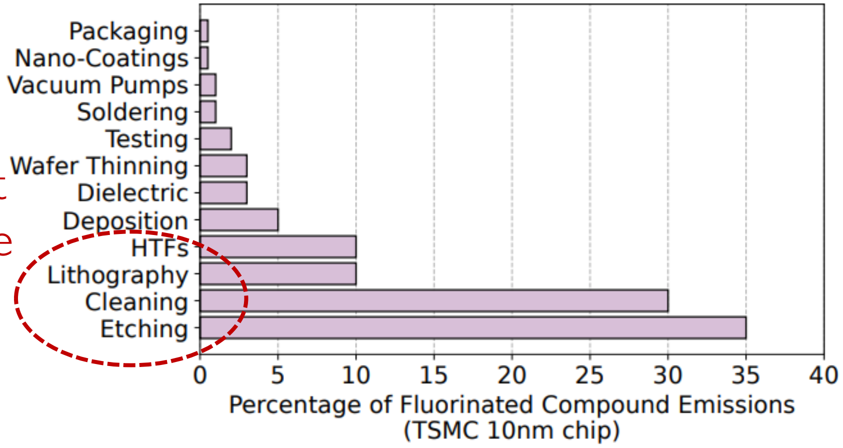
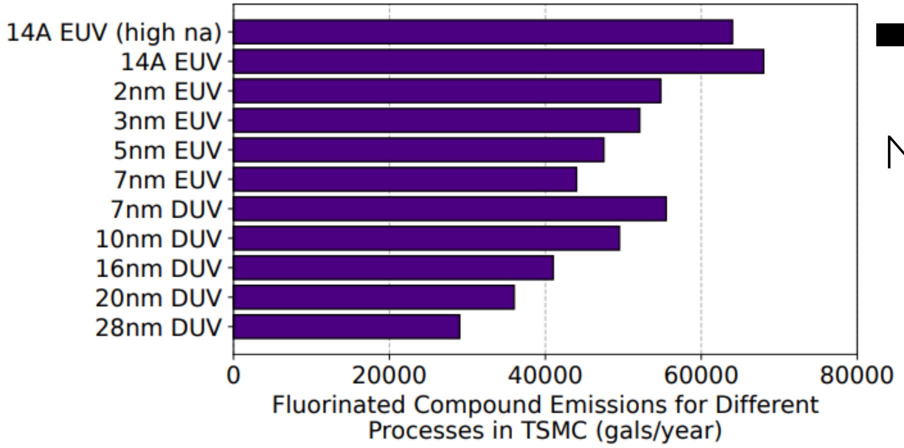
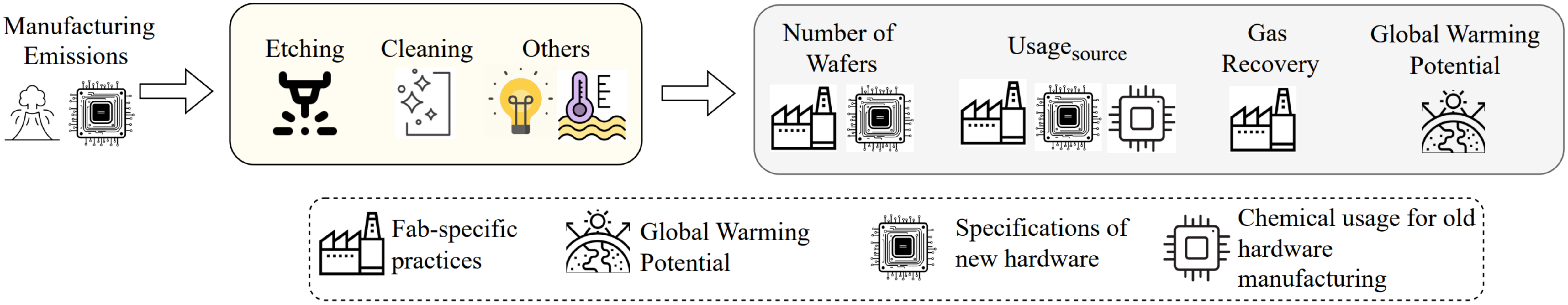




Newer technology tends to have higher emissions!

ForgetMeNot models emissions from various sources for targeted emissions control



ForgetMeNot models fluorinated compound emissions of new hardware by combining fabrication facility practices, reference hardware data, and new hardware specs. This helps manufacturers reduce emissions during fabrication and enables consumers to choose lower-emission hardware.

Usage of forever chemicals from each emission source during hardware manufacturing drives total emissions

Gas recovery factor

$$E_{\text{Total}} = \sum_i E_i = \sum_i N_{\text{Wafers}} \times \text{Usage}_i \times (1 - \eta_{\text{Rec}}) \times \text{GWP}_i$$

Global warming potential of the fluorinated compound used by the emission source

Fluorinated compound usage per wafer from emission source

$$N_{\text{Wafers}} = \frac{1}{\text{Yield} \times N_{\text{Dies per wafer}}} = \frac{1}{\text{Yield} \times \frac{A_{\text{Usable wafer}}}{A_{\text{Die}}}} = \frac{A_{\text{Die}}}{\text{Yield} \times A_{\text{Wafer}} \times \gamma_{\text{Usable}}} = \frac{A_{\text{Die}}}{\text{Yield} \times \pi (\frac{D_{\text{Wafer}}}{2})^2 \times \gamma_{\text{Usable}}}$$

Number of wafers needed per chip is calculated from die area (cores × area/core + cache × area/MB), wafer yield, and usable factor

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Global Warming Potential and fluorinated compound usage models vary for different emission sources

Etching

$$\text{Usage}_{\text{Etch}} = k_{\text{Etch}} \times A_{\text{Die}} \times N_{\text{Etch, ref}} \times \left(\frac{N_{\text{ref}}}{N}\right)^{\alpha_{\text{Etch}}} \times \phi_{\text{Lith}}$$

Major compounds: $CF4$, $C2F6$,$CHF3$
Combined GWP: 9928 gCo2eq

Usage scales with die area and etching steps, which increase sub-linearly with smaller nodes; EUV requires fewer steps than DUV

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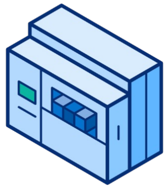
Usage scales with die area and etching steps, which increase sub-linearly with smaller nodes; EUV requires fewer steps than DUV

Cleaning frequency rises with smaller nodes to prevent defects; usage proportional to die area and cleaning steps

$$\text{Usage}_{\text{Clean}} = k_{\text{Clean}} \times A_{\text{Die}} \times N_{\text{Clean, ref}} \times \left(\frac{N_{\text{ref}}}{N}\right)^{\alpha_{\text{Clean}}} \times \phi_{\text{Lith}}$$

Major compounds: $NF3, SF6$
Combined GWP: 19550 gCo2eq



Chamber Cleaning

Etching, chamber cleaning, photolithography, and heat transfer fluids are the major sources of fluorinated compound emissions

Photolithography

$$\text{Usage}_{\text{Photo}} = k_{\text{Photo}} \times A_{\text{Die}} \times N_{\text{Photo, ref}} \times \left(\frac{N_{\text{ref}}}{N}\right)^{\alpha_{\text{Photo}}} \times \phi_{\text{Lith}}$$

Major compounds: $CHF3$, $C4F8$

Combined GWP: 12356 gCo2eq

Precise patterning at smaller nodes requires additional steps; DUV needs more masks/steps than EUV, increasing fluorinated compound usage

Etching, chamber cleaning, photolithography, and heat transfer fluids are the major sources of fluorinated compound emissions

Photolithography

$$\text{Usage}_{\text{Photo}} = k_{\text{Photo}} \times A_{\text{Die}} \times N_{\text{Photo, ref}} \times \left(\frac{N_{\text{ref}}}{N}\right)^{\alpha_{\text{Photo}}} \times \phi_{\text{Lith}}$$

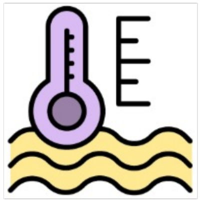
Major compounds: $CHF3$, $C4F8$
Combined GWP: 12356 gCo2eq

Precise patterning at smaller nodes requires additional steps; DUV needs more masks/steps than EUV, increasing fluorinated compound usage

Heat transfer fluid usage depends on processing time and chip TDP rather than die size; higher power chips need more cooling

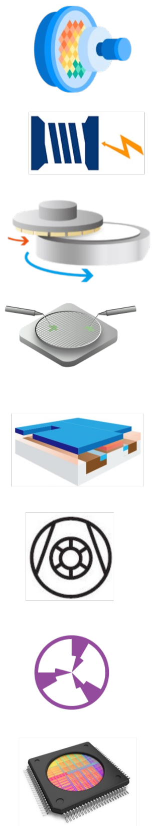
$$\text{Usage}_{\text{HTF}} = k_{\text{HTF}} \times t_{\text{process, ref}} \times \left(\frac{N_{\text{ref}}}{N}\right)^{\alpha_{\text{Time}}} \times \text{TDP}$$

Major compounds: $C3F8$, $C4F8$
Combined GWP: 9405 gCo2eq



Heat Transfer Fluids

Fluorinated compound usage across other sources can be expressed in terms of die area, technology node scaling, lithography type, and device characteristics



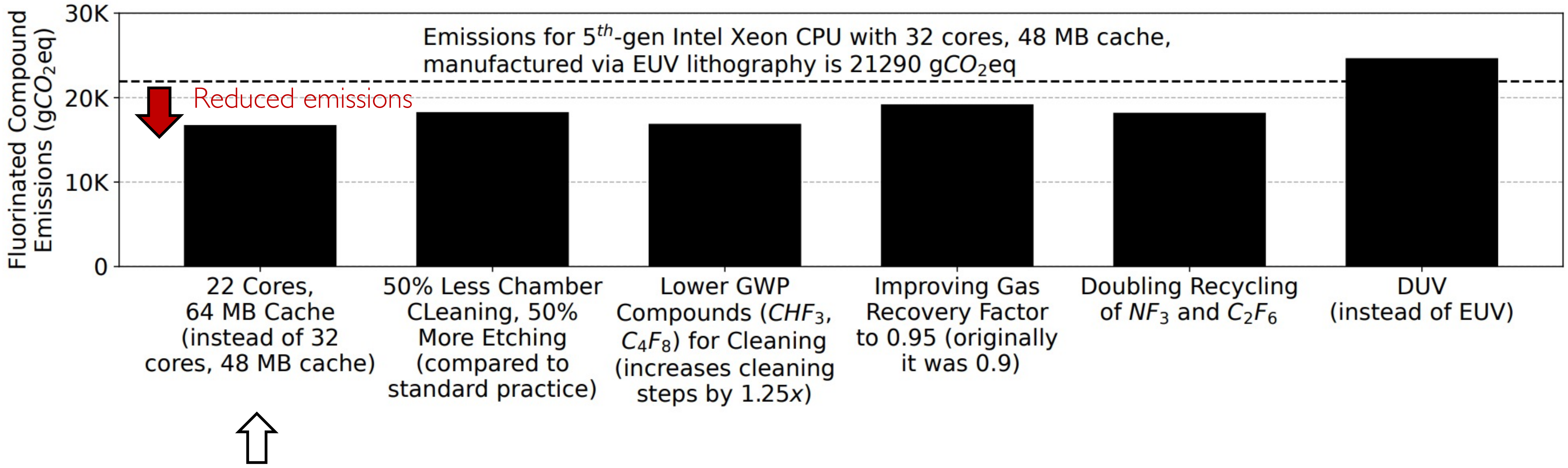
Source	Compounds	GWP	Fluorinated Compound Usage Model
Solvent Fluids	C_2F_6, NF_3	13140	$\text{Usage}_{\text{Solv}} = k_{\text{Solv}} \times A_{\text{die}} \times N_{\text{Solv Steps, ref}} \times \left(\frac{N_{\text{ref}}}{N}\right)^{\alpha_{\text{Solv}}}$
Dielectric Fluids	C_4F_8, CHF_3	9136	$\text{Usage}_{\text{Dielec}} = k_{\text{Dielec}} \times A_{\text{Die}}$
Wafer Thinning	SF_6, CF_4	17490	$\text{Usage}_{\text{Thin}} = k_{\text{Thin}} \times A_{\text{wafer}}$
Testing	C_3F_8, SF_6	16285	$\text{Usage}_{\text{Test}} = k_{\text{Test}} \times A_{\text{Die}} \times N_{\text{Test, ref}} \times \left(\frac{N_{\text{ref}}}{N}\right)^{\alpha_{\text{Test}}}$
Soldering	SF_6	17140	$\text{Usage}_{\text{VPS}} = k_{\text{VPS}} \times N_{\text{Solder, ref}} \times \left(\frac{\text{Package Size}}{\text{Package Size}_{\text{ref}}}\right)^{\alpha_{\text{VPS}}}$
Vacuum Pumps	CF_4, C_2F_6	9264	$\text{Usage}_{\text{Vacuum}} = k_{\text{Vacuum}} \times N_{\text{Pump, ref}} \times \left(\frac{N_{\text{ref}}}{N}\right)^{\alpha_{\text{Vacuum}}}$
Plasma Coatings	CHF_3, C_4F_8	11000	$\text{Usage}_{\text{PPNC}} = k_{\text{PPNC}} \times A_{\text{Die}} \times N_{\text{PPNC, ref}} \times \left(\frac{N_{\text{ref}}}{N}\right)^{\alpha_{\text{PPNC}}}$
Packaging	SF_6, C_3F_8	18600	$\text{Usage}_{\text{Pack}} = k_{\text{Pack}} \times \text{Package Size}$

ForgetMeNot model emissions from individual sources separately, enabling fine-grained analysis of manufacturing-related emissions

Parameter Type	**Parameters**
Fabrication facility-specific practices and emission sources	η_{Rec}, Yield, D_{Wafer}, γ_{Usable}, A_{Die}, k_{Etch}, k_{Clean}, k_{Photo}, k_{HTF}, k_{Solv}, k_{Dielec}, k_{Thin}, k_{Test}, k_{VPS}, k_{Vacuum}, k_{PPNC}, k_{Pack}, α_{Etch}, α_{Clean}, α_{Photo}, α_{Time}, α_{Solv}, α_{Test}, α_{VPS}, α_{Vacuum}, α_{PPNC}, ϕ_{Lith}
Reference older generation hardware	N_{ref}, $N_{\text{Etch, ref}}$, $N_{\text{Clean, ref}}$, $N_{\text{Photo, ref}}$, $t_{\text{process, ref}}$, $N_{\text{Solv Steps, ref}}$, $N_{\text{Test, ref}}$, $N_{\text{Solder, ref}}$, $N_{\text{Pump, ref}}$, Package Size_{ref}
New hardware specifications	N, TDP, Package Size, Cores, Cache, Memory Size, Storage Size

Fab-specific practices and base usage coefficients derived from public emissions data (TRI/EPA) and manufacturing literature, calibrated using well-documented older generation hardware (e.g., 14nm CPUs) as reference baseline for scaling to newer designs

How can fabrication facilities use ForgetMeNot to reduce emissions?



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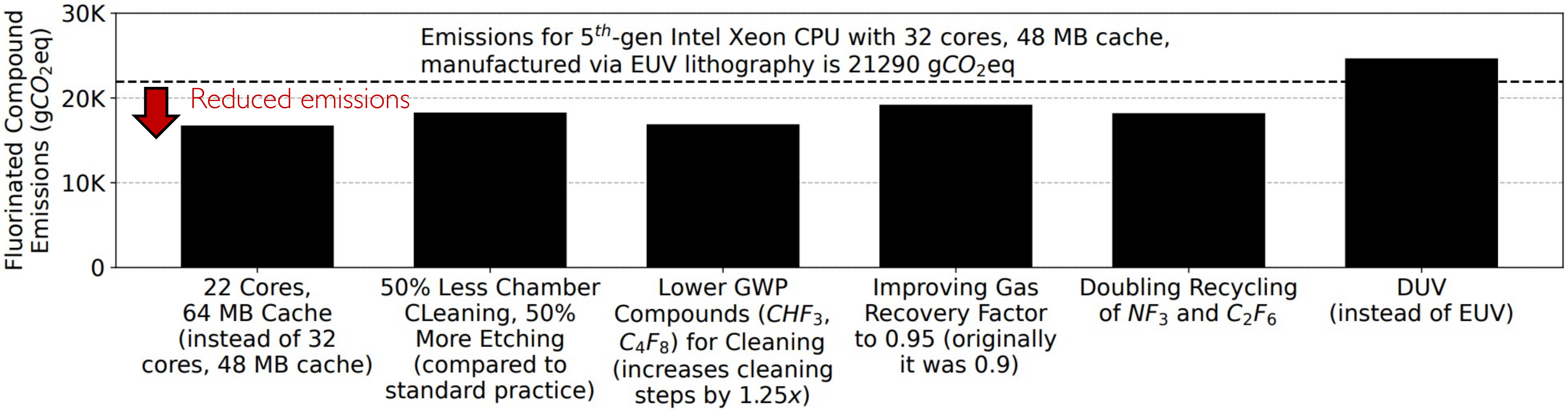
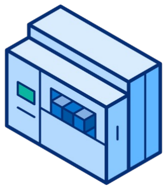


Etching

Combined GWP: 9928 gCo2eq



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Combined GWP: 19550 gCo2eq

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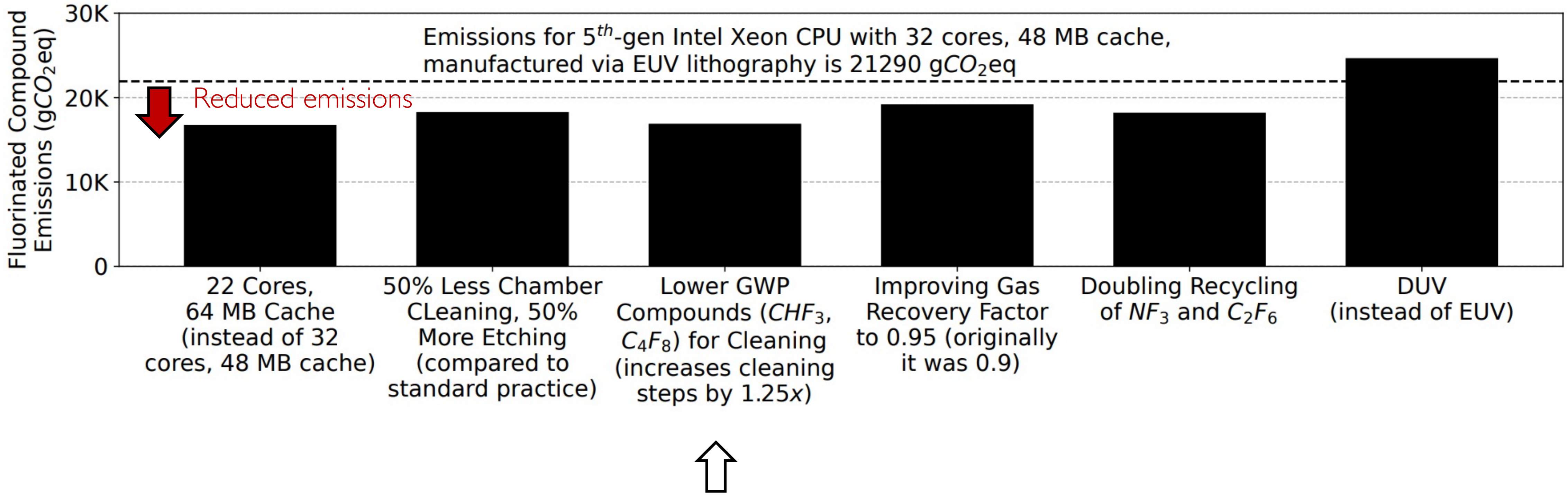

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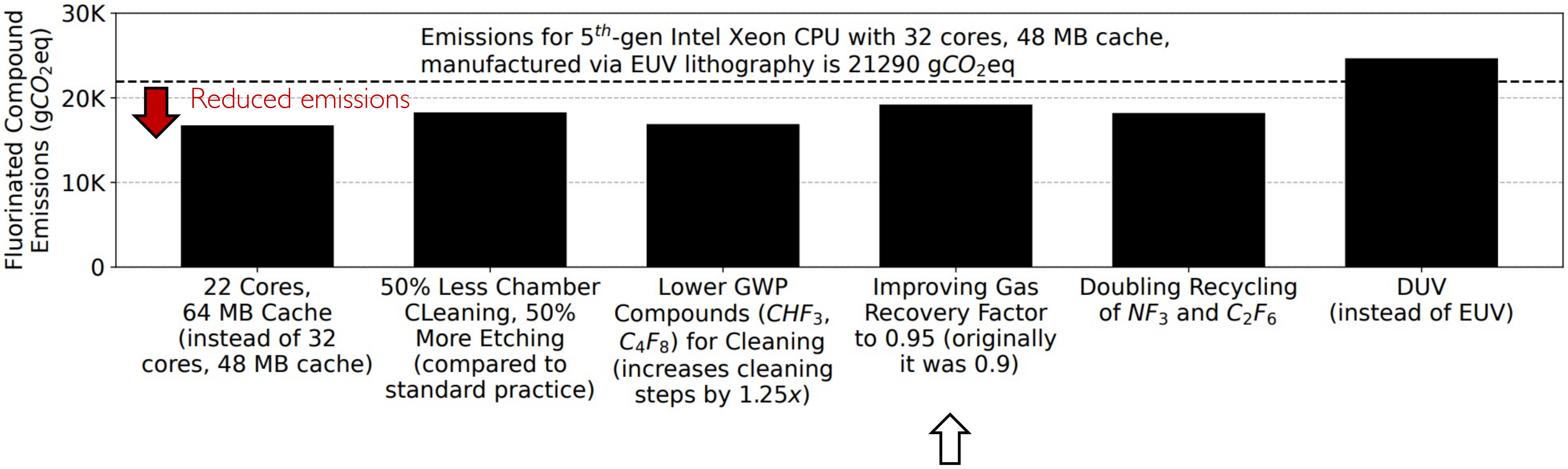

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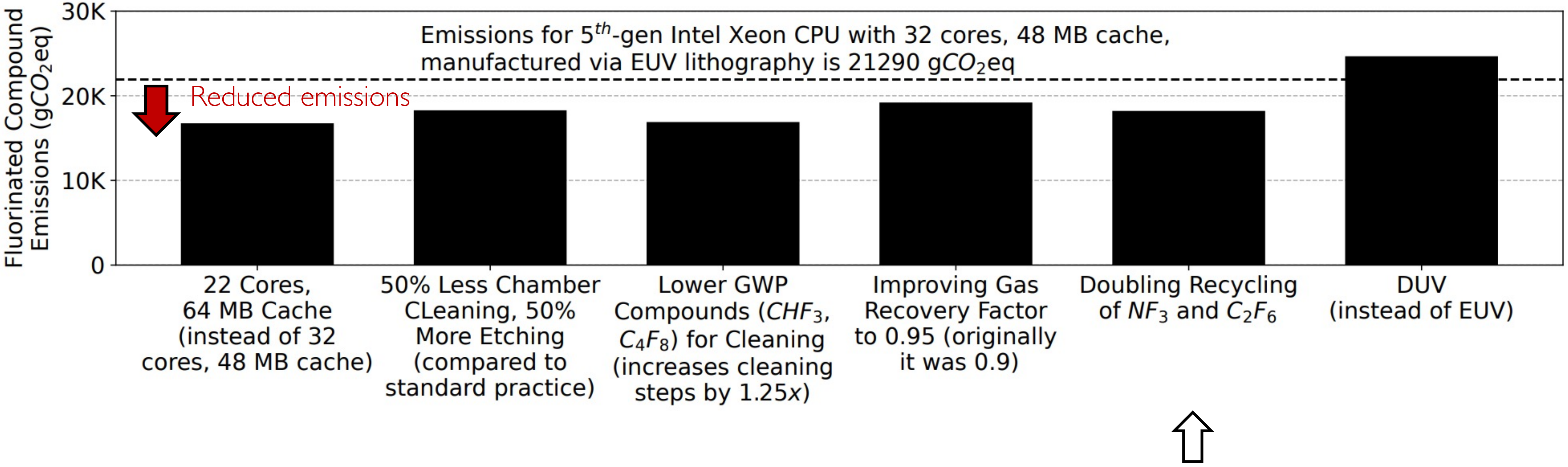

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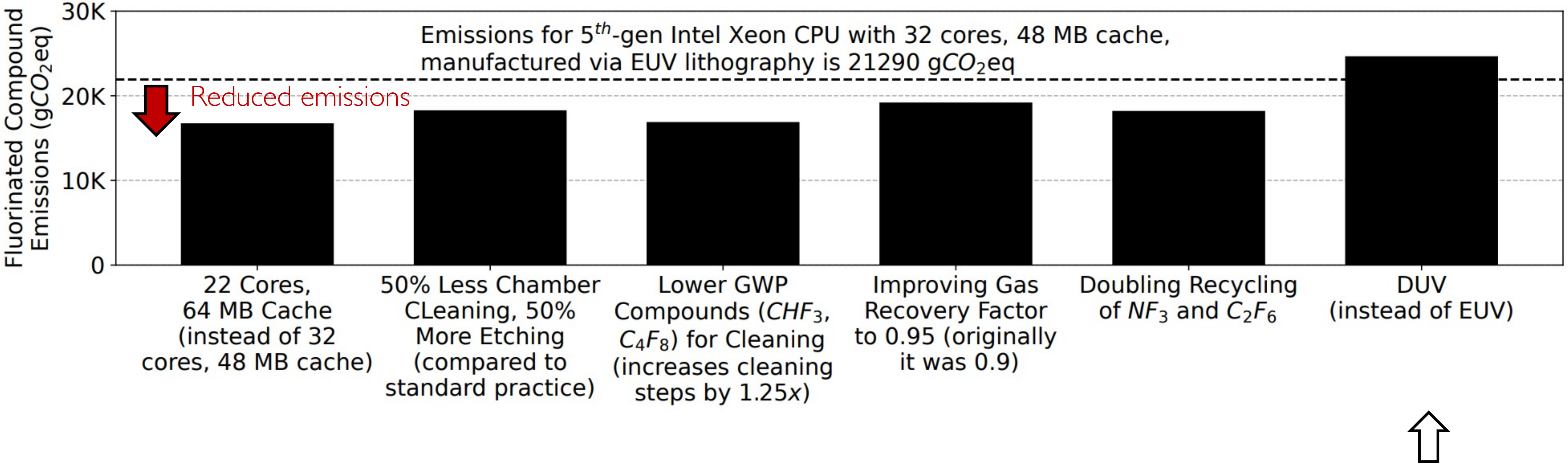

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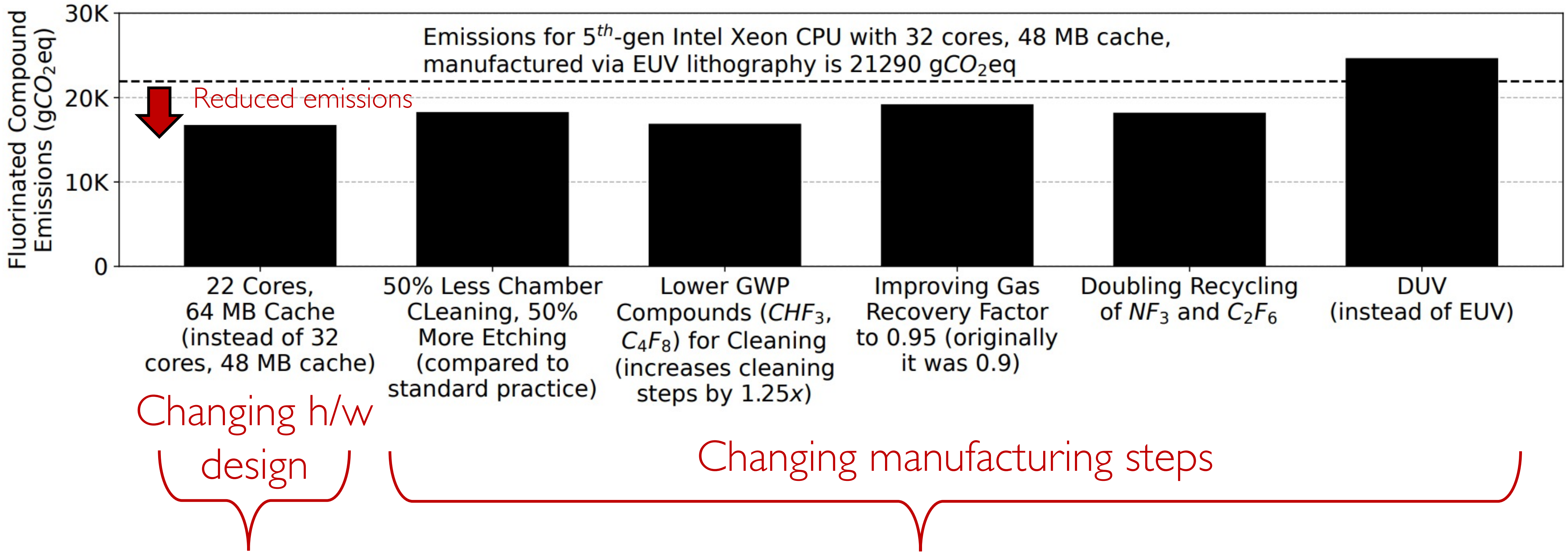
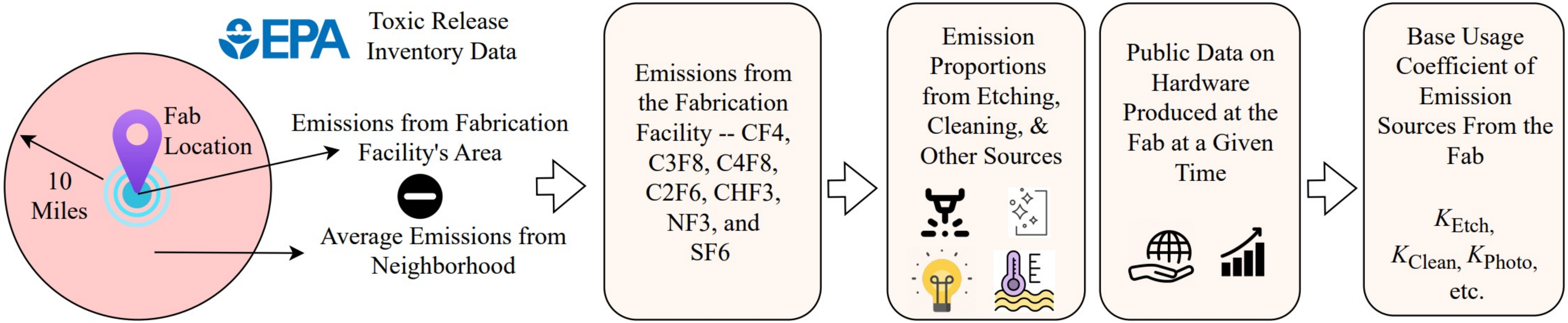


Fabrication facilities can use ForgetMeNot to model emissions from different sources and make choices of hardware design and manufacturing steps to reduce emissions.

ForgetMeNot develops methodology to estimate emission parameters from fabrication facility

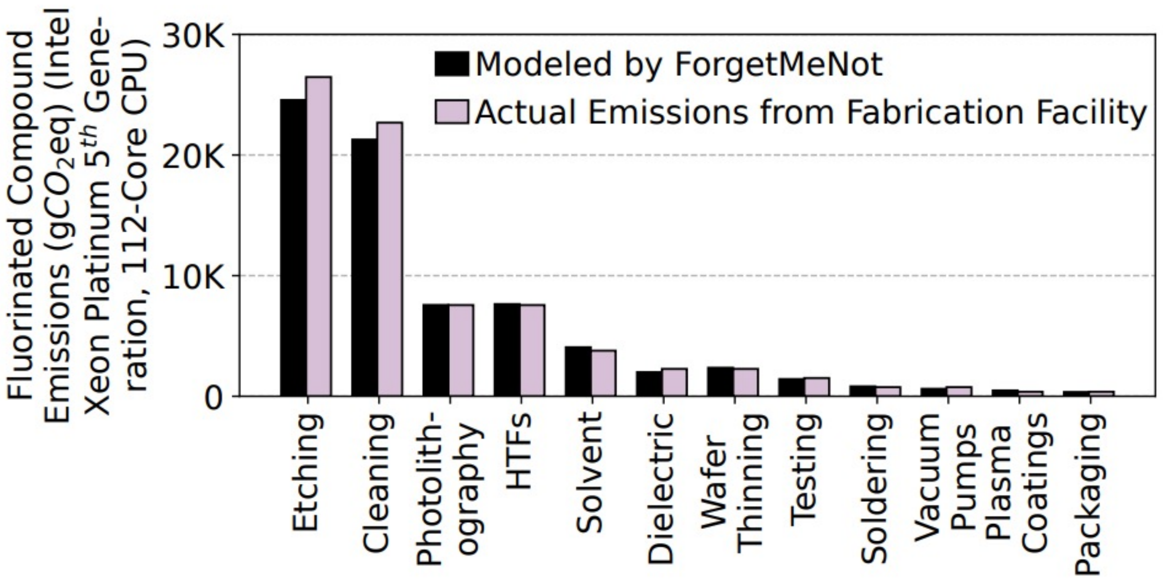


US Environment Agency's Toxic Release Inventory (TRI) data

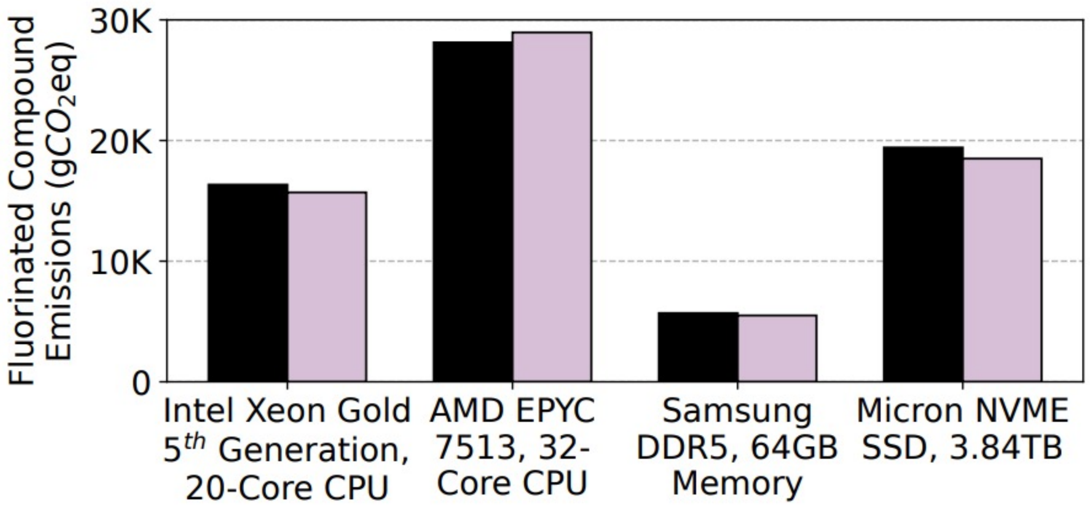
Industry datasets provide manufacturing process parameters: IEEE IRDS, Semiconductor manufacturing process (SECOM) data, and Advanced Semiconductor Supply Chain Dataset

ForgetMeNot uses publicly-available data to estimate the fabrication specific parameters, like the base usage coefficients, that is used in its emission modeling

ForgetMeNot's modeled emissions closely match actual fabrication facility emission measurements



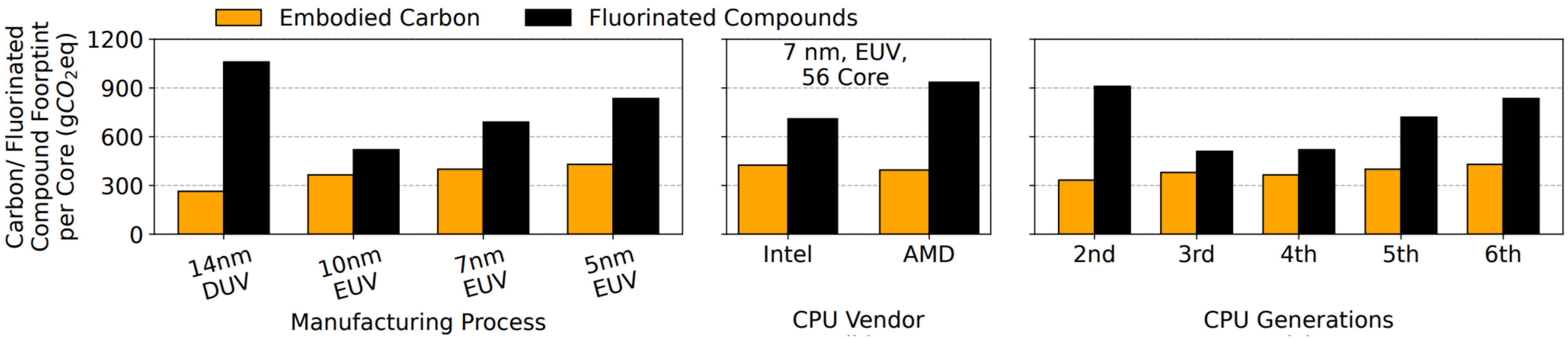
Accurate modeling for individual emission sources in the manufacturing process



Accurate modeling of the total emission for manufacturing complete hardware

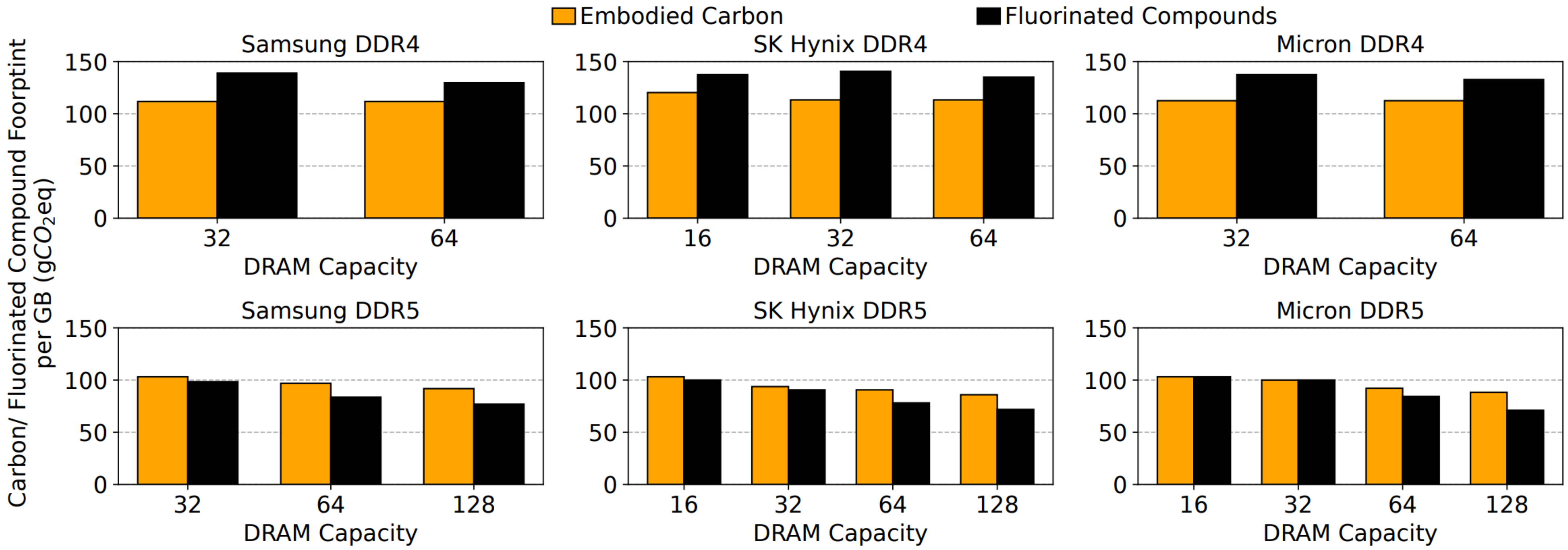
ForgetMeNot can effectively generalize modeling across different fabrication facilities and hardware, modeling emissions based on the process parameters and facility-specific practices

Fluorinated compound emission trends across manufacturing technologies, vendors, & CPU generations



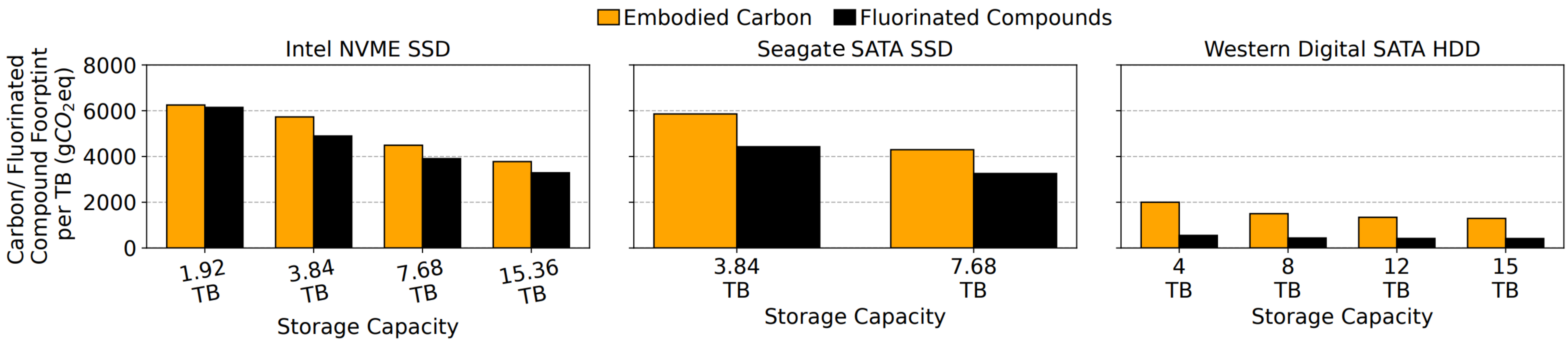
Fluorinated compounds consistently exceed embodied carbon across manufacturing processes, vendors, and generations. Newer nodes and generations increase both emission types, while EUV lithography reduces fluorinated emissions compared to DUV

DDR5 memory delivers both performance and sustainability gains over DDR4



DDR5 modules show lower carbon and fluorinated emissions per GB than DDR4 across all capacities and vendors. Unlike CPUs, fluorinated emissions are comparable to embodied carbon in DRAM manufacturing.

SSDs dominate environmental footprint of servers over memory and compute components



SSDs contribute the largest share of server emissions, exceeding CPU and memory combined. HDDs offer 66-87% lower emissions than SSDs, while higher capacities reduce per-TB footprint for all storage types

Service providers can use ForgetMeNot to estimate emissions and procure sustainable server configurations

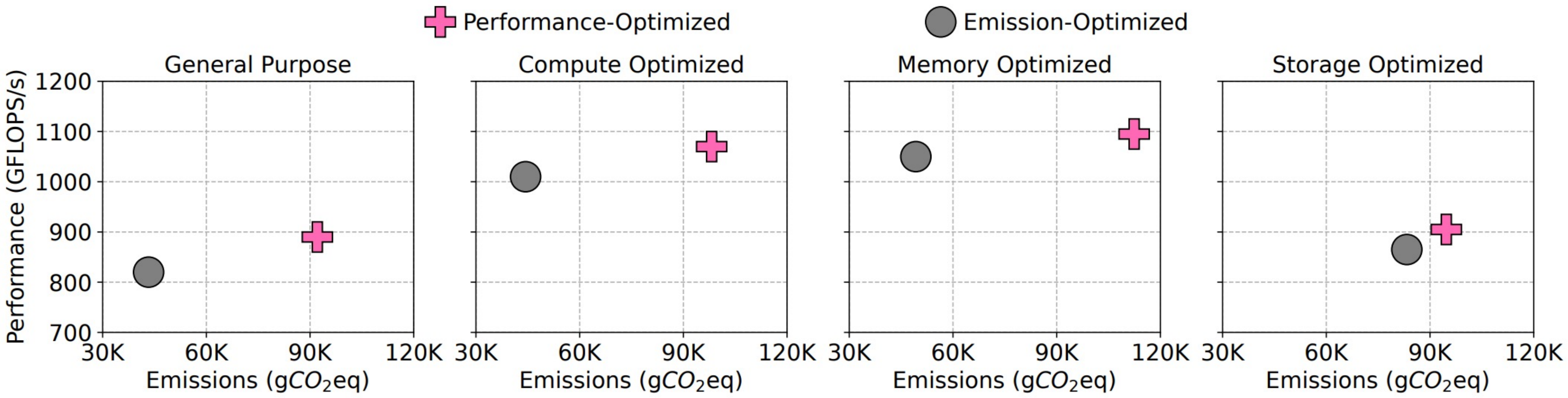
	General Purpose	Compute Optimized	Memory Optimized	Storage Optimized
Highest Emission	175019 gCO_2eq	175019 gCO_2eq	175019 gCO_2eq	175019 gCO_2eq
Median Emission	96741 gCO_2eq	98189 gCO_2eq	102389 gCO_2eq	114725 gCO_2eq
Lowest Emission	43300 gCO_2eq	44360 gCO_2eq	49260 gCO_2eq	83300 gCO_2eq
Lowest Emission Hardware	5^{th}-gen Intel Xeon Gold with 20 cores, SK Hynix 32 GB DDR5 DRAM, Seagate 8TB HDD	4^{th}-gen Intel Xeon Gold with 24 cores, SK Hynix 32 GB DDR5 DRAM, Seagate 8TB HDD	4^{th}-gen Intel Xeon Gold with 24 cores, SK Hynix 64GB DDR5 DRAM, Seagate 8TB HDD	5^{th}-gen Intel Xeon Gold with 20 cores, SK Hynix 32GB DDR5 DRAM, Samsung 7.68TB NVMe SSD

Analysis spans 9,300+ server configurations: multiple CPU generations (Intel Xeon/AMD EPYC), memory types (DDR4/DDR5), and storage options (SSDs/HDDs)

Datacenter procurement of low-emission hardware creates market demand that incentivizes fabs to prioritize sustainable manufacturing over high-emission components

Performance vs. Emissions Trade-off: Diminishing Returns at High Environmental Cost

Linpack HPL benchmarks



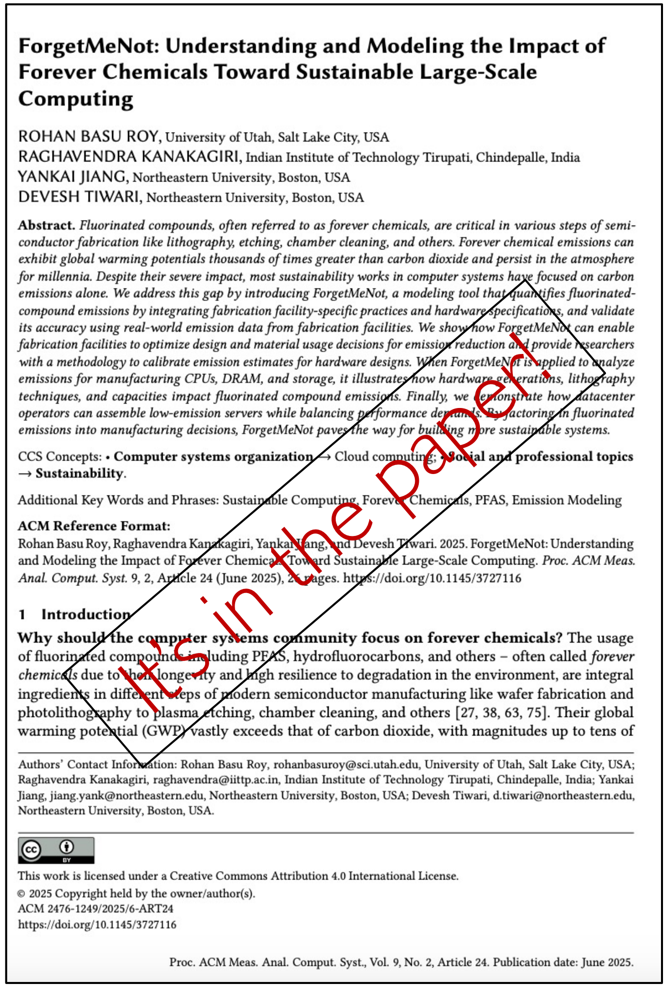
Performance-optimized servers offer only 8 -12% throughput improvement but increase emissions by 50%+. The smallest performance gains come at the highest environmental cost, making emission-optimized configurations the sustainable choice for most workloads.

ForgetMeNot reveals the full sustainability picture that carbon-only accounting misses

Metric	**AMD EPYC 7713**	**Intel Xeon Platinum 8481Y**	**AMD EPYC 7543**	**Intel Xeon Platinum 8492Y**	**AMD EPYC 7551**
Ranking based on embodied carbon	2	1	4	3	5
Ranking based on total $CO_2 - eq$ **emission (embodied carbon and fluorinated compound)**	4	2	5	1	3
Ranking based on performance (TFLOPs)	1	4	3	5	2

Server rankings change significantly when fluorinated compounds are included. Intel 8481Y ranks best for embodied carbon alone, but Intel 8492Y has lowest total emissions. Carbon-only modeling tools like may lead to suboptimal sustainability choices.

ForgetMeNot models forever chemical emissions in chip manufacturing, enabling sustainable hardware decisions



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ROHAN BASU ROY, University of Utah, Salt Lake City, USA
RAGHAVENDRA KANAKAGIRI, Indian Institute of Technology Tirupati, Chindepalle, India
YANKAI JIANG, Northeastern University, Boston, USA
DEVESH TIWARI, Northeastern University, Boston, USA

Abstract. *Fluorinated compounds, often referred to as forever chemicals, are critical in various steps of semiconductor fabrication like lithography, etching, chamber cleaning, and others. Forever chemical emissions can exhibit global warming potentials thousands of times greater than carbon dioxide and persist in the atmosphere for millennia. Despite their severe impact, most sustainability works in computer systems have focused on carbon emissions alone. We address this gap by introducing ForgetMeNot, a modeling tool that quantifies fluorinated-compound emissions by integrating fabrication facility-specific practices and hardware specifications, and validate its accuracy using real-world emission data from fabrication facilities. We show how ForgetMeNot can enable fabrication facilities to optimize design and material usage decisions for emission reduction and provide researchers with a methodology to calibrate emission estimates for hardware designs. When ForgetMeNot is applied to analyze emissions for manufacturing CPUs, DRAM, and storage, it illustrates how hardware generations, lithography techniques, and capacities impact fluorinated compound emissions. Finally, we demonstrate how datacenter operators can assemble low-emission servers while balancing performance demands. By factoring in fluorinated emissions into manufacturing decisions, ForgetMeNot paves the way for building more sustainable systems.*

CCS Concepts: • **Computer systems organization** → Cloud computing; • **Social and professional topics** → **Sustainability**.

Additional Key Words and Phrases: Sustainable Computing, Forever Chemicals, PFAS, Emission Modeling

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1 Introduction

Why should the computer systems community focus on forever chemicals? The usage of fluorinated compounds including PFAS, hydrofluorocarbons, and others – often called *forever chemicals* due to their longevity and high resilience to degradation in the environment, are integral ingredients in different steps of modern semiconductor manufacturing like wafer fabrication and photolithography to plasma etching, chamber cleaning, and others [27, 38, 63, 75]. Their global warming potential (GWP) vastly exceeds that of carbon dioxide, with magnitudes up to tens of

Authors' Contact Information: Rohan Basu Roy, rohanbasuroy@sci.utah.edu, University of Utah, Salt Lake City, USA; Raghavendra Kanakagiri, raghavendra@iittp.ac.in, Indian Institute of Technology Tirupati, Chindepalle, India; Yankai Jiang, jiang.yank@northeastern.edu, Northeastern University, Boston, USA; Devesh Tiwari, d.tiwari@northeastern.edu, Northeastern University, Boston, USA.

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Derivation of fluorinated compound usage per manufacturing step

Methodologies to determine fabrication facility-specific parameters from public data

Guides datacenter operators in navigating emission-performance trade-offs

ForgetMeNot models emissions from fabrication to final testing of hardware, enabling targeted emission control