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Towards Carbon Neutrality: Effect of Gas Abatement Selection and Destruction Efficiency

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Subfab Environmental Footprint

- The subfab is the final repository for all gases used in the semiconductor manufacturing process

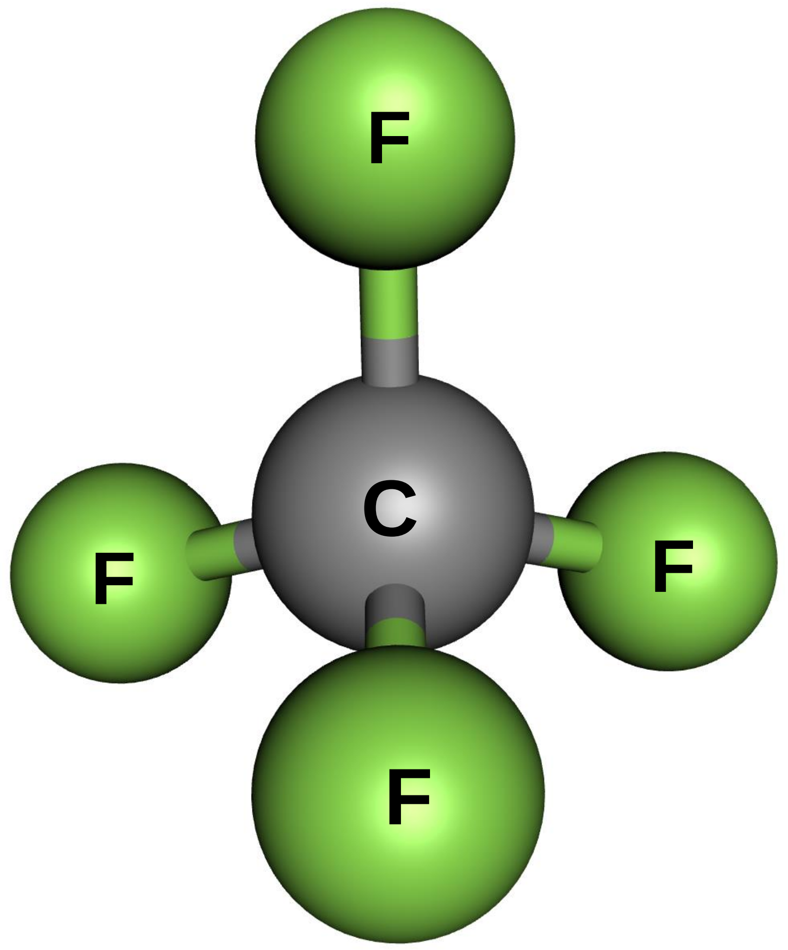
- Many classes of gasses are used during processing and have different health hazards
  - Hydrides
    - SiH_4, AsH_3, PH_3 – profoundly toxic and pyrophoric (spontaneously combusts in presence of O_2)
  - Metal Chlorides
    - $TiCl_4$, $TaCl_5$ – corrosive, reacts with air to form dust and HCl
  - PFCs (perfluorinated compounds)
    - CF_4, NF_3, etc. – relatively stable and inert at room temperatures

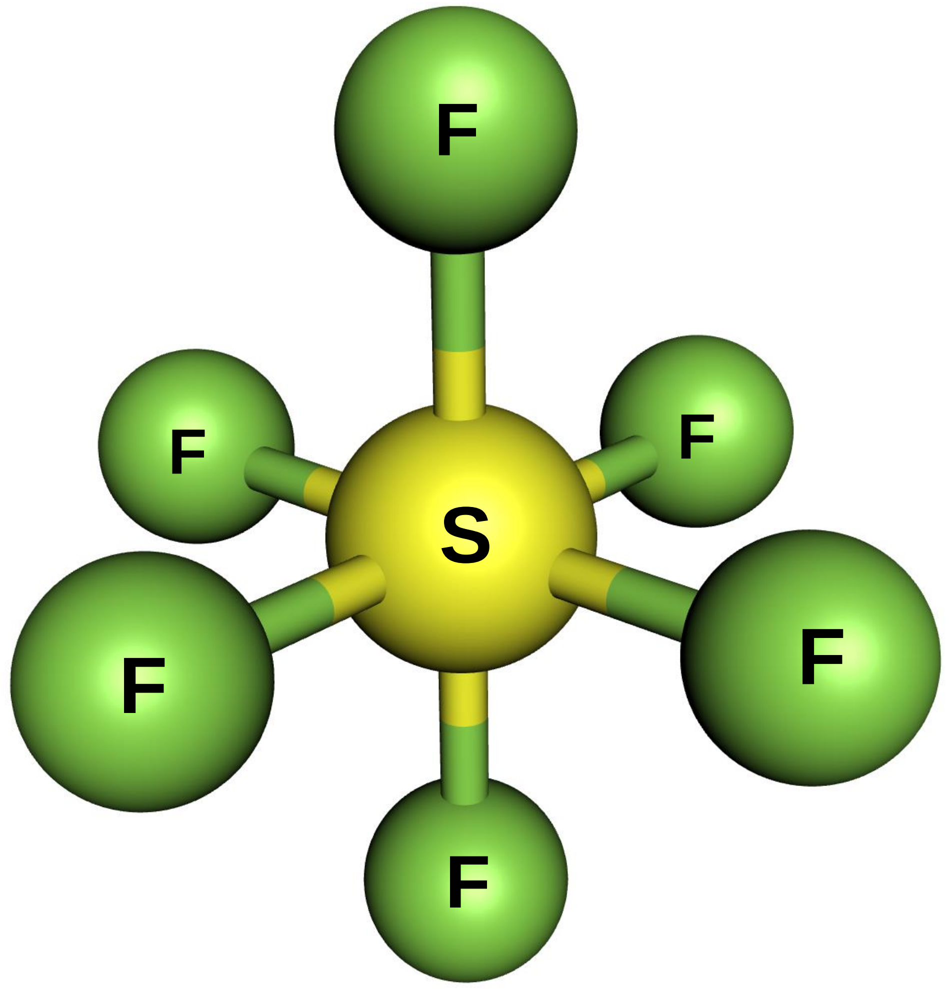
Hydride and Metal Chloride Chemistry

- Non-stable
  - Undergo exothermic reaction with low activation energies
- Will react with many compounds under ordinary conditions
  - Can easily be wet or dry scrubbed
- Easily burned in a flame, plasma or thermal system
- Can use these compounds’ reactive chemistry against them to easily destroy them

PFC Chemistry

- Highly stable, non-toxic gases
- Do not react with most reagents under ordinary conditions
  - Can't readily be wet or dry scrubbed
  - Chemical inertness due to high S-F / C-F bond energy (Thermodynamics)
- Complete screening of the sulphur / carbon atom by fluorine atoms (Kinetics)
- Can only be destroyed with sophisticated burner or plasma (either pre or post-pump) technology and create toxic HF upon destruction

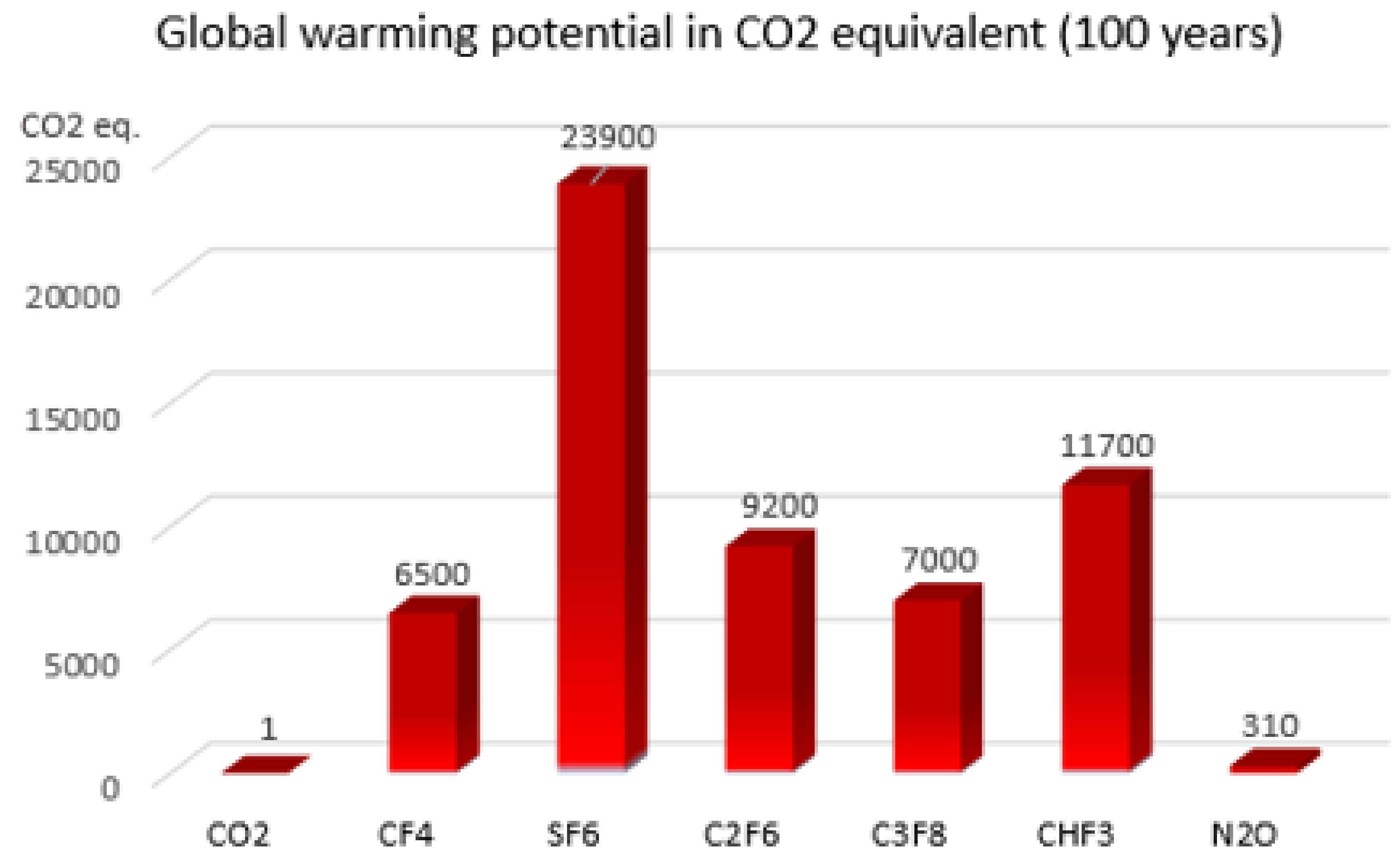




Why Abate PFCs?

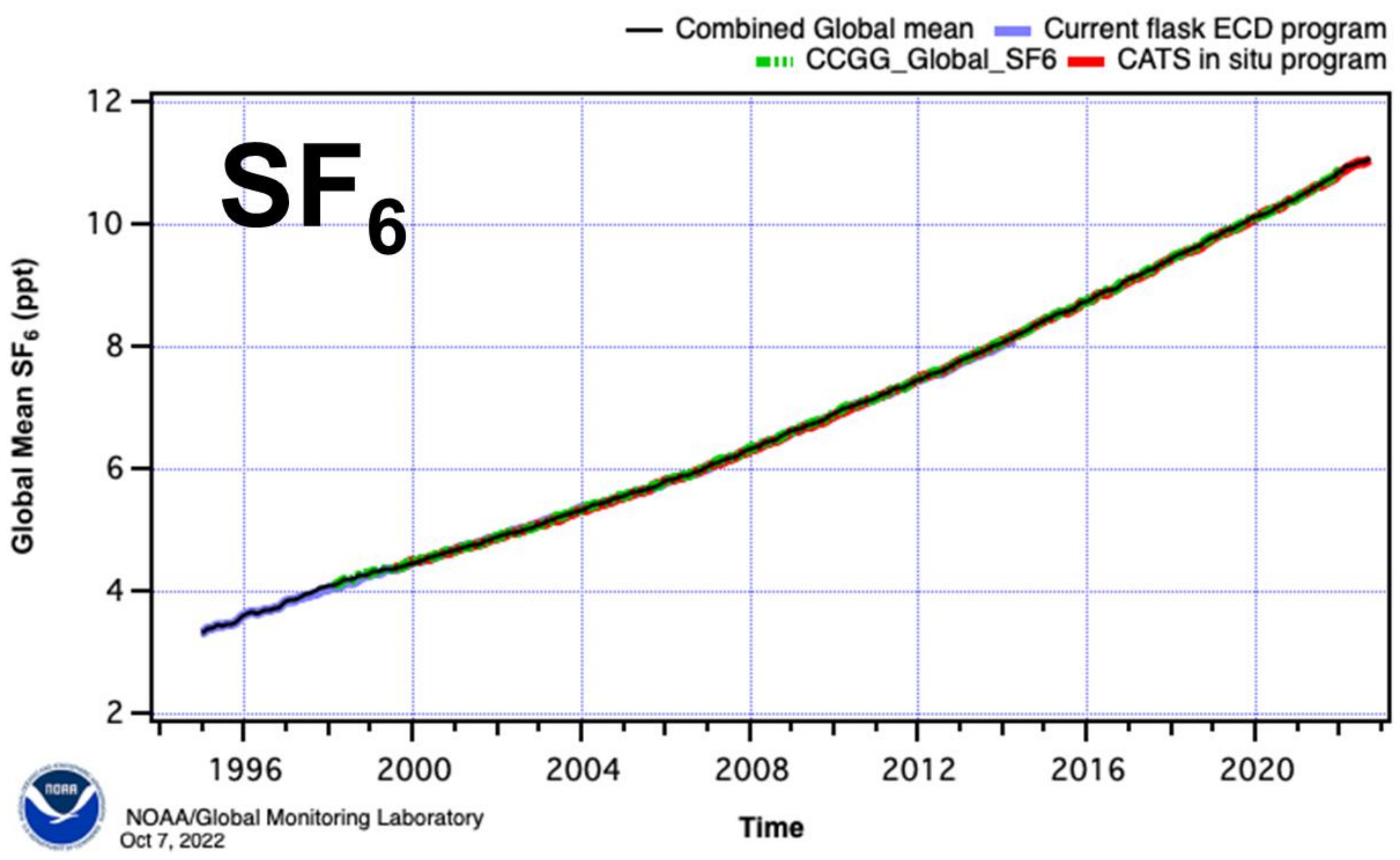
While stable, PFC gases are potent global warmers that should be destroyed

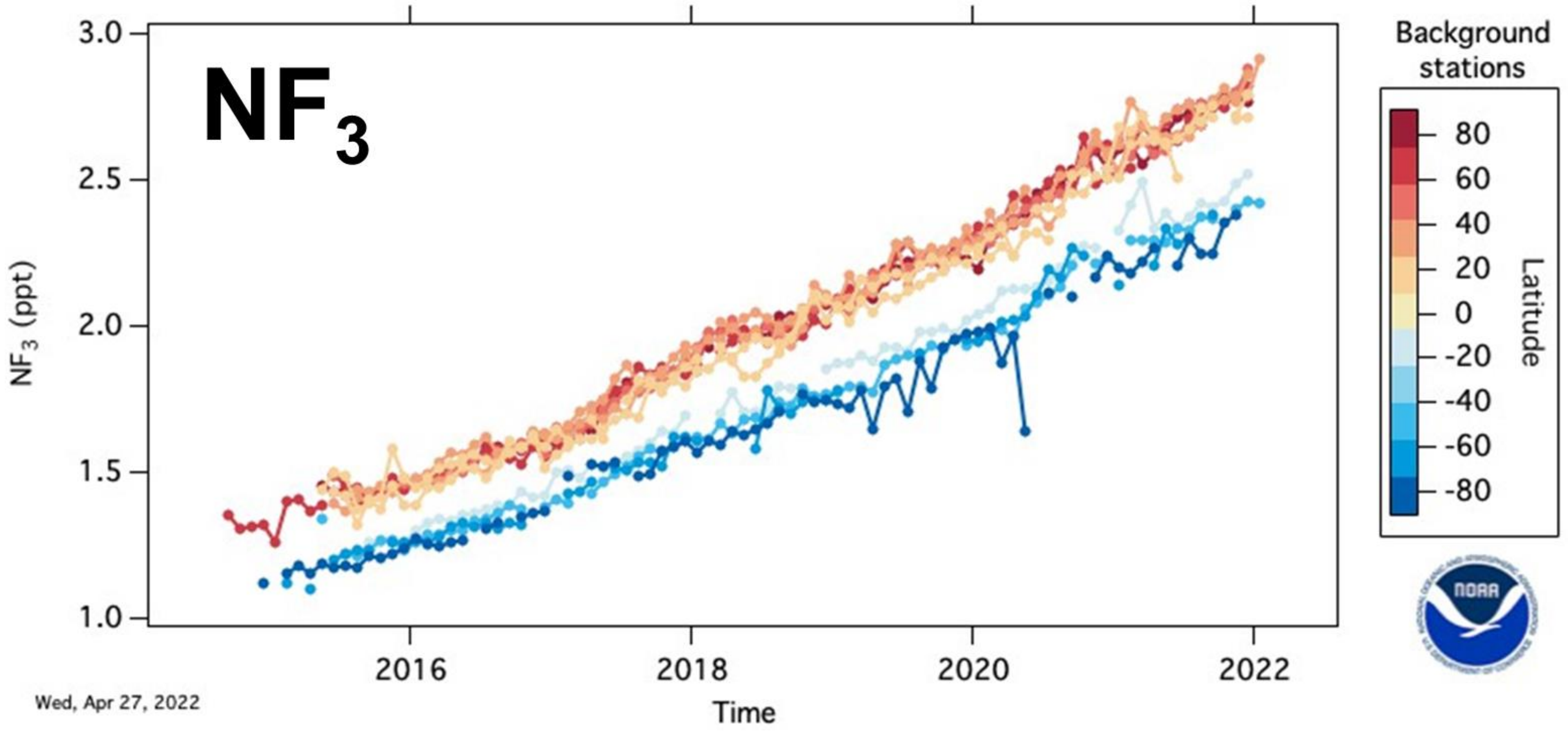
Formula	Greenhouse Gas	100-year GWP (AR4)
CO_2	Carbon dioxide	1
CH_4	Methane	25
N_2O	Nitrous oxide	298
SF_6	Sulphur hexafluoride	22,800
CHF_3	Hydrofluorocarbon-23	14,800
CH_2F_2	Hydrofluorocarbon-32	675
CF_4	Perfluoromethane	7,390
C_2F_6	Perfluoroethane	12,200
C_3F_8	Perfluoropropane	8,830
C_4F_{10}	Perfluorobutane	8,860
C_4F_8	Perfluorocyclobutane	10,300
C_5F_{12}	Perfluoropentane	13,300
C_6F_{14}	Perfluorohexane	9,300

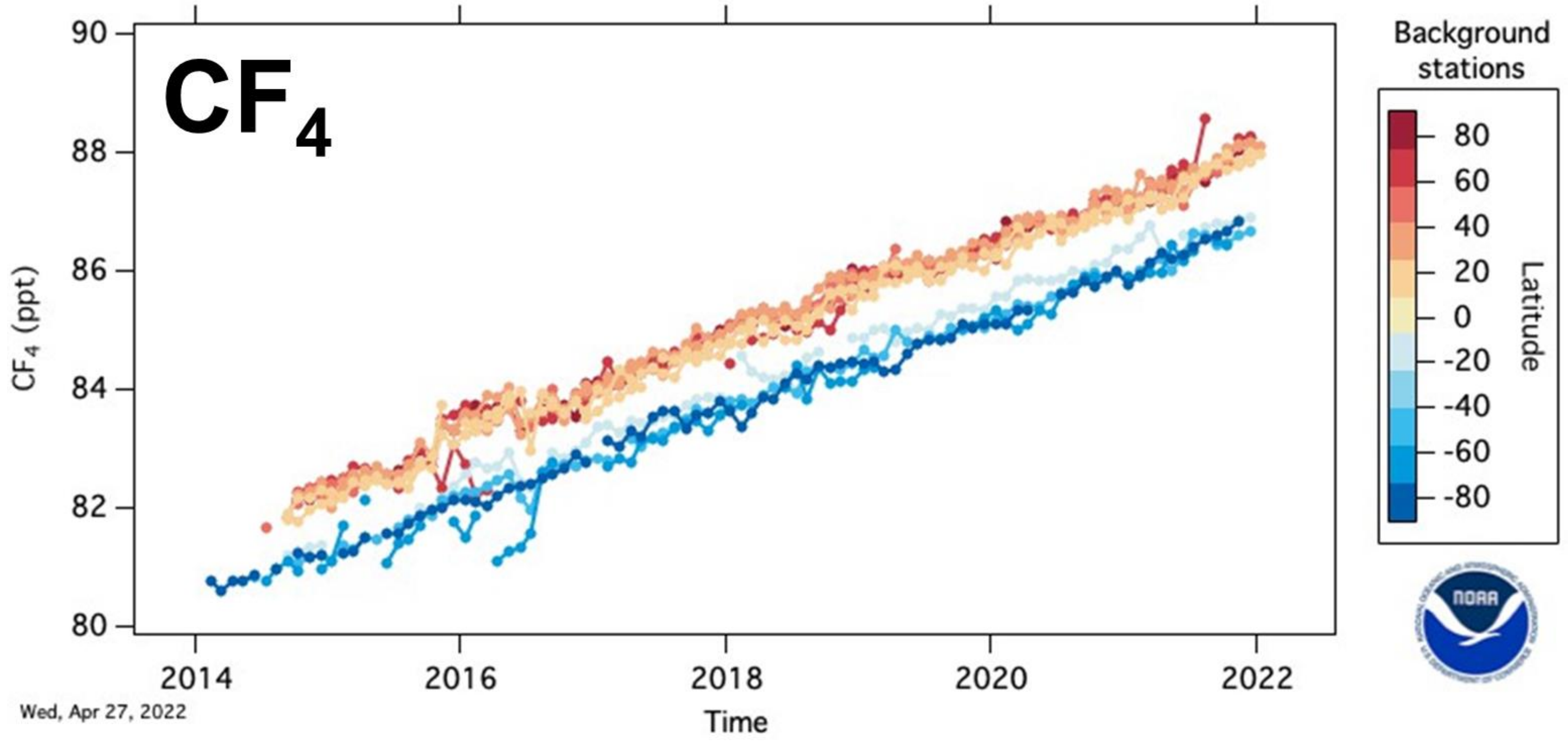


Simply put, abatement strives to minimize the environmental footprint of the fab

How Have We Done Thus Far?

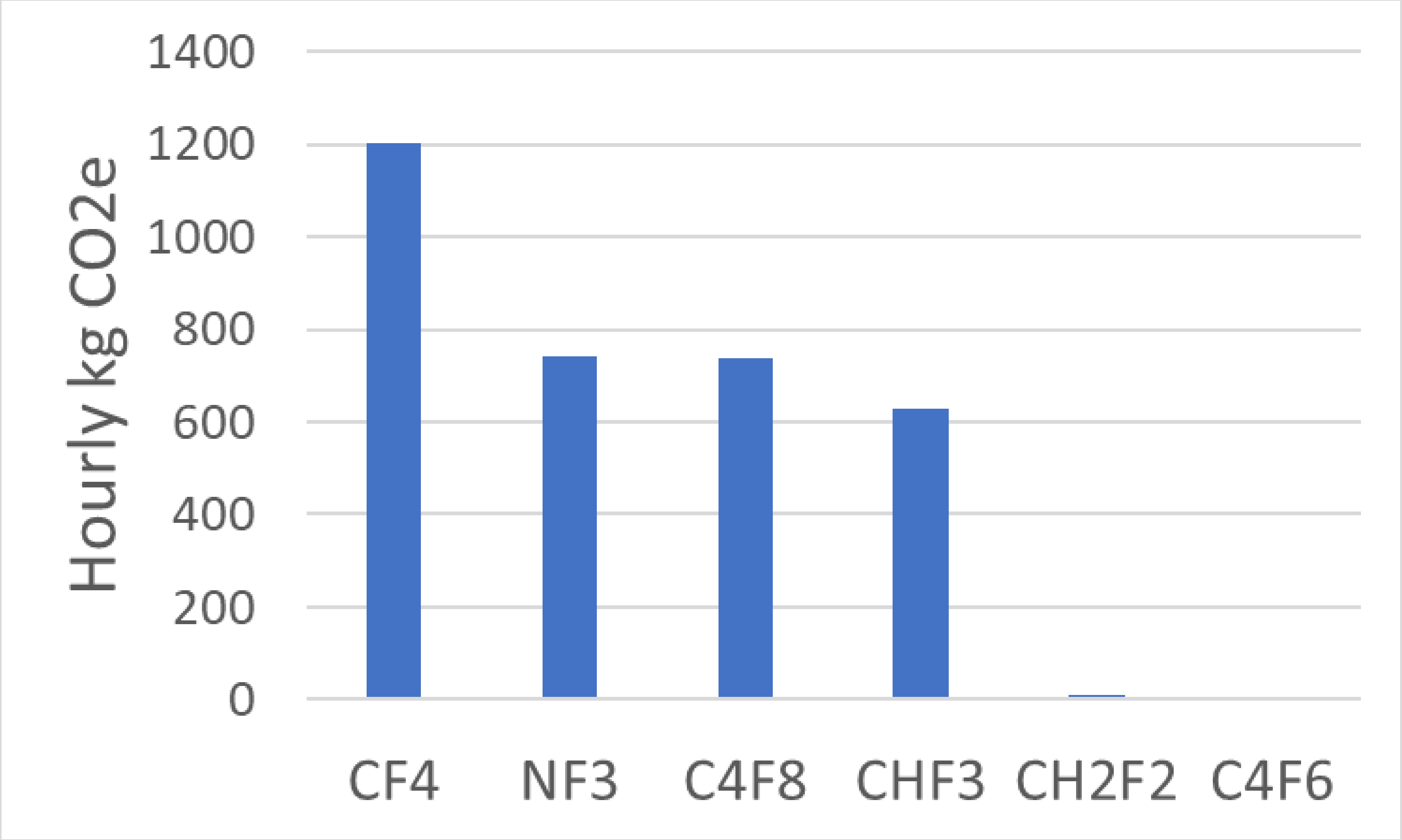






Putting in Perspective

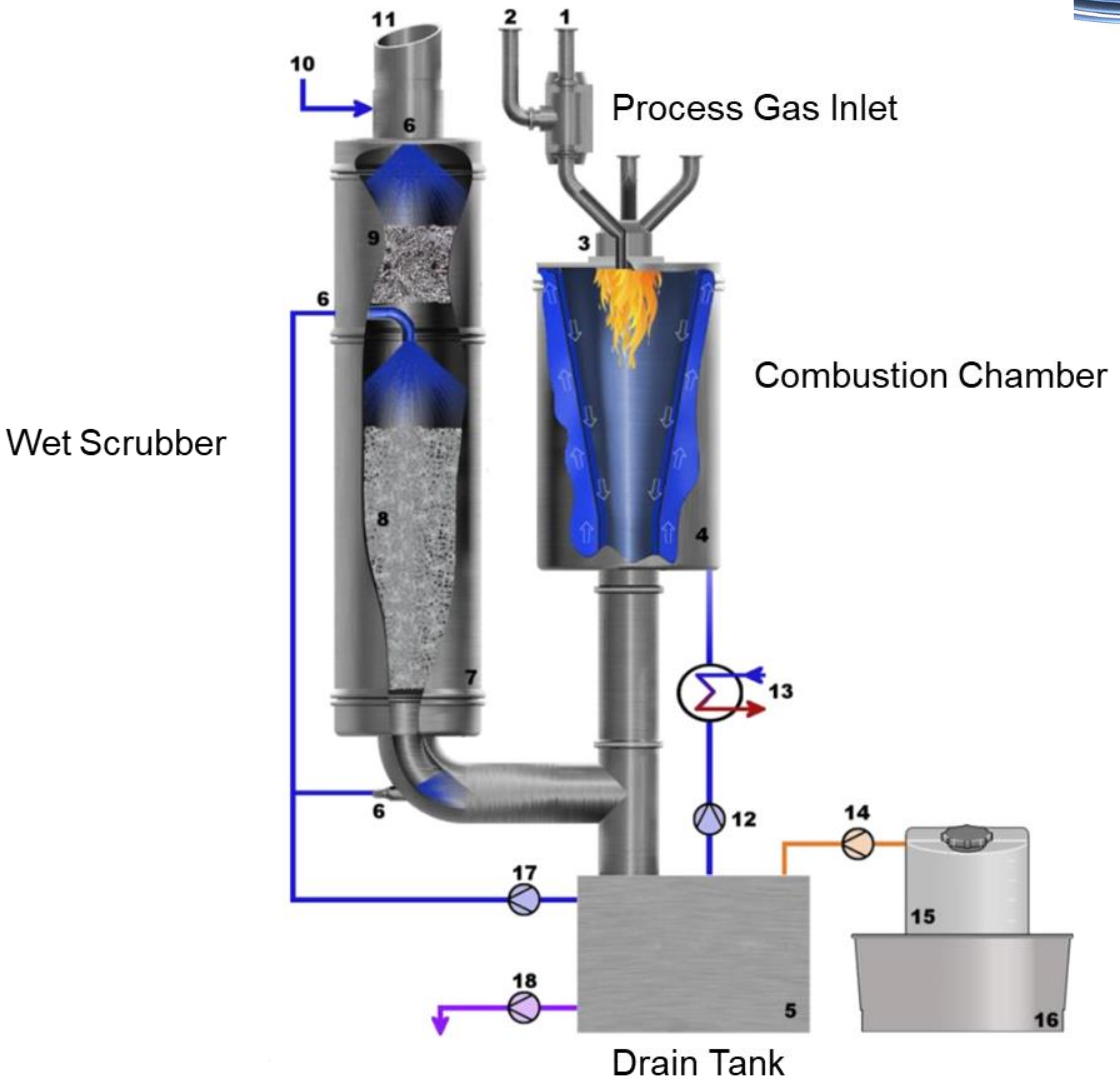
- Assume an etch chamber that uses:
  - 800 sccm CF_4
  - 260 sccm NF_3
  - 152 sccm C_4F_8
  - 260 sccm CHF_3
  - 100 sccm CH_2F_2
  - 50 sccm C_4F_6



- This process, if unabated, would generate ~the CO_2e of five cars annual carbon output, per day
  - ~20,000 kg CO_2e for etch vs. 4,600 kg CO_2e for car
  - Assumptions made for chamber conversion and uptime

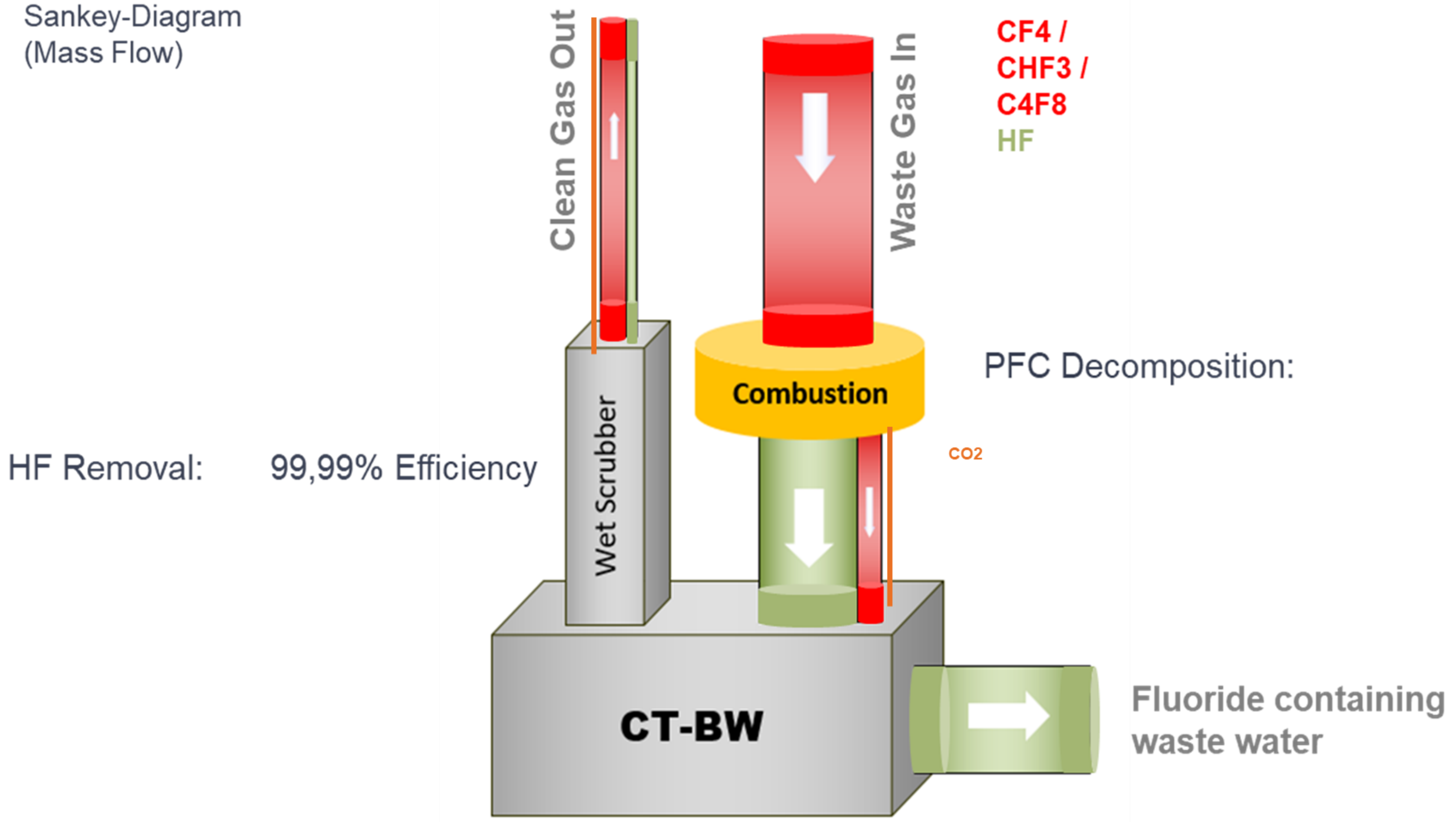
Environmental Footprint of Abatement

- Like process tools, abatement requires several input media to function properly, such as:
  - Fuel (if burn/wet)
  - Oxygen
  - Electricity (more if plasma/wet)
  - Softened fresh water
  - Cooling water
  - Nitrogen
  - Dosing media



Abatement Waste

- After combustion, abatement will emit
  - CO_2 (or CO2e from plasma electrical usage)
  - Unreacted PFCs
  - HF wastewater
  - Particulate matter
  - Heat



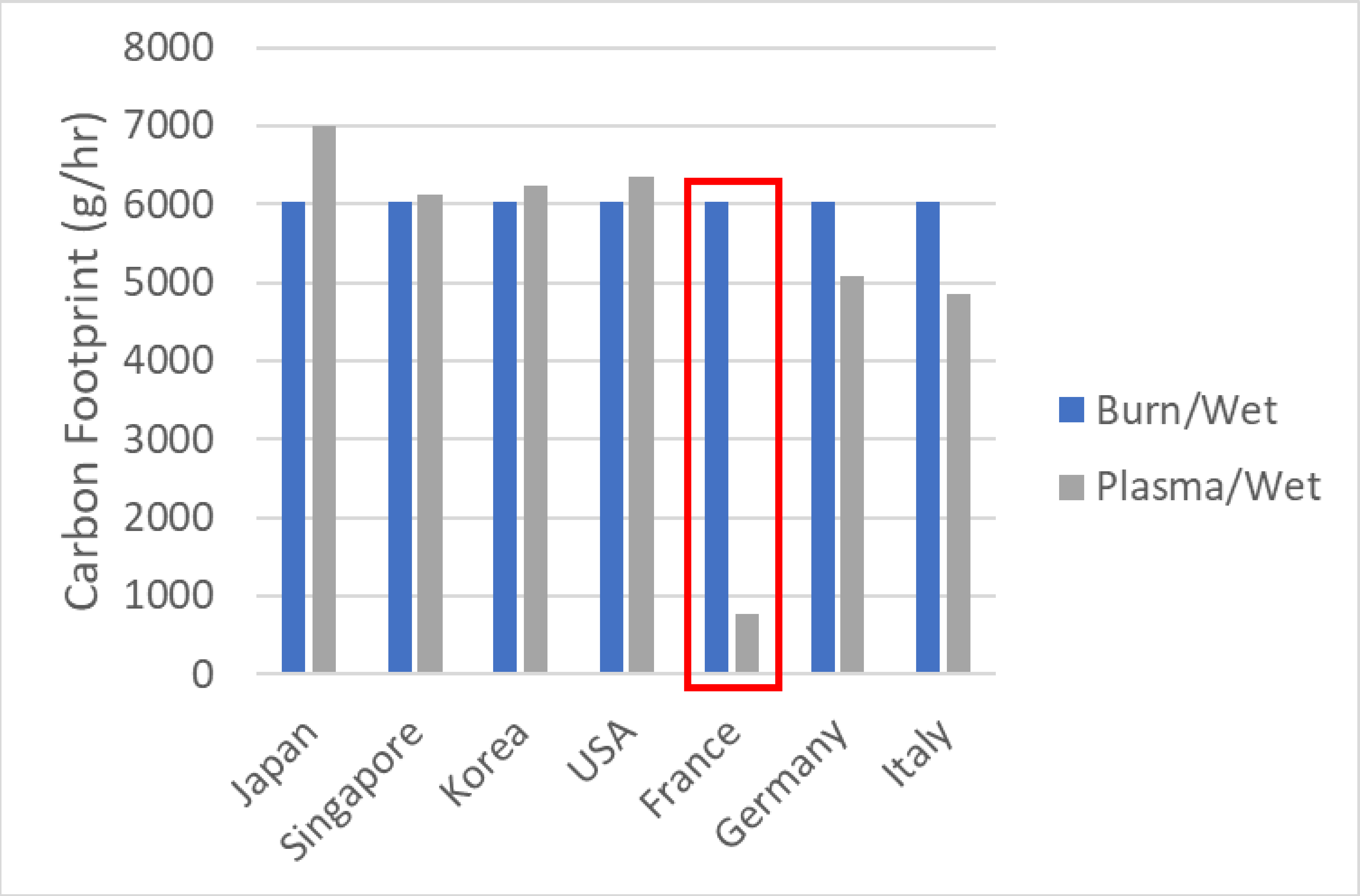
Abatement Operation – Carbon Footprint

- As significant amounts of energy are required to break the C-F bond, the abatement system will have a non-zero carbon footprint
- Some “green” options exist
  - Hydrogen fuel
    - No CO or CO_2 emissions but more expensive than methane
  - Plasma
    - Energy could be generated from renewables
  - High temperature thermal system
    - Uses less power than plasma but PFC DRE may lag best-in-class technologies

Abatement Operation – Carbon Footprint

- Analysis between various technologies is straightforward with region-specific kW/h carbon footprint data
  - Assume 50 slm average CH_4 flow for burn/wet
  - 15 kW for plasma/wet

By Country	Emission kg CO2e/kWh
Japan	0.4658
Singapore	0.408
Korea	0.4156
USA	0.42394
France	0.05128
Germany	0.33866
Italy	0.32384

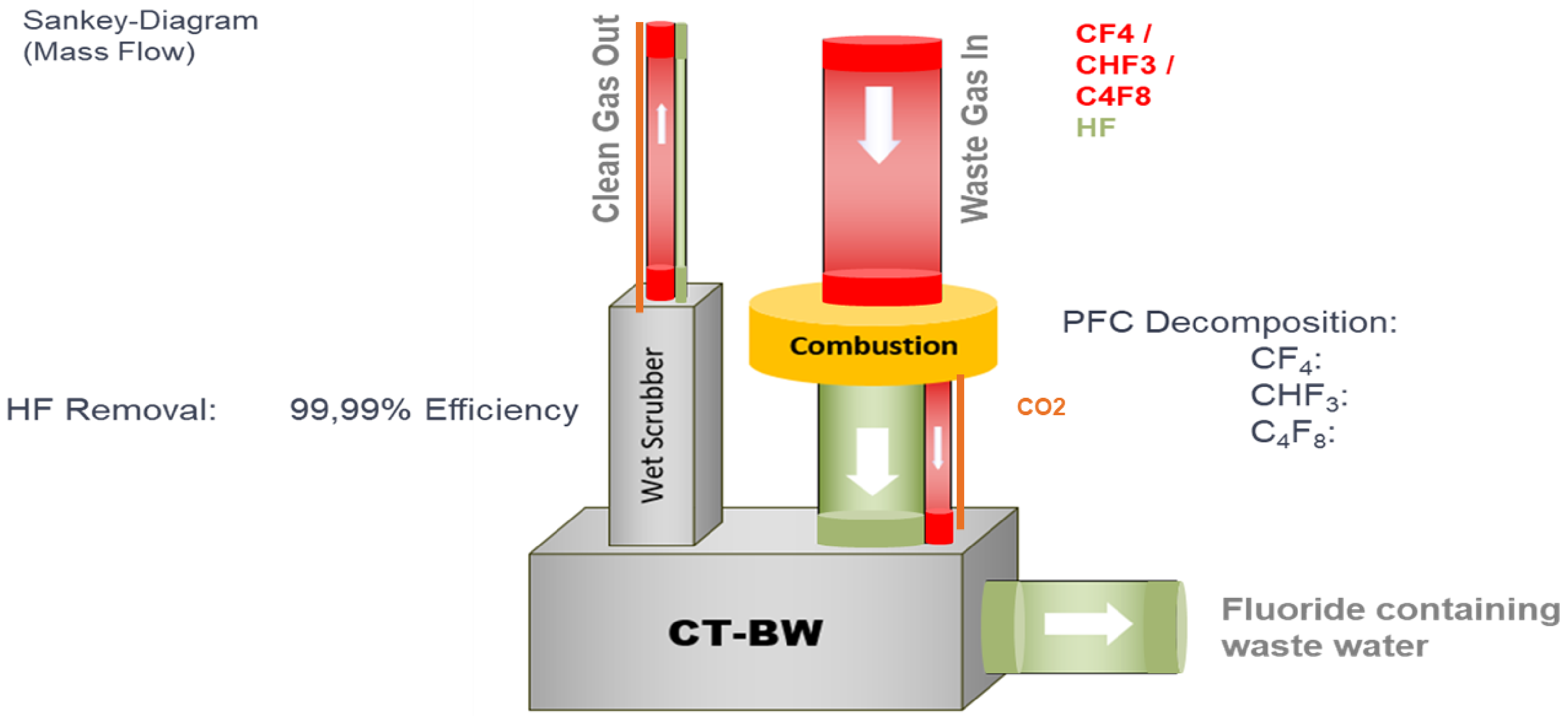


2021 Grid Electricity Emissions Factors v1.1 – March 2022, carbonfootprint.com

Abatement Waste – Carbon Footprint

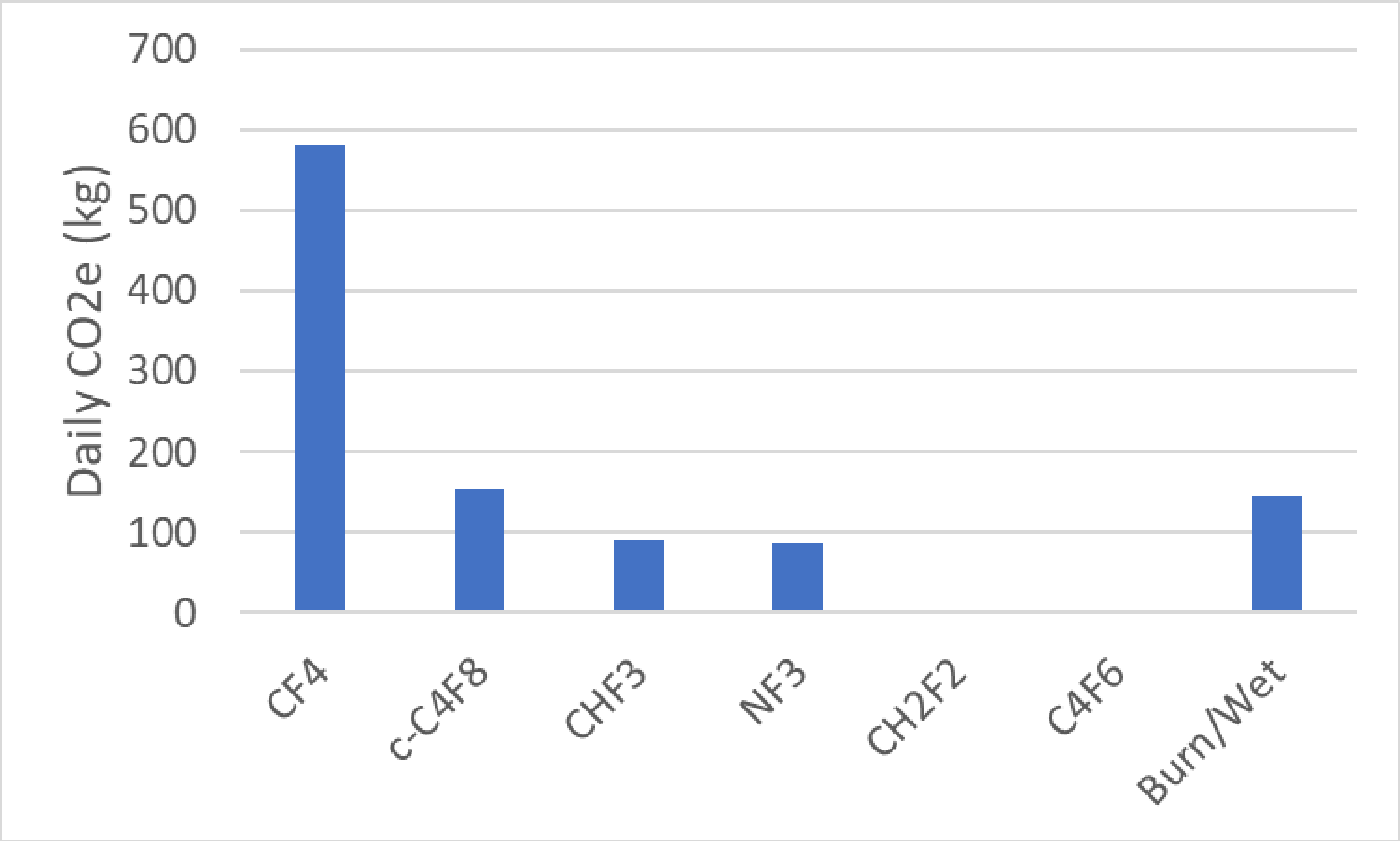
- In addition, abatement carbon footprint will depend on the CO_2e of the unabated waste gas
- Assume that CF_4 DRE is 90% for these moderate burner/plasma powers
  - Reasonable assumption supported by FTIR data
- Also assume that all other species DRE is >99%
  - Also supported by FTIR data

Species	Flow (sccm)
CF4	800
NF3	260
C4F8	152
CHF3	260
CH2F2	100
C4F6	50



Abatement Waste – Carbon Footprint

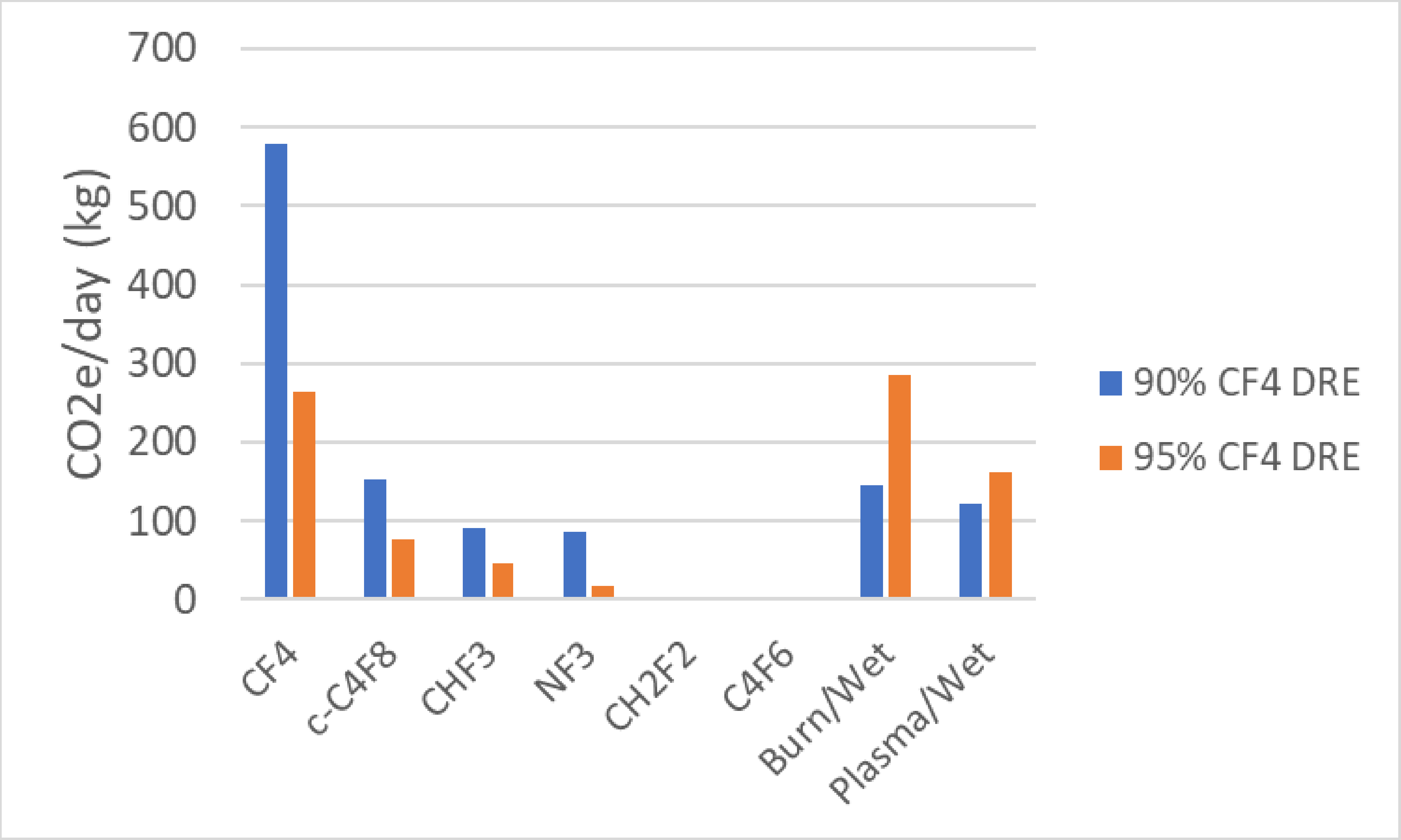
- Quick analysis shows that 10% unreacted CF_4 far outweighs any abatement carbon footprint
- Other species are relatively comparable to abatement footprint
- Does increasing burner or plasma power outweigh increased carbon footprint?



Abatement Waste – Carbon Footprint

- A moderate increase in abatement operations carbon footprint is rewarded with a larger decrease in overall carbon footprint

- Destroying PFCs (specifically CF_4) should be the primary goal for abatement systems, even if it is more fuel or power intensive

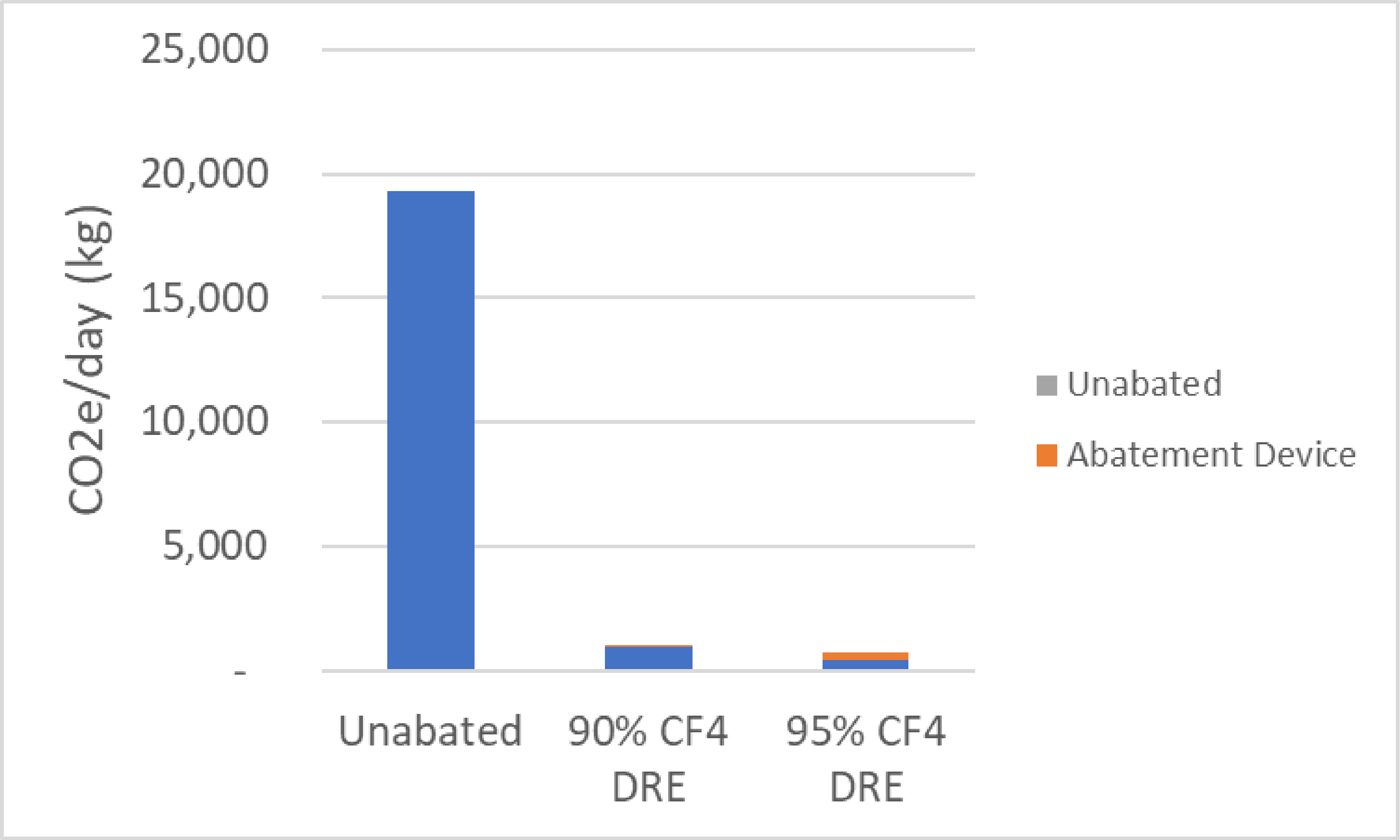


Total Abatement Carbon Footprint

- Abating PFCs, even at a relatively low efficiency, is always the best practice

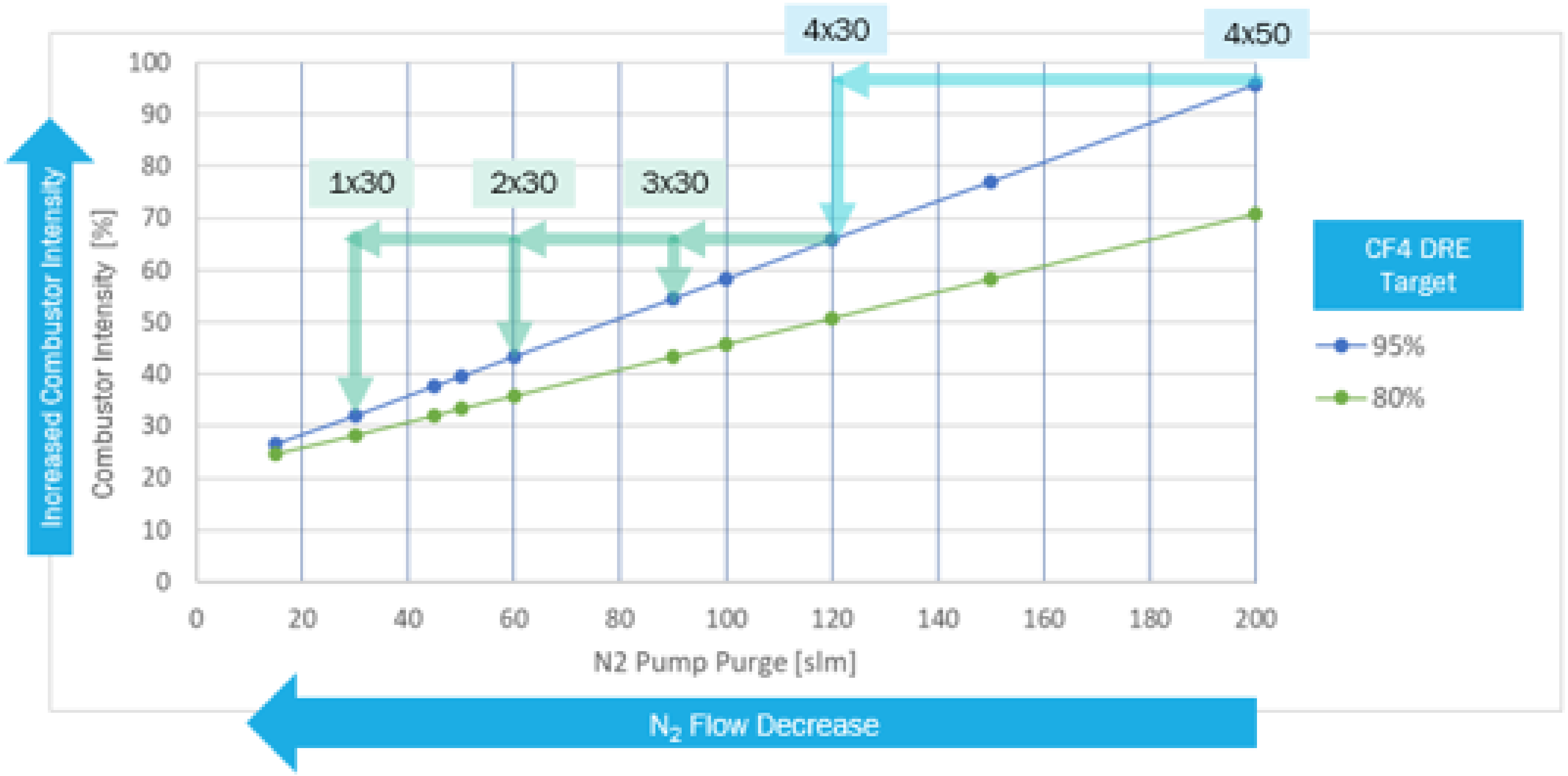
- Higher CF_4 DRE has diminishing returns for carbon footprint reduction
  - Still a reduction overall, just not as much “bang for buck”
  - Moving from 90% to 95% CF_4 DRE results in ~3.7 kg CO2e destroyed for every input kg of methane fuel

- Regardless, massive leverage and benefit for input carbon/power to reduce overall footprint



Looking Beyond Abatement

- Abatement is beholden to the gas mixture that is delivered to it
  - Process gases won't change for external factors
- Another lever to improve PFC DRE exists
- Pump N_2 is a heat sink that suppresses the temperature in the abatement system
- Reducing pump N_2 is a lever that can both reduce abatement carbon footprint as well as improve PFC DRE
- Can achieve upwards of 99% CF_4 DRE at low N_2 flows



Summing Up

- Most important factor when calculating subfab carbon footprint is how effectively the abatement selection destroys CF_4
  - Carbon footprint for burn/wet and plasma wet are roughly the same order of magnitude (except in France)

- A higher burner/plasma power benefit outweighs the increased carbon footprint
  - Diminishing returns, but still very much positive ratio (roughly 10:1 benefit for additional power)

- Reducing pump N_2 is an extremely potent way to reduce carbon footprint without changing any abatement technology setup

Thank You