Environmental impact of energy frontier accelerators and particle physics detectors

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& Ken Bloom (U of Nebraska)

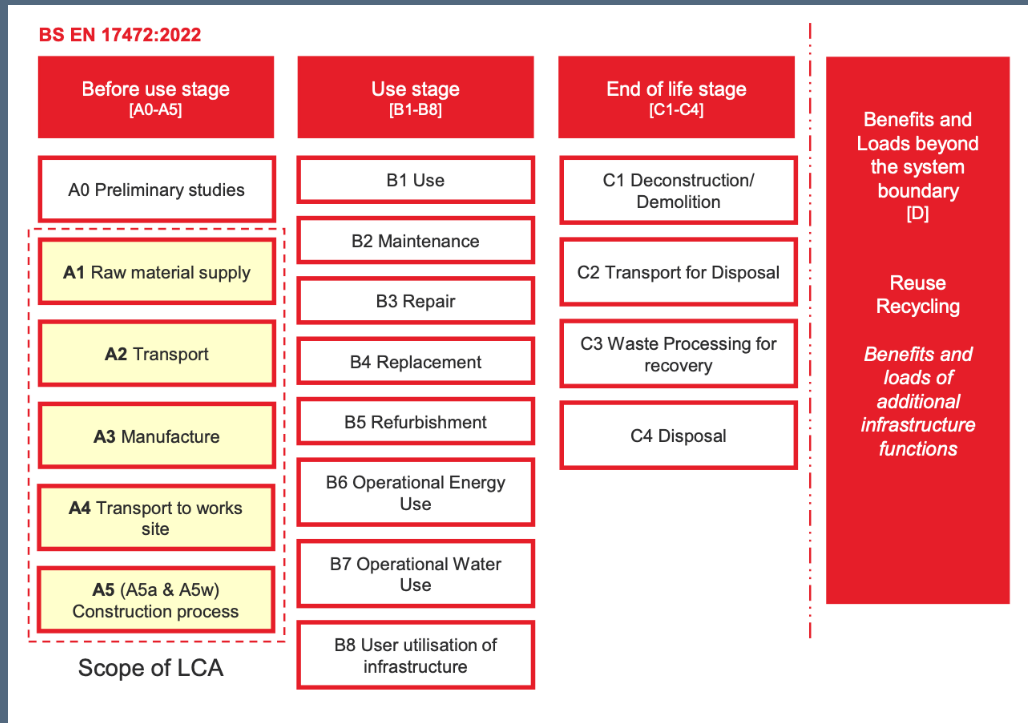
24th September 2024 (422.2 CO_2 ppm – 4.3 ppm (1%) 1 year change!)

Outline

- See my IOP 2024 talk
- Today:
  - Sneak peek at a review article that Ken I are working on (release in November) including looking at:
    - Comparison of CO2e emissions for energy frontier accelerators
    - Discussion of CO2e emissions associated with energy frontier detectors

Emissions from Future Energy Frontier Colliders

- Several contenders to post HL-LHC: lepton collider (e and μ) and hadron colliders
- ARUP engineering company did comprehensive civil engineering LCA for ILC (TDR design (33km) not Snowmass one) and CLIC (Klystron & Drive Beam) construction
- Considered A1-A5
- FCC has now started this process (WSP)



[ARUP final report]

Emissions from accelerators

Linear Colliders	COM E	Location	Notes
ILC (e+e-)	250 GeV, 500 GeV	Japan	SRF, 2 Linacs, site length about 20.5 km, total tunnels: 33km
CLIC (e+e-)	380 GeV	CERN	2 beams: drive-beam (normal RF), main beam, tunnel length: 11.47 km
Cool Copper Collider (CCC) (e+e-)	250 GeV, 550 GeV	USA	high-gradient at Liq N2 Temp., tunnel length: 8 km, "cut and cover" design
Circular Colliders			
FCC-ee/hh	88 - 365 GeV/100 TeV	CERN	Tunnel length: 90.2 km, hh: pCM of 10 TeV
CEPC/SppC	91.2 - 360 GeV/100 TeV	China	Tunnel length: 100 km, hh: pCM of 10 TeV
Muon Collider	10 TeV	USA	Accelerator ring circ.: 17 km, collider ring circ.: 10 km
LEP3	240 GeV	CERN	Use LHC tunnel, improved RF
HE-LHC	27 TeV	CERN	Use LHC tunnel, needs FCC-hh-like 16 T curved dipoles

LEP3 HE-LHC

- ARUP:
  - emissions per total length:
    - CLIC: 6.38 $ktCO_2e/km$
    - ILC: 7.34 $ktCO_2e/km$
  - Caverns & buildings: 30% of main tunnel emissions
  - A4-A5: 25% of tunnels+aux.

Emissions from accelerators

Table 1 Carbon emissions from civil construction for future colliders.

Collider	Emissions ($MtCO_2e$)	Notes (see text for more complete information)
ILC (Japan) 250 GeV, 500 GeV	0.266	From ARUP report [x].
CEPC (China) 91.2 - 360 GeV	1.138	From CEPC presentation [x] which uses the factors of 7.0 $ktCO_2e/km$, 30% for the auxiliary buildings and 25% for A4-A5 contributions.
FCC-ee (CERN) 88 - 365 GeV	1.056	From FCC presentation [x], the deduced emissions per length of the main tunnel is 7.2 $ktCO_2e/km$.
CLIC (CERN) 380 GeV Drive Beam	0.127	From ARUP report [x].
CCC (USA) 250 GeV, 550 GeV	0.146	From CCC paper [x].
Muon Collider (USA) 10 TeV	0.378	Using 27 km for the sum of the accelerator and collider rings [x] and using factors of 7.0 $ktCO_2e/km$, 60% for the auxiliary buildings and 25% for A4-A5 contributions.
FCC-hh (CERN) 100 TeV	0.245	Re-using the FCC-ee tunnel, using factors of 7.2 $ktCO_2e/km$, 10% for the auxiliary buildings and 25% for A4-A5 contributions.
SPPC (China) 100 TeV	0.263	Re-using the CEPC tunnel, using factors of 7.0 $ktCO_2e/km$, 10% for the auxiliary buildings and 25% for A4-A5 contributions.
LEP3 (CERN) 240 GeV	0.061	Re-using LHC tunnel, using factors of 6.0 $ktCO_2e/km$, 10% for the auxiliary buildings and 25% for A4-A5 contributions.
HE-LHC (CERN) 27 TeV	0.061	Re-using LHC tunnel, using factors of 6.0 $ktCO_2e/km$, 10% for the auxiliary buildings and 25% for A4-A5 contributions.

CEPC

FCC

CCC

60%: large detector cavern

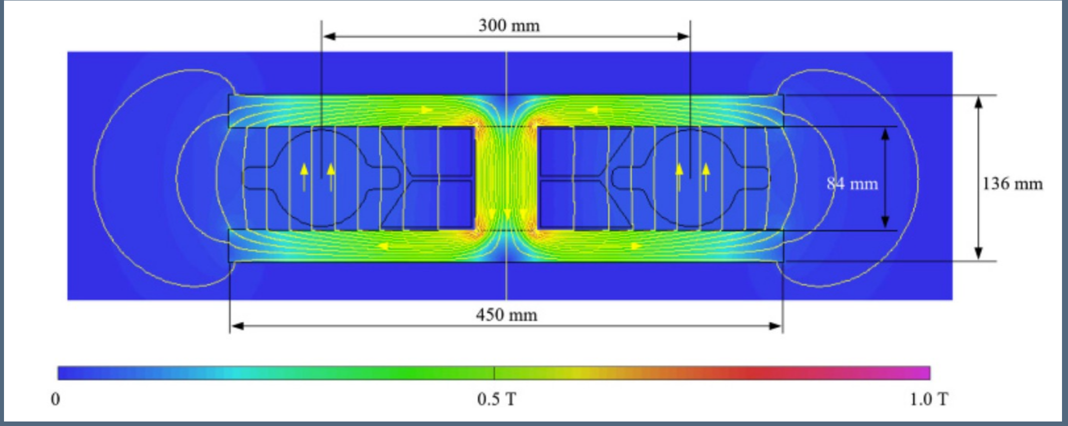
10%: some re-use of caverns

Emissions from accelerator components

- Embedded emissions into material not considered by ARUP-type analysis so far
- Quick order of magnitude estimate:
  - Linear Colliders:
    - SRF: Niobium cavities, eg. ILC: each cavity = 39.6 kg Niobium, carbon intensity ~75 kgCO2e/kg, ~3 tCO2e/cavity, about 8000 cavities → total of 26 ktCO2e = 27% of civil construction
  - Circular Colliders:
    - Dipole magnets: FCC-ee: 2900 dipoles, 219 kg/m Fe (Carbon intensity =2.0 kgCO2e/kg), 19.9 kg/m Al (6.8 kgCO2e/kg), magnetic length: 24m, ~14 tCO2e/dipole → Total of 40 ktCO2e (7%)

Figure 2.2
A 1.3 GHz superconducting nine-cell niobium cavity.

ILC TDR Vol. 3.ii



FCC-ee CDR

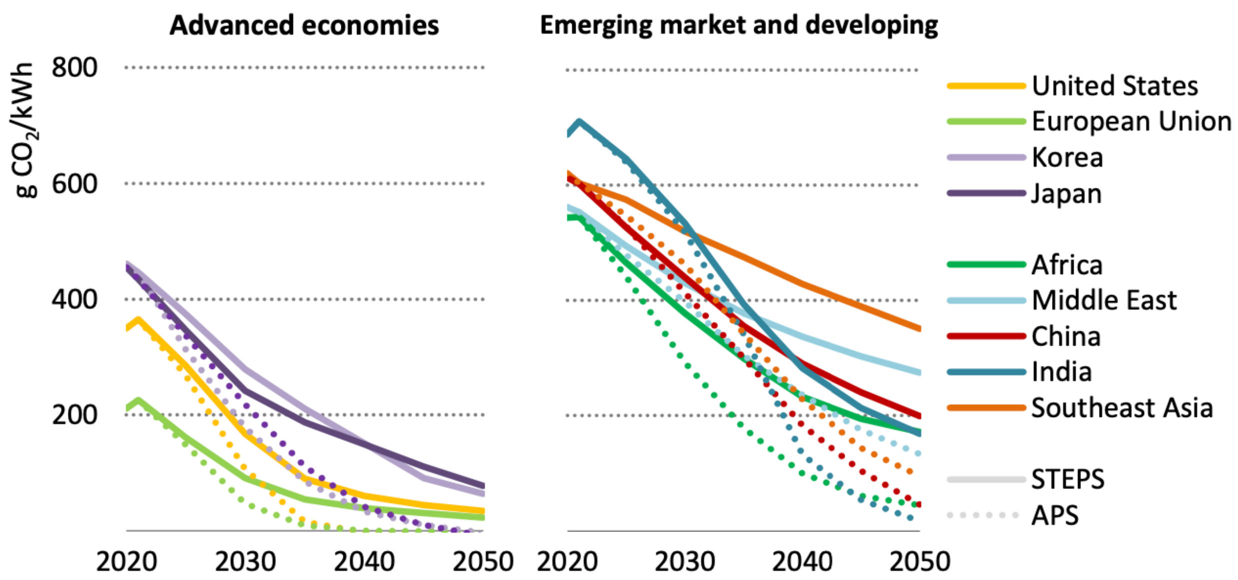
Emissions from operations

- Scope 1: direct emissions from organization/vehicles etc.
- Scope 2: indirect emissions from electricity generation, heating, etc. (does NOT include the emissions from building the national electricity providers)
- Scope 3: all other indirect emissions, upstream and downstream (procurement, business travel, personnel commutes, catering, etc.)
- In 2040+: Advanced economies will have zero carbon grids!
  - If they don't, there is NO POINT discussing particle physics research!
  - It is our collective and individual responsibility as citizens and scientists to HELP governments deliver this!

Emissions from operations

2022 IEA report

Figure 6.14 ▷ Average CO_2 intensity of electricity generation for selected regions by scenario, 2020-2050



CO_2 intensity of electricity generation varies widely today, but all regions see a decline in future years and many have declared net zero emissions ambitions by around 2050

2023 IEA report

fuels. By 2030, global power sector emissions are down about 15% in the STEPS, 30% in the APS and 45% in the NZE Scenario, which sees electricity sector emissions subsequently fall to net zero by 2035 in advanced economies in aggregate, 2040 in China and just before 2045 globally (Figure 3.17). This makes the power sector the first to reach net zero emissions.

Emissions from operations

- The **Net Zero Emissions by 2050 (NZE) Scenario** shows a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050, with advanced economies reaching net zero emissions in advance of the other scenarios. This scenario

It is consistent with limiting the global temperature rise to 1.5 °C without a temperature overshoot (with a 50% probability).

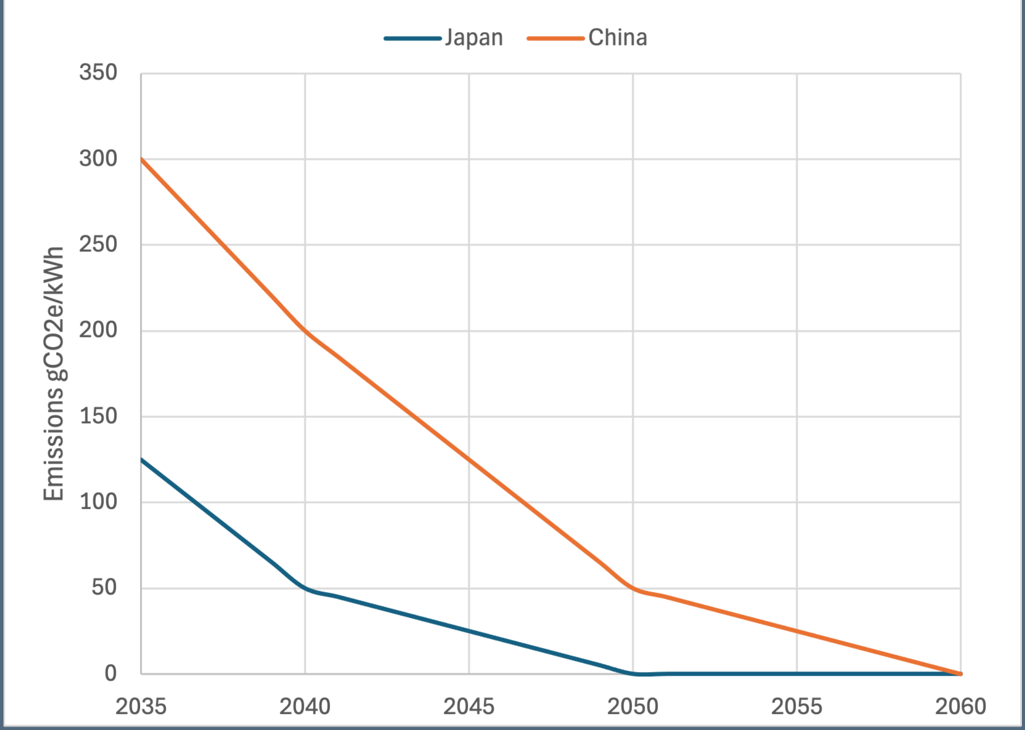
- The **Announced Pledges Scenario (APS)** takes account of all the climate commitments made by governments around the world including Nationally Determined Contributions as well as longer term net zero emissions targets, and assumes that they will be met in full and on time. The global trends in this scenario represent the cumulative extent of

- The **Stated Policies Scenario (STEPS)** does not take for granted that governments will reach all announced goals. Instead, it explores where the energy system might go without additional policy implementation. As with the APS, it is not designed to achieve

Emissions from operations

Table 2 Carbon emissions due to operations of future colliders. For the CCC collider the numbers in brackets correspond to the optimized power design (20).

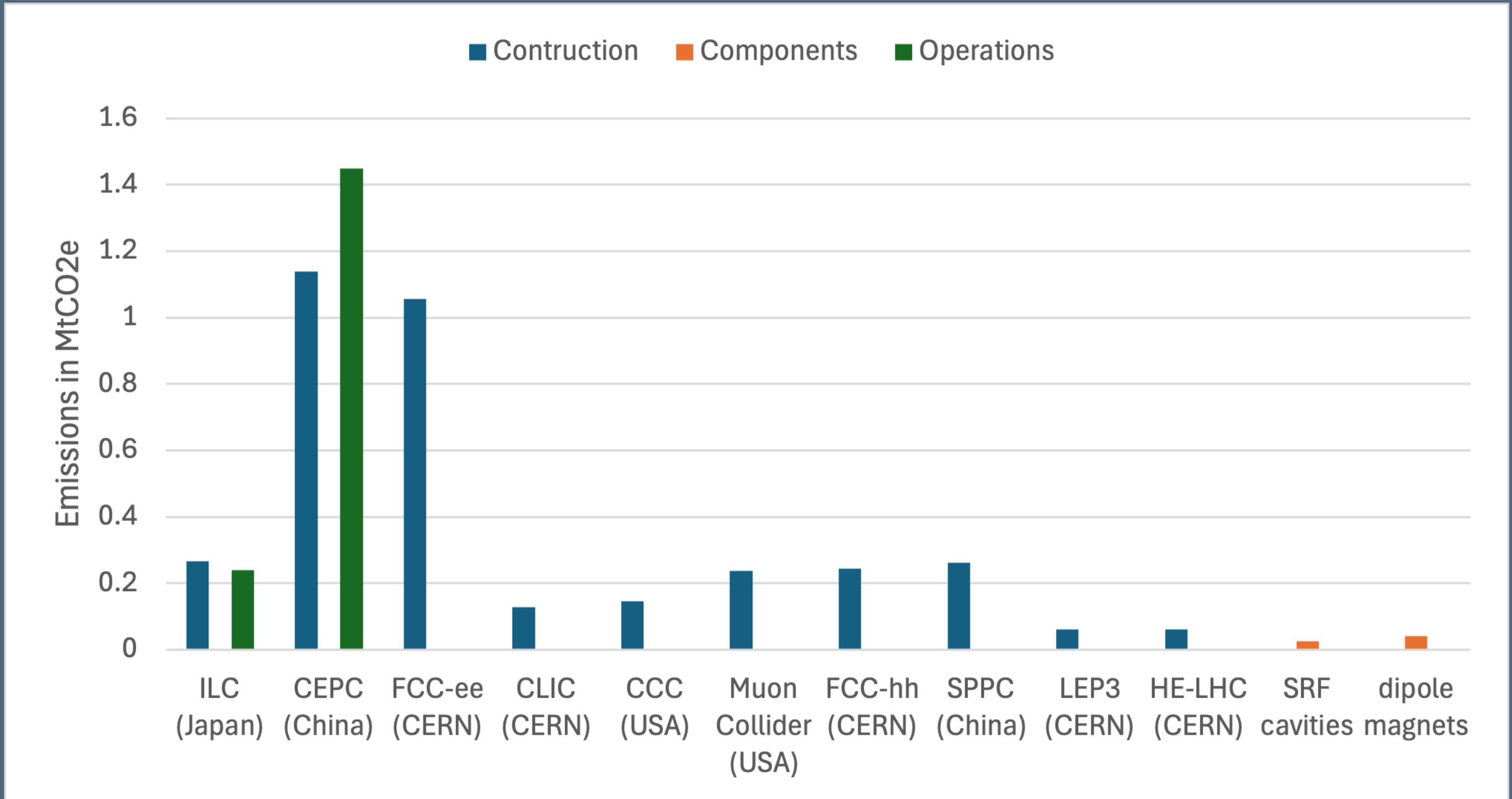
Collider	Start date	Duration (y)	Total Power (MW)	Emissions ($MtCO_2e$)
ILC (Japan) 250 GeV, 500 GeV	2035	20	111, 173	0.24
CEPC (China) 91.2 - 360 GeV	2040	18	283 - 430	1.448
FCC-ee (CERN) 88 - 365 GeV	2040	14	222 - 357	0
CLIC (CERN) 380 GeV Drive Beam	2040	8	110	0
CCC (USA) 250 GeV, 550 GeV	2040	20	150 (87), 175 (96)	0



Assume 10^7s operations per year

- Still a priority to minimize average and peak power:
  - power demand will massively increase
  - power will be expensive

Emissions from construction+operations

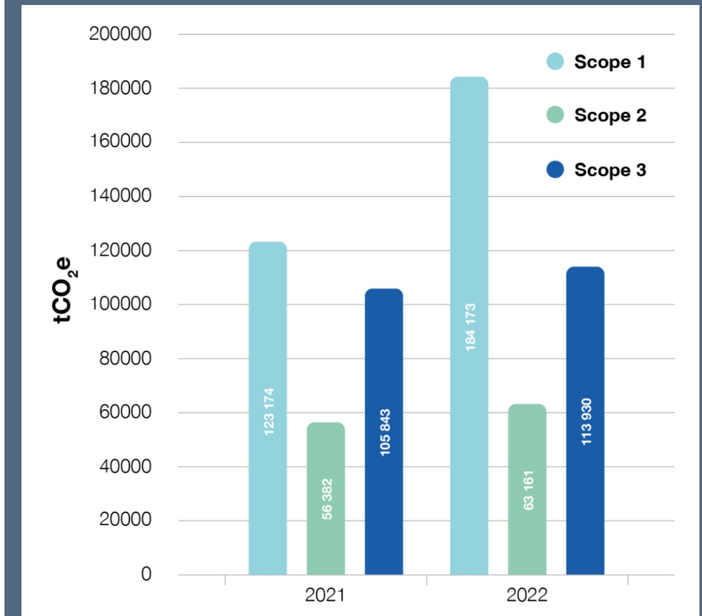


1 $MtCO_2$ / 10,000 scientists = 100 tCO_2 per scientist when should be 1-2 tCO_2 pp/y (and now ~10 tCO_2 pp/y in UK)
Divide by population? Ok, but then need to get comparative numbers (NHS, defense, arts, etc.)

CERN environmental report 2021-22

Emissions from detectors

- Dominant CO2e emissions from CERN: gases used in experiments!



bad

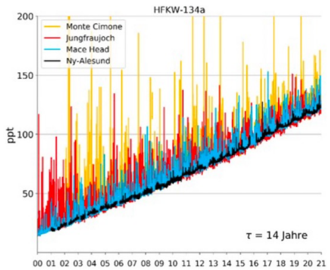
good

GROUP	GASES	tCO_2e 2021	tCO_2e 2022
Perfluorocarbons (PFCs)	CF_4, C_2F_6, C_3F_8, C_4F_{10}, C_6F_{14}	55 921	68 989
Hydrochlorofluorocarbons (HFCs)	HFC-23 (CHF_3) HFC-32 (CH_2F_2) HFC-134a ($C_2H_2F_4$) HFC-404a HFC-407c HFC-410a HFC-507	36 557	86 211
Other F-gases	SF_6, NF_3	16 838	18 355
Hydrofluoroolefins (HFO)/HFCs	R-449 R1234ze NOVEC 649	86	199
	CO_2	13 771	10 419
Total Scope 1		123 174	184 173

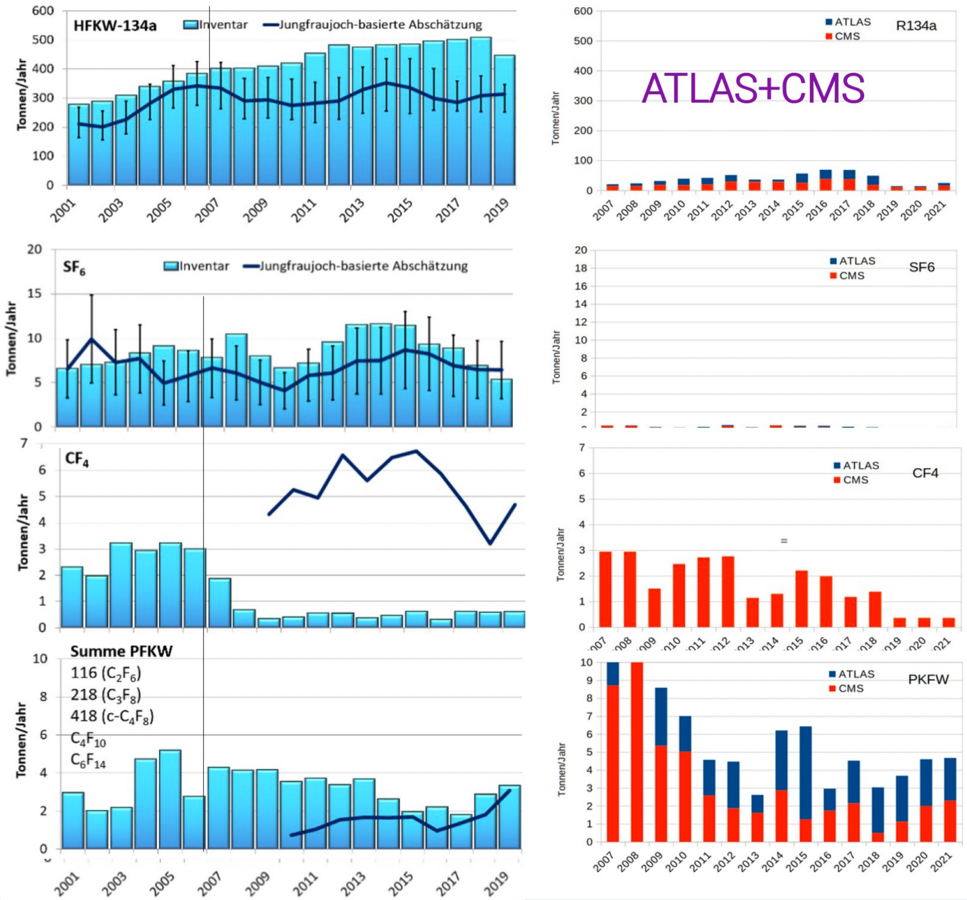
Emissions from detectors: large?

GHGs in Switzerland and ATLAS+CMS

- According to Kyoto protocol, the emissions of GHG gases need to be monitored
  - Inventory
  - Measurements

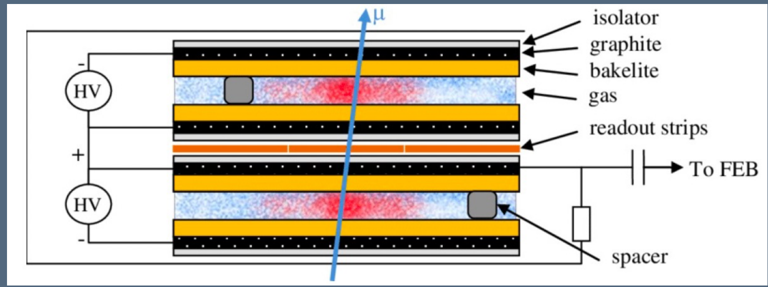


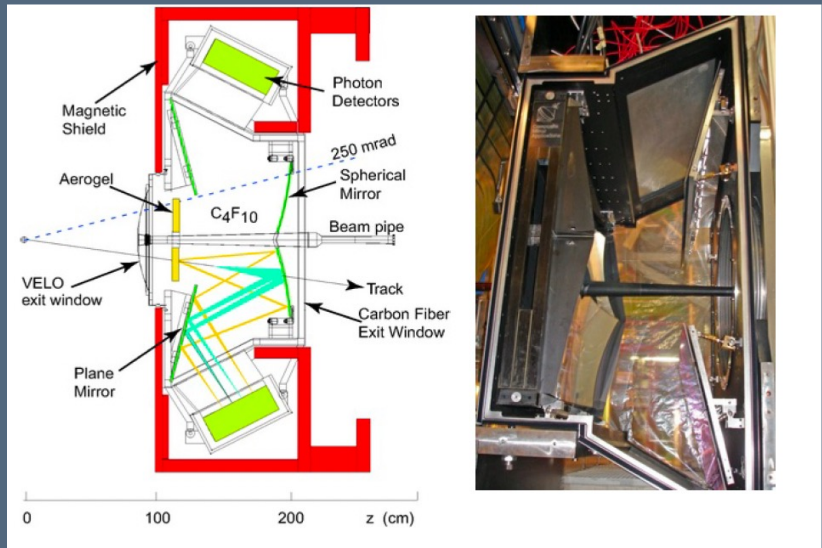
https://www.empa.ch/documents/56101/190047/CLIMGAS-CH_2021/bf747be6-bddf-4247-aea2-d0390c3eadc2



Emissions from detectors

- GHG in detectors
  - Tracking (eg RPCs) or TOF (eg RICH)
  - Methods for minimizing releases to the atmosphere:
    - Gas recirculation
    - Gas recuperation
- GHG for cooling
- Replacement of GHG with ECO-gases

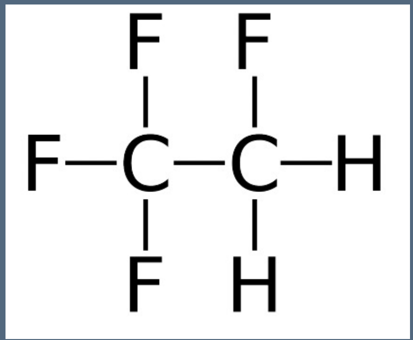




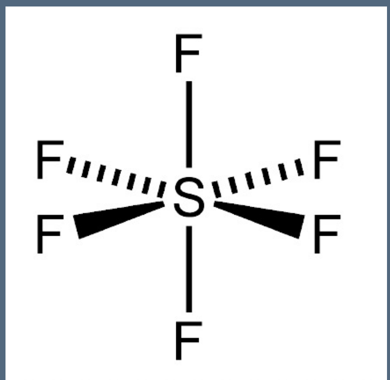
GWP$_{100}$ from AR5

Emissions from detectors

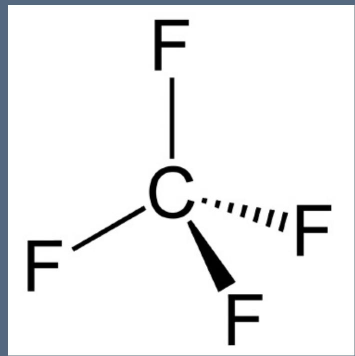
- Main GHG in play:



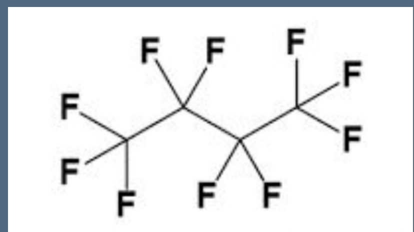
$C_2H_2F_4$/R-134a (1300)
RPC: primary ionization, charge multiplication
Eg ATLAS/CMS: ~15 m^3



SF_6(23,500)
RPC: electron quenchers

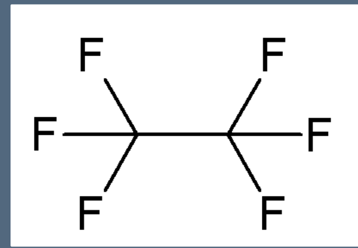


CF_4 (6630)
RICH: optical properties, wire chambers: anti-polymerization, MPGD: time resolution
Eg RICH2: 100 m^3

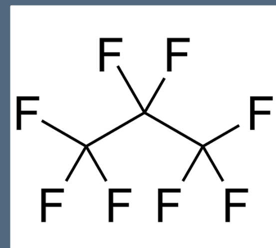


C_4F_{10} (9200)
RICH: optical properties
Eg RICH1: 4 m^3, Compass: 100 m^3

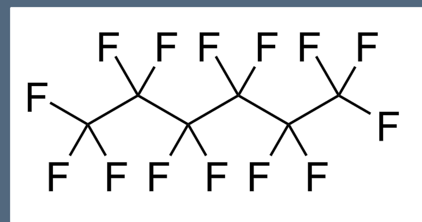
cooling



C_2F_6 (11,100)
RICH radiator and Si coolant



C_3F_8 (8900)
Used for evaporative cooling of TOTEM and ATLAS Si

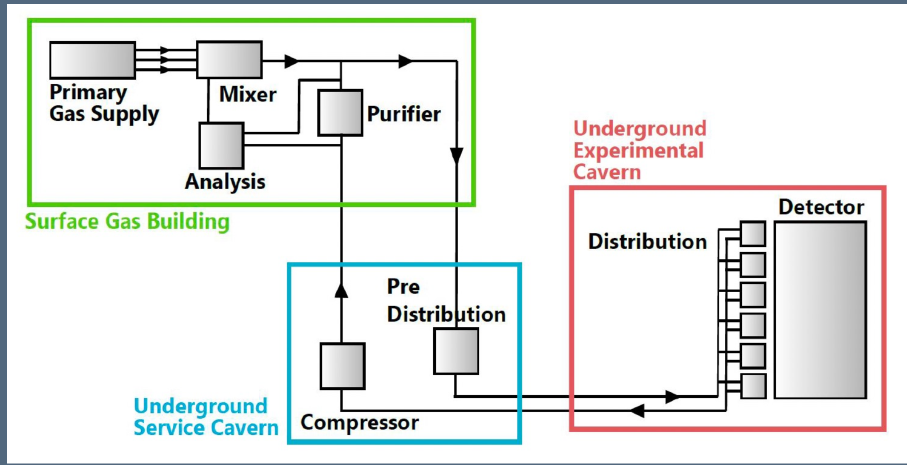


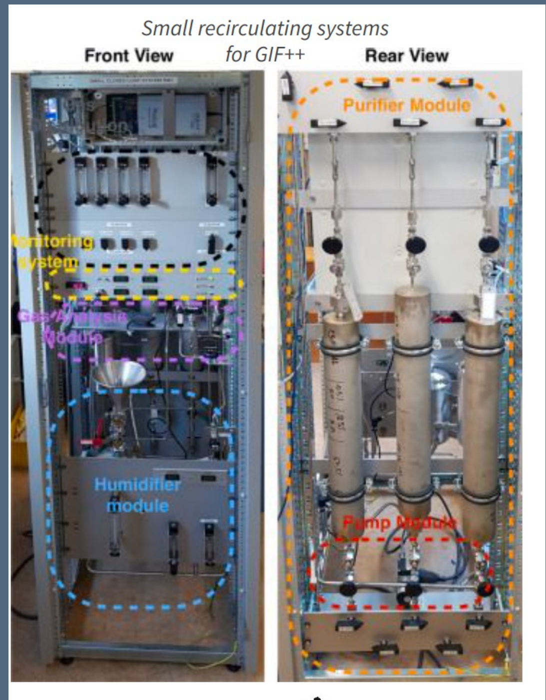
C_6F_{14} (7910)
Liquid coolant in all LHC exp.

Emissions from detectors

G. Rigoletti, ICHEP 2024

- Gas Recirculation at LHC:
  - For large volumes:
    - ~15 at LHC, 24/7, 99.99% uptime
    - 10% injection of new gas usually still needed for detector performance
    - Expensive and complex systems
    - Optimization ongoing
  - Micro-systems:
    - As small and cheap as possible
    - Portable and standardize

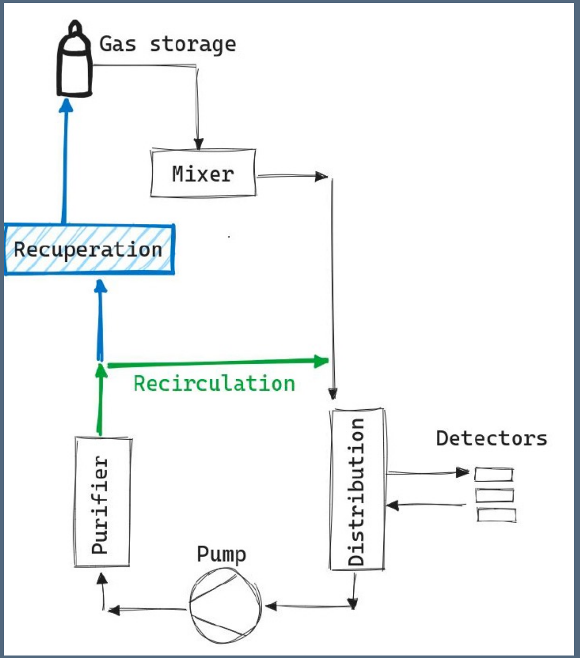




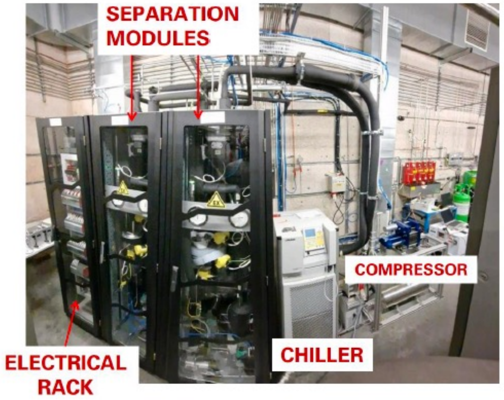
Emissions from detectors

G. Rigoletti, ICHEP 2024

- Gas Recuperation at LHC:
  - because can't have 100% recirculation
- Principle:
  - GHG components are separated at the exhaust
  - GHG stored and re-used as fresh gas
- For large systems:
  - Non-standard and complex
- 60-85% of exhausted gas recuperated with > 90% quality
- Eg: CMS RPC R-134a, CMS CSC CF_4, LHCb RICH2 CF_4, LHCb RICH1 C_4F_{10}
  - (see backup slide)



CMS RPC R-134a recuperation



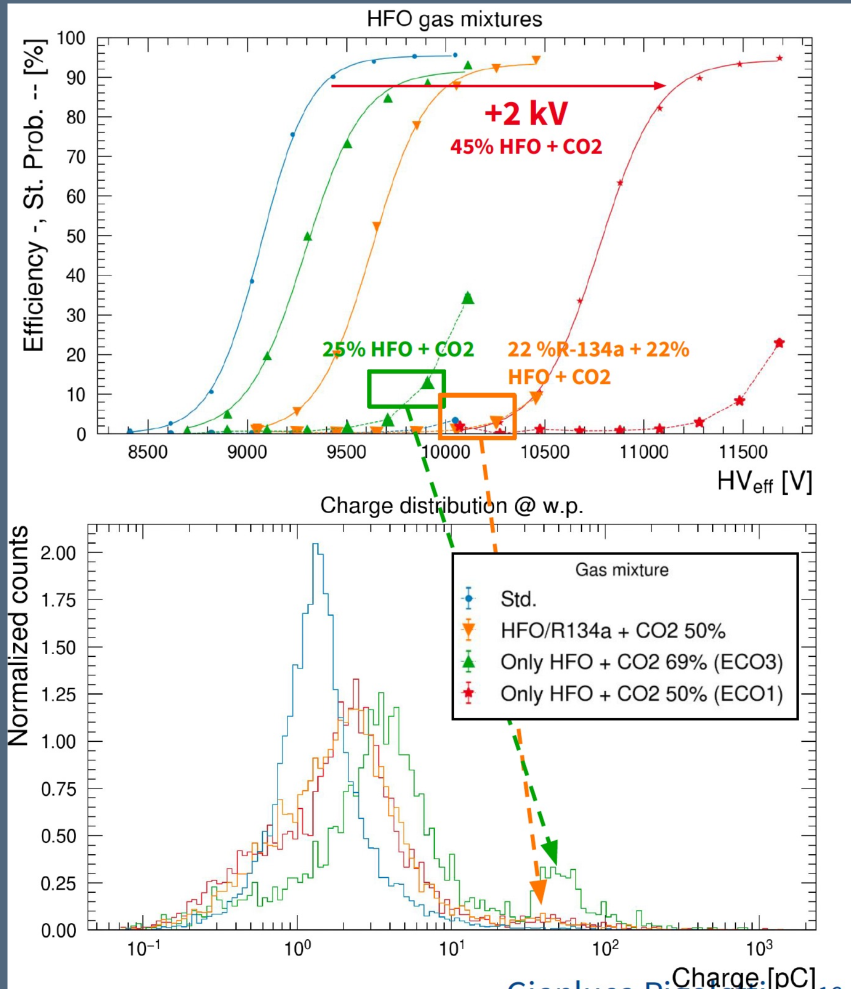
Emissions from detectors

[G. Rigoletti, ICHEP 2024]

[D. Ramos, ICHEP 2024]

[EPJ Plus (2023)]

- In 2040+: no more F-gases, eco-gases only solution!
- Go from C_nF_n → $C_nF_{2n}O$ (HFOs, PFKs)
- Eg RPC ECOGas@GIF++ collaboration
  - Muon beam tests, ageing tests
- Ex: $C_2H_2F_4$/R-134a → $C_3H_2F_4$/ R-1234ze (<7)+CO_2
  - Need a higher HV wp, increased currents, increased streamers
  - Mid-term solution: 30% CO_2, 64% $C_2H_2F_4$, 5% i-C_4H_{10}, 1% SF_6 (14% reduction of GWP)
  - Currently used in ATLAS RPCs
  - However [CBM-TOF (MRPC) group] decided to keep R-134a because of ageing issues



Emissions from detectors

- Potential replacement for SF_6:
  - promising: 0.3% SF_6 → 0.5% Amolea 1224yd, 0.1% Novec 4710
  - Chemical and pollutant investigations
- Potential replacement for CF_4 and C_4F_{10} :
  - C5F12/N2 (45% GWP reduction)
  - Novec 5110 ($C_5F_{10}O$)/N2, GWP<1
  - Optical and thermodynamic studies ongoing

G. D. Hallewell, EPJ Plus (2023)

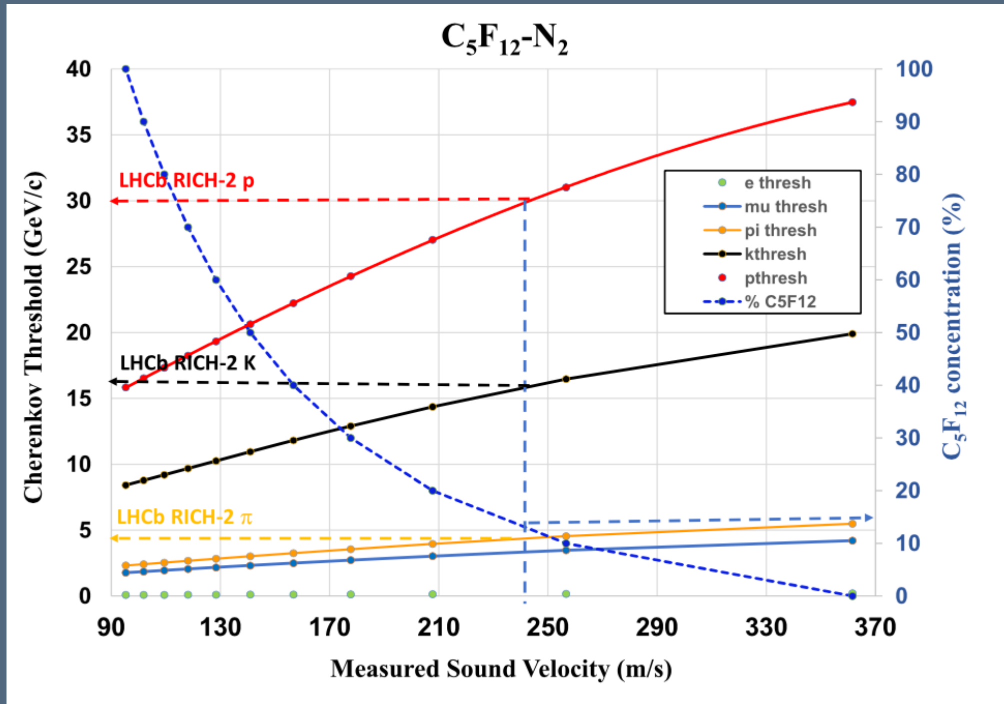


Fig. 7 Left: Cherenkov thresholds for particle species versus measured sound velocity in a radiator gas combining C_5F_{12} with N_2. Right: C_5F_{12} concentration. The C_5F_{12} concentration to match the LHCb RICH-2 $p^{\pm}$, $K^{\pm}$ & $\pi^{\pm}$ thresholds (with much lower GWP load: Table 1) is shown on the right axis

Emissions from detectors

G. D. Hallewell, EPJ Plus (2023)

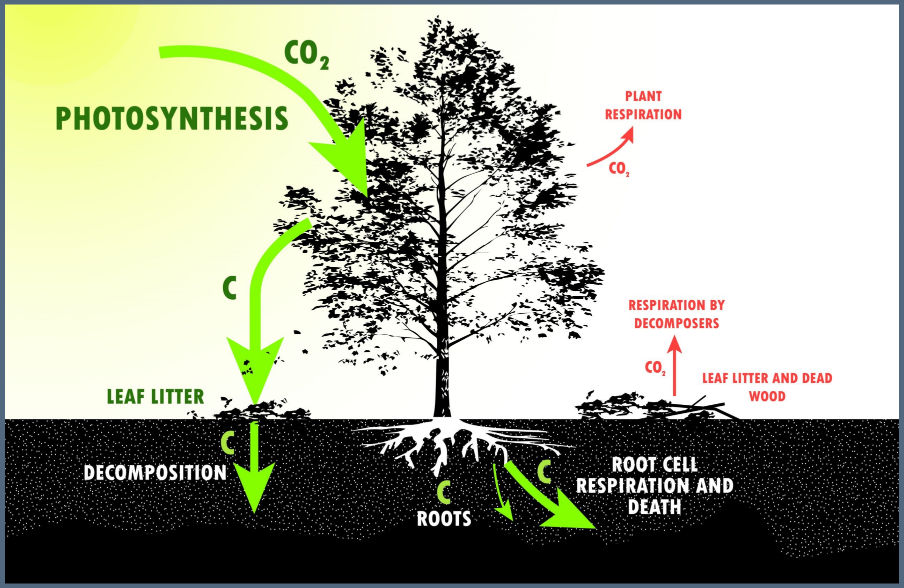
G. D. Hallewell, ICHEP 2024

- LHC exp. moving to CO_2 cooling
  - But because of high triple point, can't cool to low enough temperatures
- Potential replacement for C_6F_{14} :
  - NOVEC 649 ($C_6F_{12}O$): similar thermophysical properties
  - Radiation hardness promising, but reacts with water
  - Now used for cooling SiPM in LHCb SciFi to -50C
- Potential replacement for C_2F_6 (C_3F_8):
  - NOVEC-like C_2F_4O (C_3F_6O)?? Toxicity issue
- 3M is stopping the Novec line! Future of HFO/PFK uncertain
- R&D driven by electronics industry!

Negative Emissions

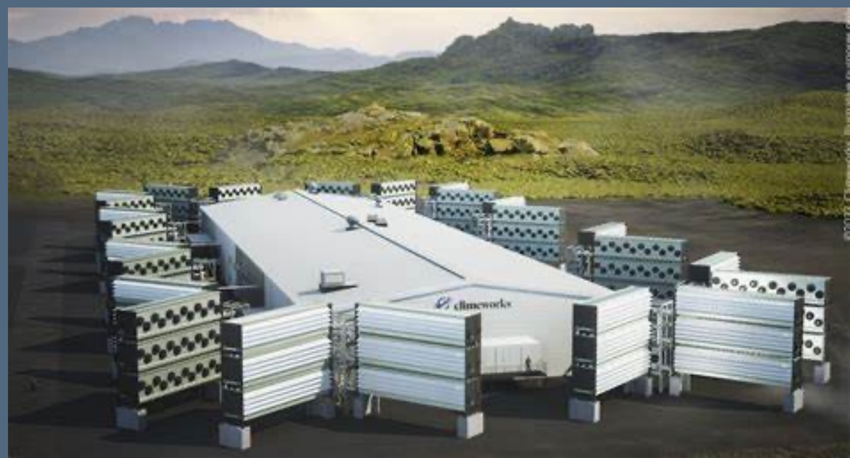
- STFC has goal of being Net-Zero by 2040…
- What are going to be the negative emissions methods?
  - Forget about power (zero by 2030 (2035))
  - Forget about "efficiency"

- What about future energy frontier collider facilities?
- Plant trees?
  - To absorb 1MtCO2 over 10 y: need ~10 M NEW trees = 4,000-10,000 ha of land = 4x – 11x area of Richmond Park
  - After those 10y you need to cut the trees and use them (eg build houses)
  - If burn them: need to capture the CO_2 and store it (BECCS)



Negative emissions

- Direct Air Capture (DAC)?
  - Biggest plant is Climeworks in Iceland, operate Orca (4 ktCO2/year, 11 t/day, 1 t/2-3h), needs 8k-18k kWh/tonne
  - Building Mammoth: 600 M USD
    - 36 ktCO2/y
    - Uses geothermal plant from Hellisheiði: 2.65 TWh/year
      - Hinckley Point C will be about 25 TWh/y
    - 1 Mt CO_2 = 28 years of using Mammoth



Conclusions

- R&D on accelerators:
  - Centre of Excellence in Sustainable Accelerators (CESA) at the STFC Daresbury Laboratory (Sustainable HEP 2024)
  - EU Horizon: Innovate for Sustainable Accelerating Systems (iSAS) (ICHEP 2024)
  - Yes minimize power
    - IMO PP facilities purchasing renewable energy providers (solar farms, etc.) is NOT a good idea!
  - Look at materials
    - Including cement!
  - The bigger the footprint, the more emissions!
- R&D on detectors:
  - Eg. we need to crack eco-gases (DRD1)
- R&D (and scaling up) on net zero agenda:
  - Help national grid decarbonize
  - Help negative emissions technologies
  - And more!

ESU PP 2024-2026: Sustainability input

- Channels to contribute to Sustainability input (s), no CERN account needed:
  - CERN mailing list
  - Mattermost team
  - Indico agendas
- First meeting this Friday (27th Sept.) at 2-3.30pm CEST
  - All meetings will be recorded
- Plan to meet every 2 weeks until converge on submission (s)
- Current organizers:
  - Veronique Boisvert (Veronique.Boisvert@cern.ch)
  - Daniel Britzger (britzger@mpp.mpg.de)
  - Yann Coadou (coadou@cppm.in2p3.fr)
  - Kristin Lohwasser (kristin.lohwasser@cern.ch)
  - Peter Millington (peter.millington@manchester.ac.uk)

Link

UK HEP Forum 2024: Sustainable future for HEP - challenges, solutions, opportunities

Nov 25 – 27, 2024
Europe/London timezone

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- Overview
- Timetable
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Contact

UKHEPForum@stfc.ac.uk

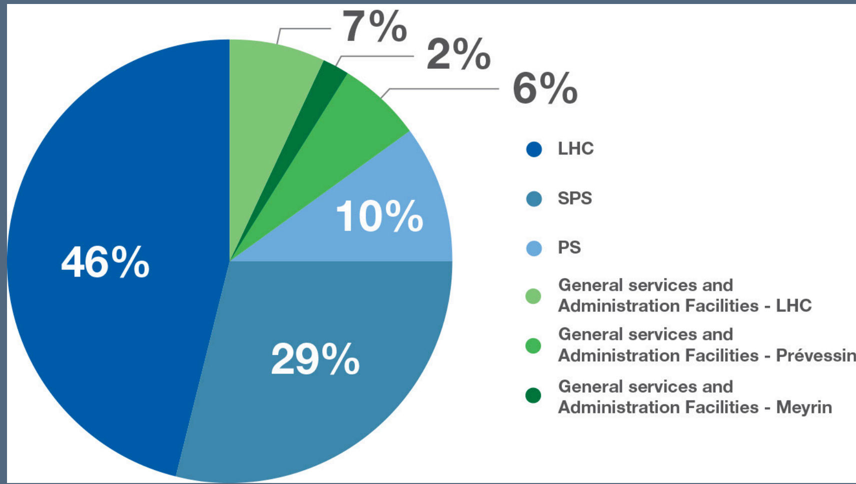
The UK HEP Forum 2024 will take place on 26-27 November 2024 at The Cosener's House in Abingdon, Oxfordshire, and via Zoom.

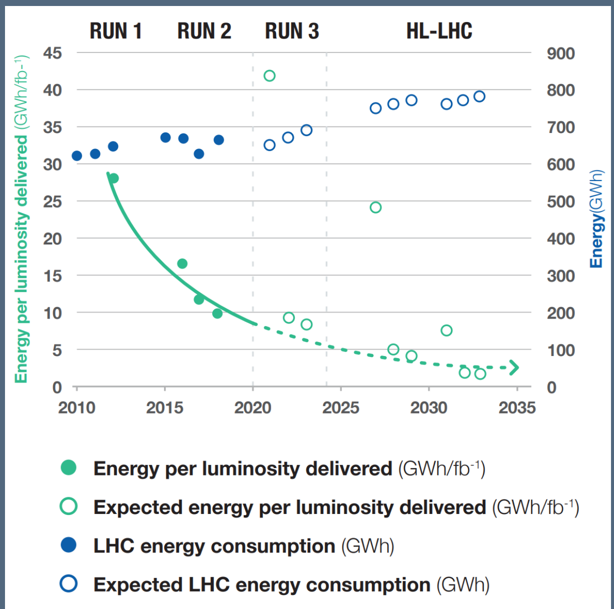
BACK UP

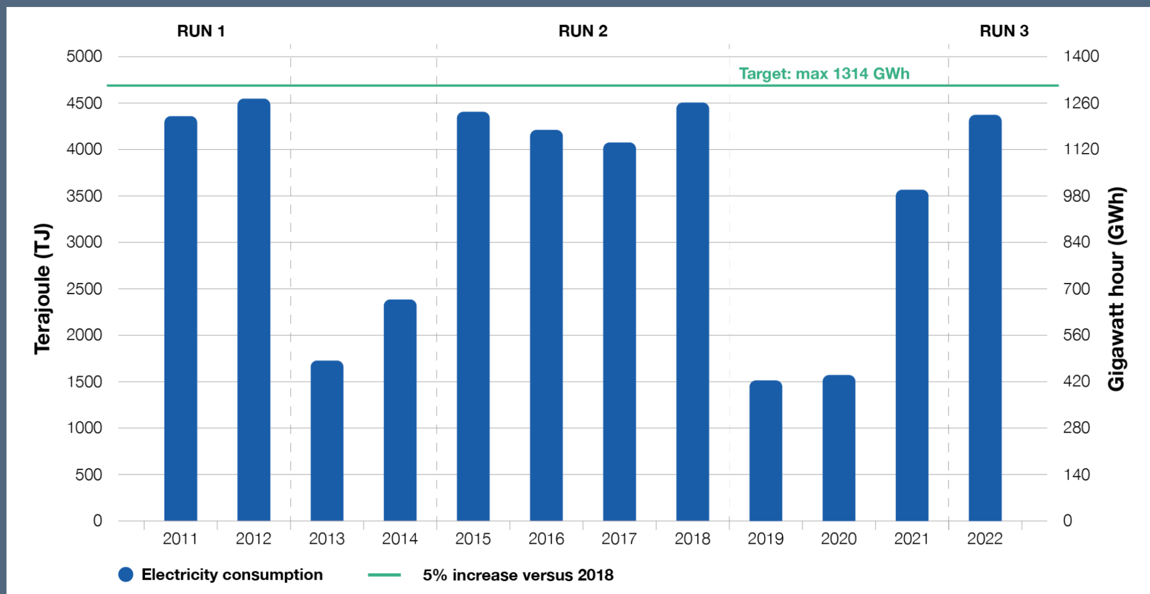
Emissions from accelerators: operations

- CERN now releases Environment reports (1st: 2017-18, 2nd: 2019-20, 3rd: 2021-22)
- CERN peak power: ~180 MW (~ 1/3 of Geneva)
- Per year: ~ 1.2 TWh (~ 2% of Switzerland, 0.03% of Europe)
- LHC: ~55% of CERN's E consumption
- Electricity mainly comes from France: 90% carbon free (2022)

Electrical power distribution 2018







Emissions from accelerators: construction

- Potential future of energy frontier: FCC (ee then hh)
  - ~100 km tunnel, caverns, buildings, roads, etc.
- Concrete needed for the tunnel, which means (Portland) cement!
- Half of emissions from Portland clinker (ref)
- Ken Bloom and my rough calculation:
  - ~260k tonnes of CO2 emissions
- Paper on emissions from road tunnels:
  - Lowest estimate: ~500k tonnes CO2 emissions
- Comparison: Using report for CO2e for construction of buildings: = building 8 London Shards!
- 1.4% of CH CO2e emissions (2016)
- Plant 6 million trees!

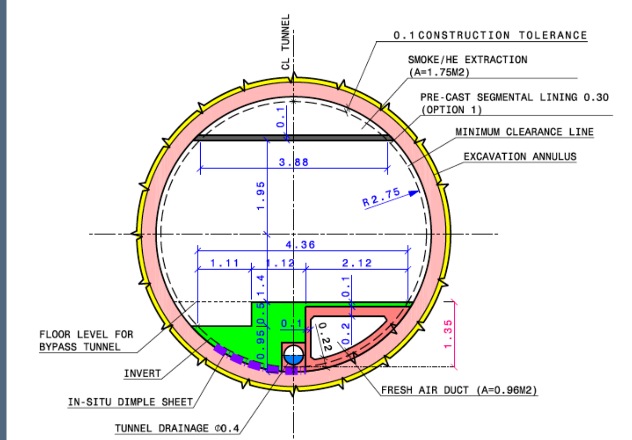


Fig. 4.4. Machine tunnel cross-section in "good" molasse.

$$CaCO_3 + \text{heat} \longrightarrow CaO + CO_2$$

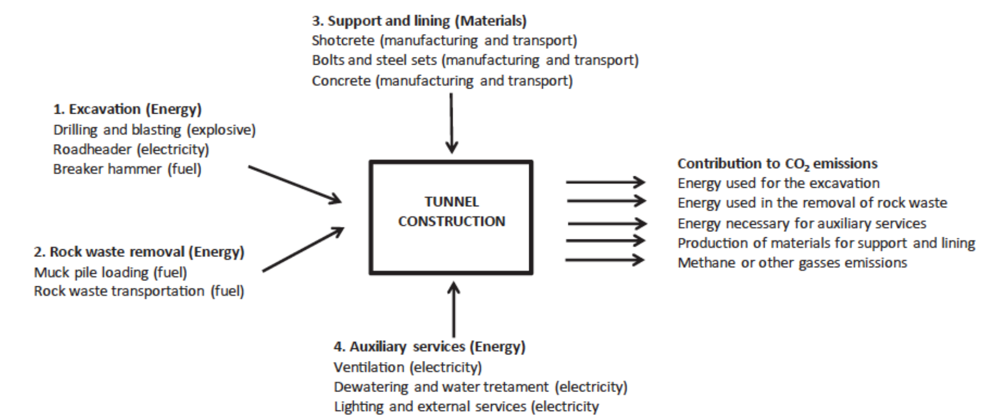
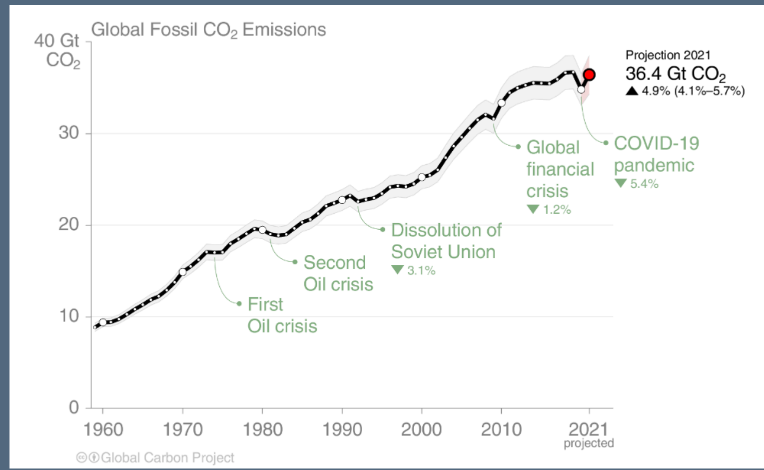


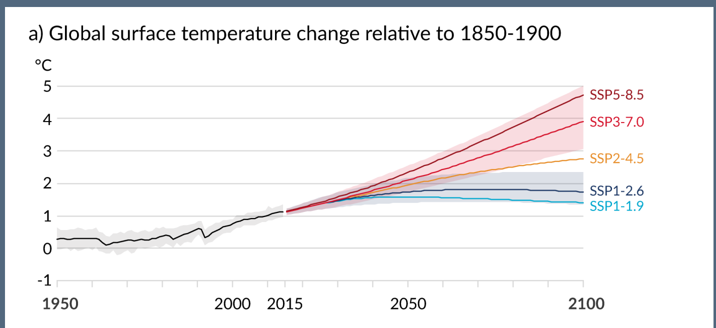
Fig. 1. Schematic overview of the system boundary.

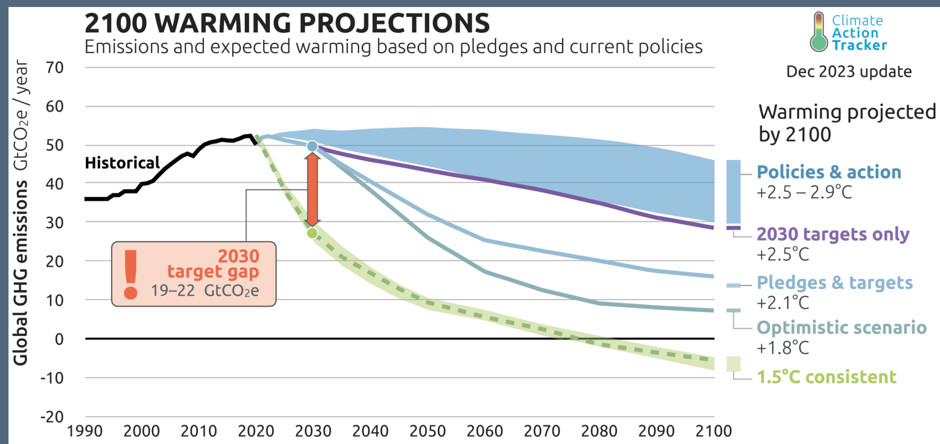
Climate Change: an emergency

- UK parliament first to approve a motion to declare an "environment and climate emergency" on 1st May 2019
- Of the top 10 GHG emitters, only Japan, Canada and the EU have legally binding target of "net zero emissions by 2050 (2045)"
  - The pandemic was a blip (lessons)
- IPCC 2015 Paris agreement: aim to stay "below 2°C" so focus on 1.5 °C
  - NDC: Countries make pledges for how to achieve this (and then increase those pledges over time)
  - Climate Action Tracker: "With all target pledges, including those made in Glasgow, global greenhouse gas emissions in 2030 will still be around twice as high as necessary for the 1.5 °C limit"



IPCC AR6





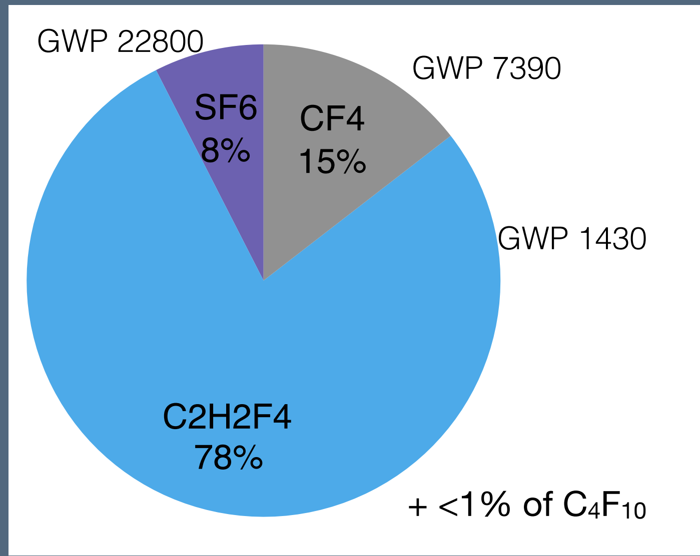
Ice ages: ~ -5℃

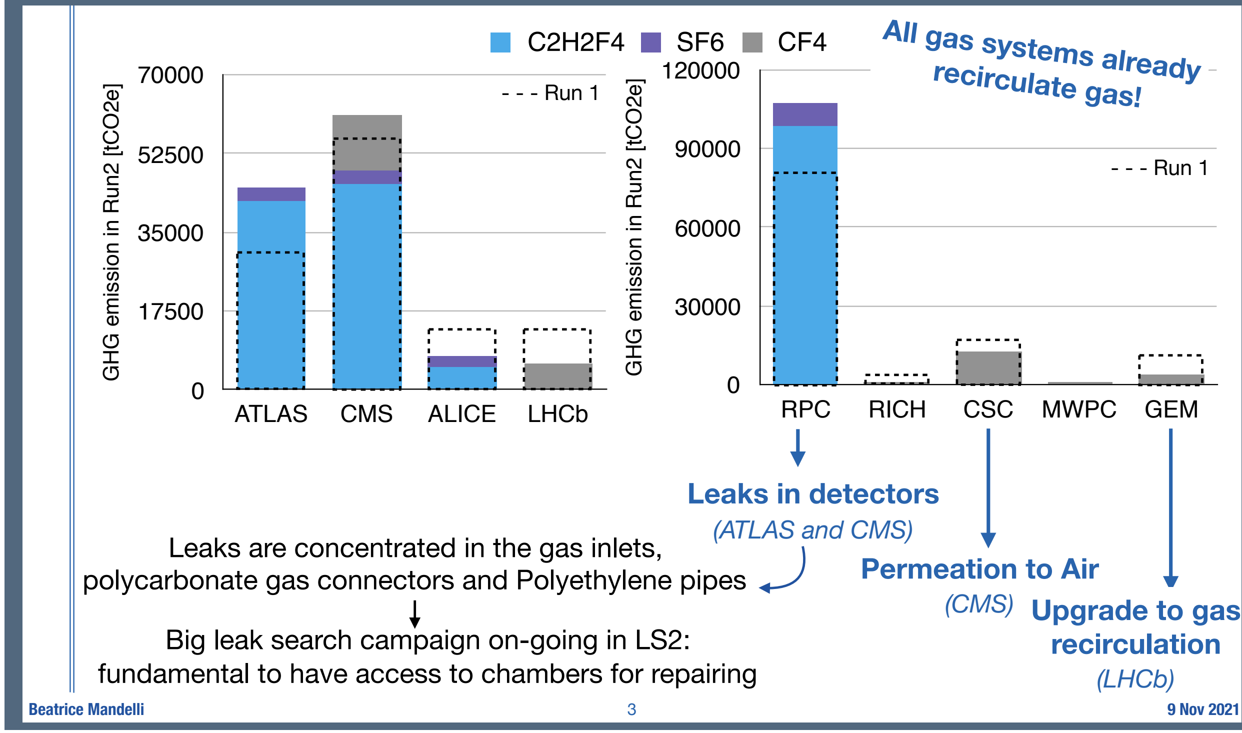
+4℃: civilization breakdown…

Emissions from detectors

- SF6, HFCs and PFCs: particle detection
- HFCs and PFCs: detector cooling
- HFCs: air conditioning systems
- SF6: also used for electrical insulation in power supply systems

Particle detection

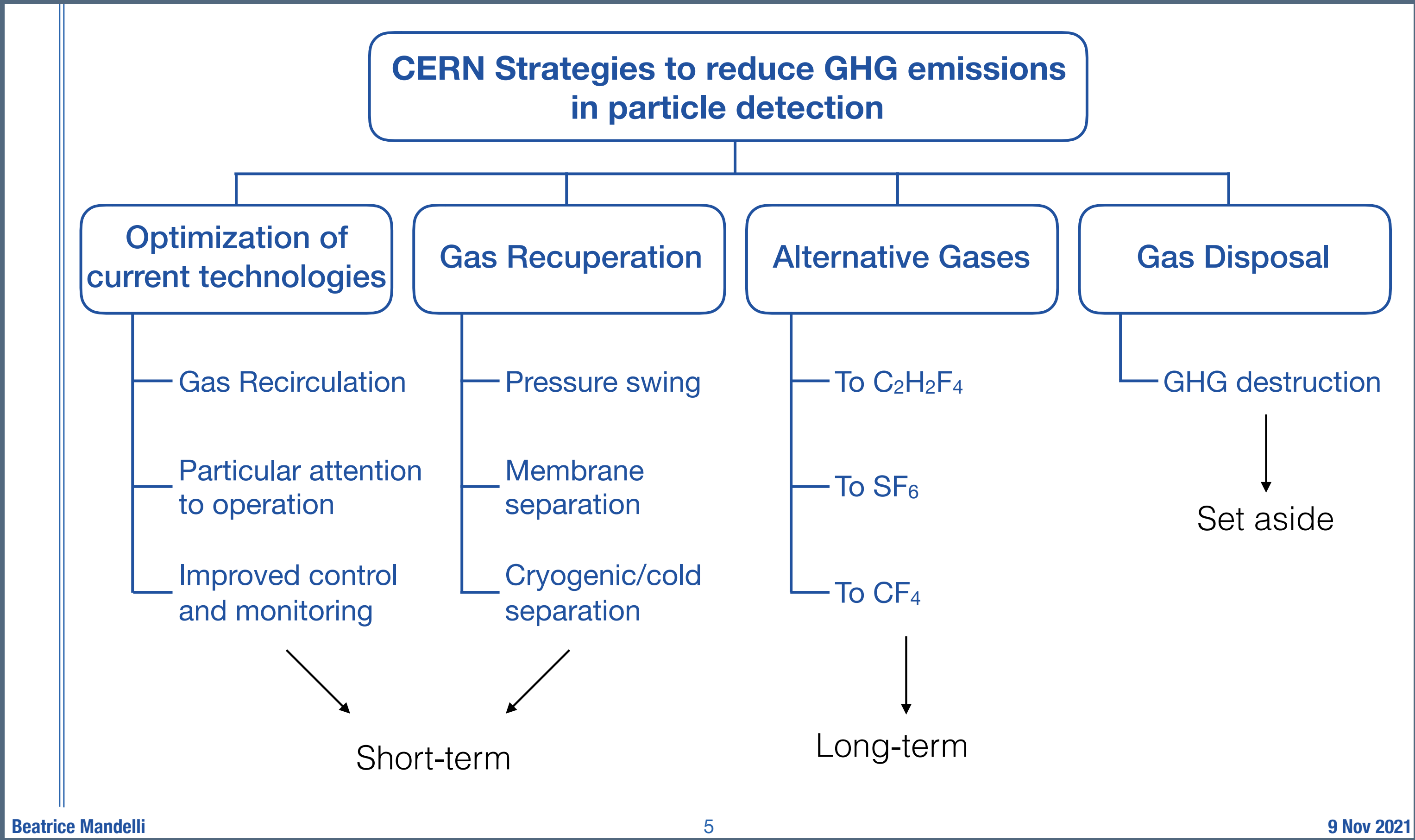




- Gas recirculation is 90%

Emissions from detectors: solutions

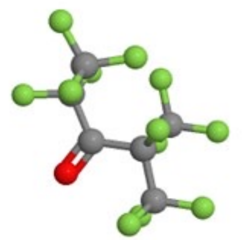
- 2020: CERN launched a working group on managing F-gases, with representatives from the departments concerned and the large LHC experiments. The group looked at issues such as the implementation of a centralised F-gas procurement policy, leak detection, replacement alternatives, training courses for personnel handling F-gases, and improving traceability and reporting.



Emissions from detectors: solutions

- Crucial to do R&D in finding replacements (eco-gases) and ensure 100% leak-free and 100% recirculation
  - **CERN has tested NOVEC 649: Equivalent radiation stability to C_6F_{14} used as a liquid coolant in all LHC experiments**

G. D. Hallewell



NOVEC 649 $C_6F_{12}O$
($GWP_{20} = \leq 1$)
[12]
$CF_3CF_2C(O)CF(CF_3)_2$

C_6F_{14}
($GWP_{20} = 5890$)
[16]

The "green" use of fluorocarbons in Cherenkov detectors and silicon tracker cooling systems: challenges and opportunities in an unfolding era of alternatives

Embedded emissions from accelerators & detectors

HECAP+ 2023

- Future projects need to compute the full life cycle analysis of emissions of all accelerator and detector components

Best Practice 6.1: Life cycle data for a silicon wafer
The ecological impacts of a 1 cm^2 silicon wafer (thickness 775 μm, diameter 300 mm, weight 0.128 kg) as identified in 2000, are summarised in Table 6.1 [194].

Inputs	Quantity	Outputs	Quantity
Hydrogen chloride HCl (hydrochloric acid)	0.00675 kg	Co-products: Si in other co-products	0.000286 kg
Graphite (as electrode material)	0.000163 kg	Co-products: Silicon tetrachloride	0.00415 kg
Wood chips	0.00183 kg	Co-products: Si residues for solar cells	65.2×10^{-6}
Petroleum coke	0.000597 kg	Polished silicon wafer	1 cm^2
Quartz	0.00486 kg		
Electricity	0.385 kWh		
Dry wood	0.00398 kg		

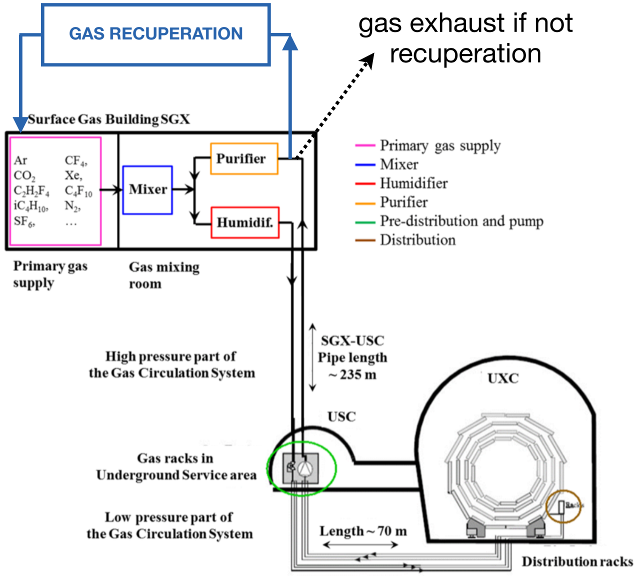
Air emissions	Quantity	Discharge to Water	Quantity
CH_4	68.8×10^{-6} kg	Metal chlorides	0.000787 kg
CO	0.000167 kg		
CO_2	0.00833 kg	Waste	Quantity
Ethane	29×10^{-6} kg	SiO_2	16.3×10^{-6} kg
H_2O	0.00188 kg		
Methanol	85.1×10^{-6} kg		
NOx	13.8×10^{-6} kg		
Particulate matter	0.000201 kg		
SO_2	34.4×10^{-6} kg		
Hydrogen	0.000125 kg		

Table 6.1: Inputs, outputs and emissions of silicon wafer production [194].

Gas Recuperation systems at LHC experiments

*Sometimes it is not possible to recirculate 100%
of the gas mixture due to detector constrains*

- Air **permeability**, max recirculation **fraction**, impurities, etc.
- A fraction of gas has to be **renewed**
  - Some gas is sent to the atmosphere
- This fraction of gas mixture can be sent to a recuperation plant where the GHG is extracted, stored and re-used
  - **Challenges**: R&D, custom development, operation and recuperated gas quality
- Gas recuperation also to **empty/fill** the detectors during LS



LHCb RICH1 and RICH2

During LS2 need to empty the detectors for maintenance/upgrade:

RICH1: 4 m^3 of C_4F_{10} → Gas recuperation system for empty/filling and cleaning from Air contamination

RICH2: 100 m^3 of CF_4 → New gas recuperation system developed for the empty and filling of the detector

CMS CSC

Small Permeability to Air: accumulation of N_2

↓

Need to inject fresh gas continuously to keep N_2 stable and guarantee detector performance

↓

~80 l/h of CF_4 would be lost in exhaust without gas recuperation system

The R134a recuperation system for RPCs

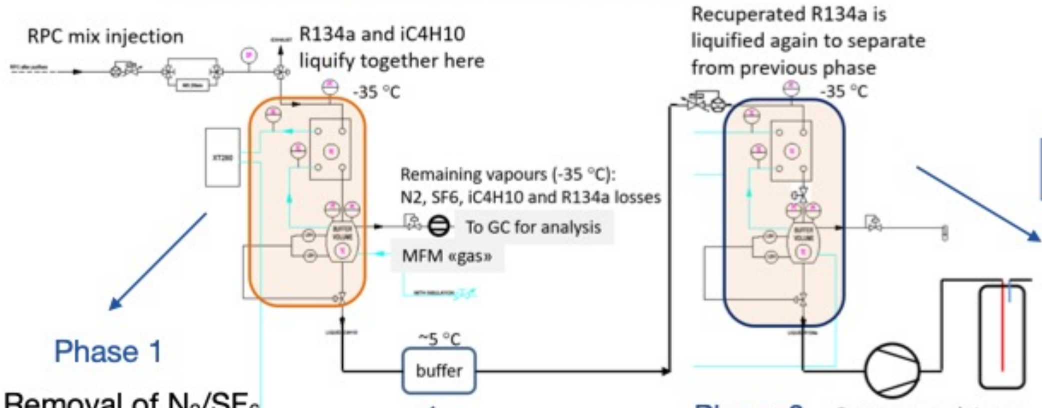
ATLAS and CMS RPC Gas Systems

- Detector volume ~15 m^3
- Gas mixture: ~95% $\mathbf{C_2H_2F_4}$, ~5% iC_4H_{10}, 0.3% $\mathbf{SF_6}$
- Gas recirculation: ~90%
  - Maximum recirculation validated for RPC detectors
- **Fundamental to repair detector leaks**
  - To have the gas at the exhaust of the gas system

R134a and iC_4H_{10} form an azeotrope

↓

A mixture of liquids whose proportions cannot be altered or changed by simple distillation



Phase 1

Removal of N_2/SF_6 by simple distillation

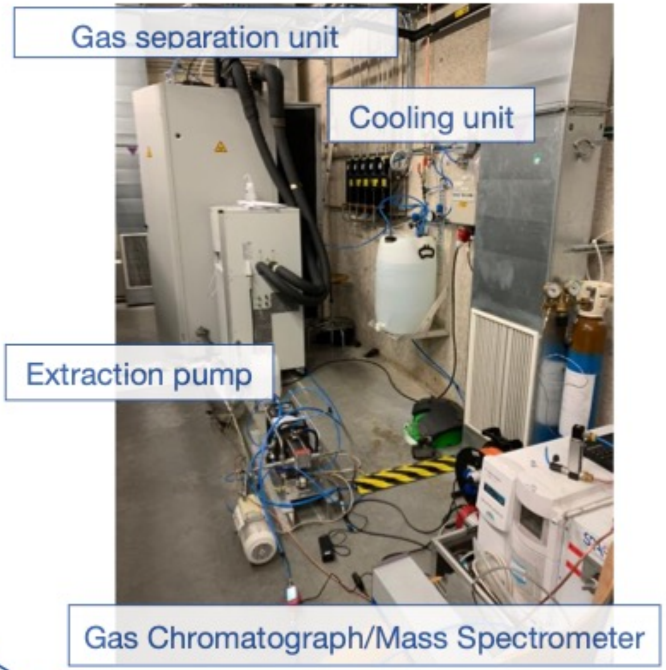
Phase 2

Detachment of R134a from iC_4H_{10}

Phase 3

Compression of R134a

$C_2H_2F_4$ recuperation prototype system under study in CMS Experiment



Recuperation efficiency ~80%

First $C_2H_2F_4$ recuperation system under construction: installation foreseen beginning of 2023 in CMS experiment

Gas disposal

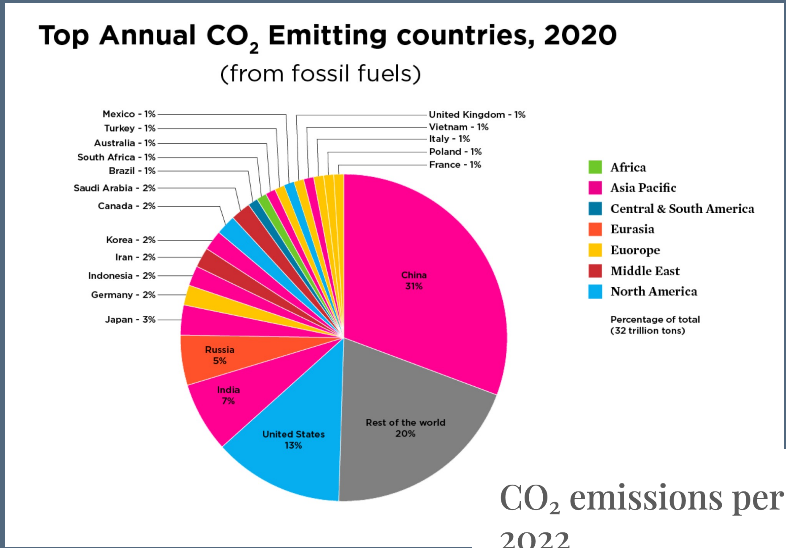
Abatement plants are employed when GHGs are polluted and therefore are not reusable

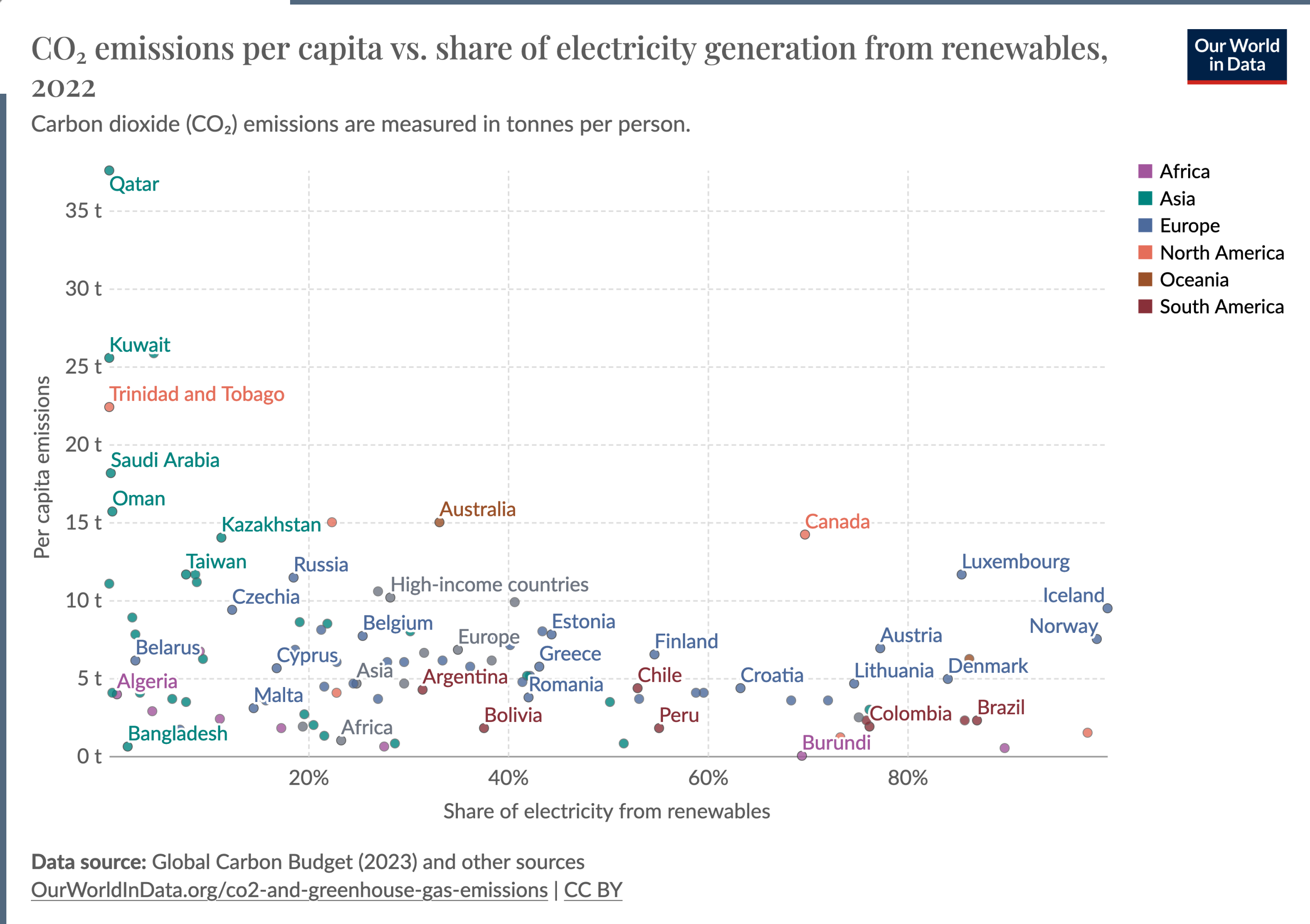
In case all studies on recuperation will not bring to efficient recuperation plants, industrial system able to destroy GHGs avoiding their emission into the atmosphere have been considered

Quite heavy infrastructure required:

- CH_4/city gas + O_2 supply + N_2 supply
- Waste water treatment
- PFC/HFC are converted in CO_2 + HF acid dissolved in water
- disposal of remaining waste/mud
  - To have the gas at the exhaust (600-1000 l/h)

Found also companies available to take PFC/HFC based mixture for disposal: but extremely expensive


Top Annual CO_2 Emitting countries, 2020
(from fossil fuels)
Mexico - 1%
Turkey - 1%
Australia - 1%
South Africa - 1%
Brazil - 1%
Saudi Arabia - 2%
Canada - 2%
Korea - 2%
Iran - 2%
Indonesia - 2%
Germany - 2%
Japan - 3%
United Kingdom - 1%
Vietnam - 1%
Italy - 1%
Poland - 1%
France - 1%
China 31%
Russia 5%
India 7%
United States 13%
Rest of the world 20%
Africa
Asia Pacific
Central & South America
Eurasia
Euorope
Middle East
North America
Percentage of total (32 trillion tons)

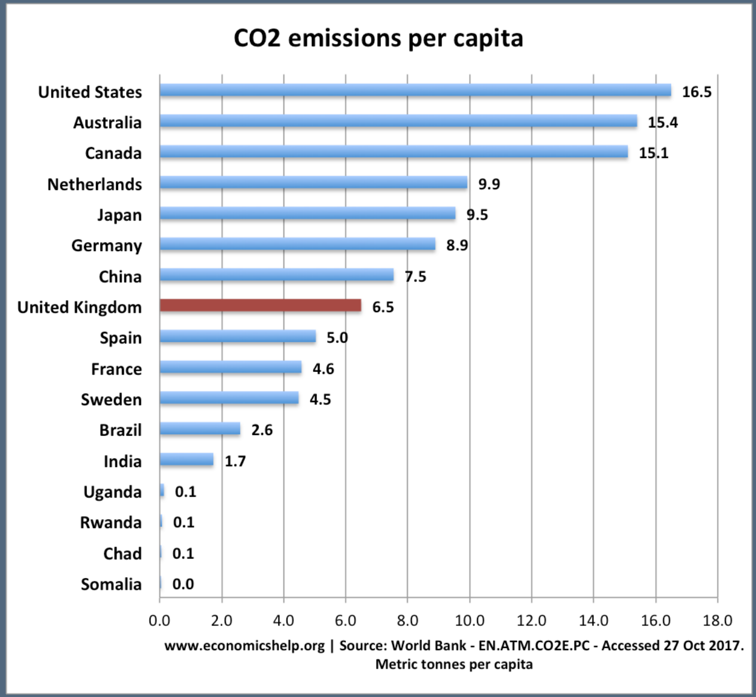

CO_2 emissions per capita vs. share of electricity generation from renewables, 2022
Carbon dioxide (CO_2) emissions are measured in tonnes per person.
Our World in Data
Africa
Asia
Europe
North America
Oceania
South America
Per capita emissions
35 t
30 t
25 t
20 t
15 t
10 t
5 t
0 t
20%
40%
60%
80%
Share of electricity from renewables
Qatar
Kuwait
Trinidad and Tobago
Saudi Arabia
Oman
Kazakhstan
Australia
Canada
Taiwan
Russia
High-income countries
Luxembourg
Iceland
Czechia
Belgium
Estonia
Norway
Belarus
Europe
Finland
Austria
Cyprus
Greece
Asia
Argentina
Chile
Croatia
Lithuania
Denmark
Algeria
Romania
Malta
Bolivia
Peru
Colombia
Brazil
Africa
Bangladesh
Burundi
Data source: Global Carbon Budget (2023) and other sources
OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY

List of top CO_2 emitters

Forbes

Country	2018 CO2 Emissions in Billion Metric Tons	Global Share	Change Since Kyoto Protocol
China	9.43	27.8%	54.6%
U.S.	5.15	15.2%	-12.1%
India	2.48	7.3%	105.8%
Russia	1.55	4.6%	5.7%
Japan	1.15	3.4%	-10.1%
Germany	0.73	2.1%	-11.7%
South Korea	0.70	2.1%	34.1%
Iran	0.66	1.9%	57.7%
Saudi Arabia	0.57	1.7%	59.9%
Canada	0.55	1.6%	1.6%

Economicshelp.org



Emissions pathway

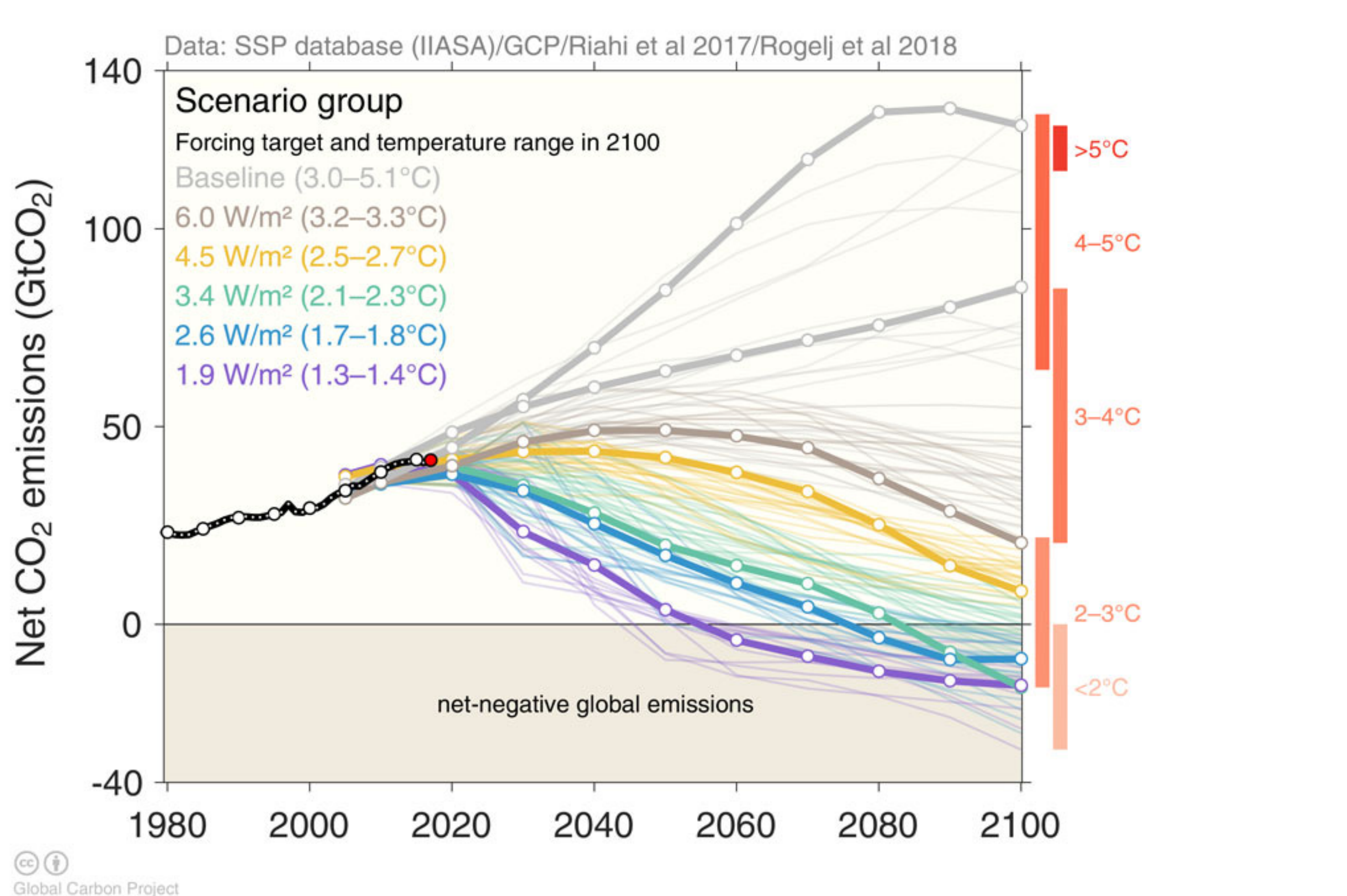
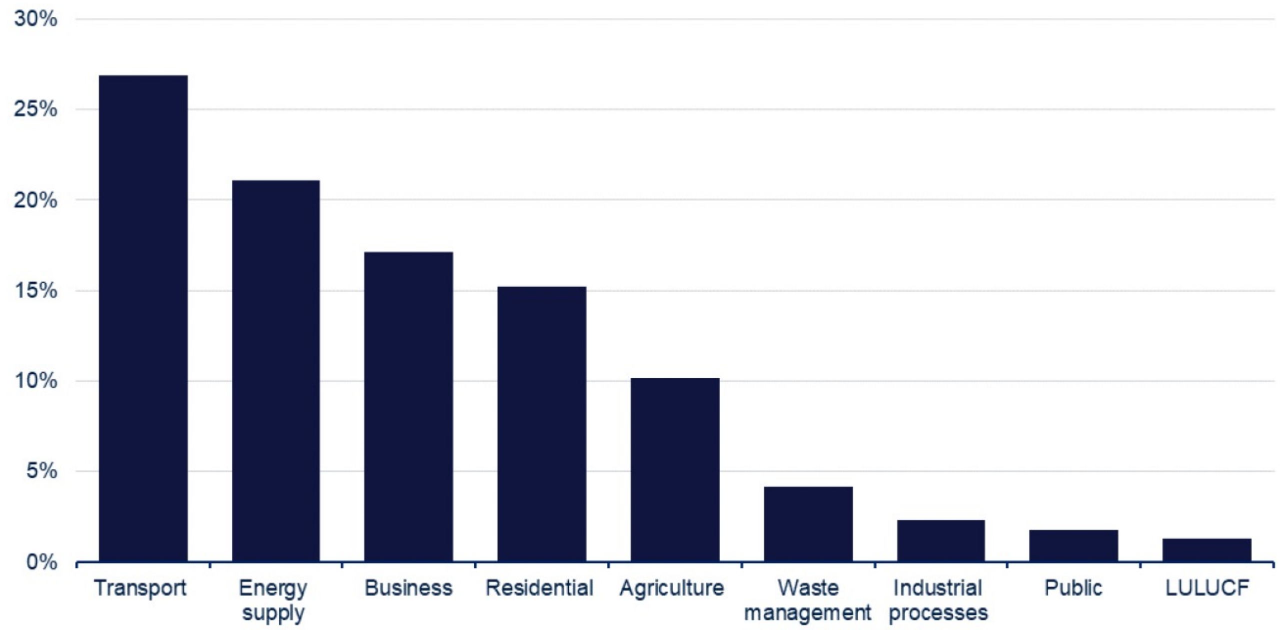


Figure 4: Territorial UK greenhouse gas emissions by NC sector, 2019 (%)



Source: Table 1.2, Final UK greenhouse gas emissions national statistics 1990-2019 Excel data tables

Note: LULUCF is land use, land use change and forestry.

[World Emissions Clock]

Green electricity grids by 2035

- Germany's target updated in 2022
  - The US, Canada and UK have already committed to a similar goal [100% renewable electricity grid by 2035]. Denmark is already aiming for more than 100% renewable power by 2027, Austria 100% by 2030 and Portugal and the Netherlands are well on track with recent plans to expand renewable capacities till 2030."

- US pledge
- UK CCC plan: