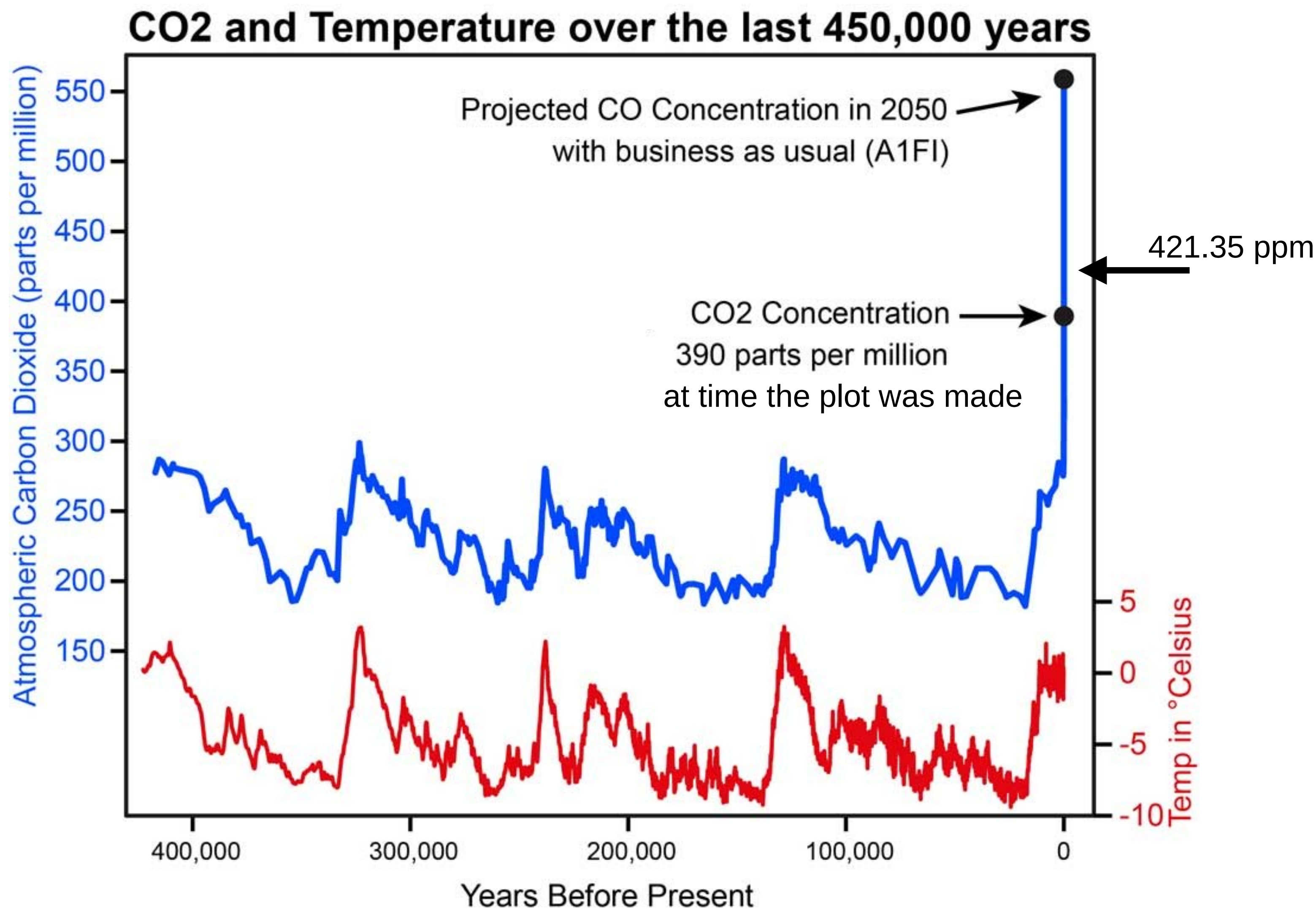
Sustainability in particle, nuclear and astroparticle physics

Kristin Lohwasser (U of Sheffield)

4th June 2025

Climate Change: We are outside the “normal” range



What are the current impacts

- We see impacts of rising temperatures: Drought, floods, high temperatures, severe weather events **with billions of damages**

- **Storm Daniel** - deadliest Mediterranean tropical-like cyclone:
  - more than two billion euros in damage,
  - devastation in Greece’s most fertile plain (20% of harvest destroyed with also long-term damage to fields due to silt)
  - more than 4000 death in Lybia
  - up to 10-50 time more likely due to climate change

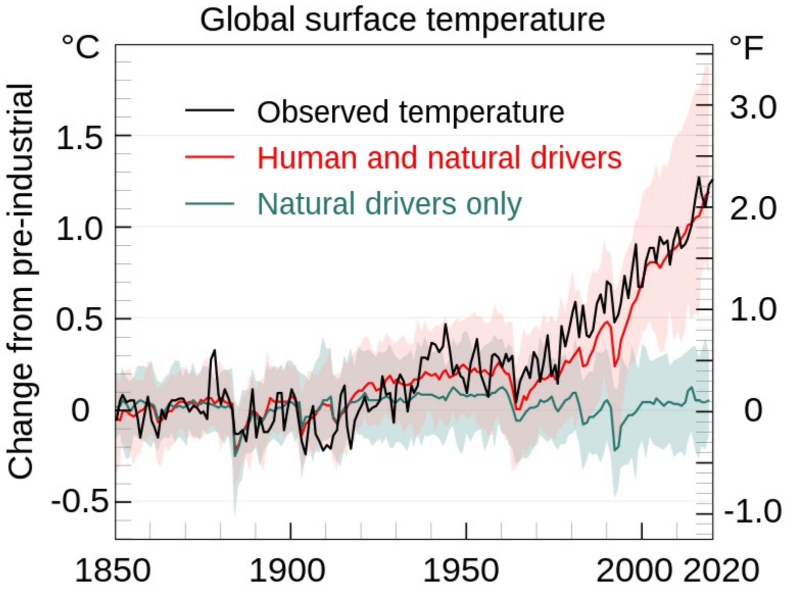
- Whilst not all of these extreme weather events are caused by climate change, *their occurrence will get more and more frequent*

Weather or Climate?

- Whilst extreme weather events have a finite probability and therefore “just” can happen, this **finite probability is strongly influenced by climate conditions**

  → ”extreme event attribution / attribution science”→ new field of study in meteorology and climate science using statistical methods and concepts not completely foreign to particle physicists.

- Using the framework of attribution science, the current level of climate change is fully attributed attributed to human activity



- Climate sets the probability (like a cross-section)
- Weather is a single event (like a collision) drawn from that cross-section
- Can attribute probabilities of (signal or background -- or rather human-made versus natural climate) to a single weather event

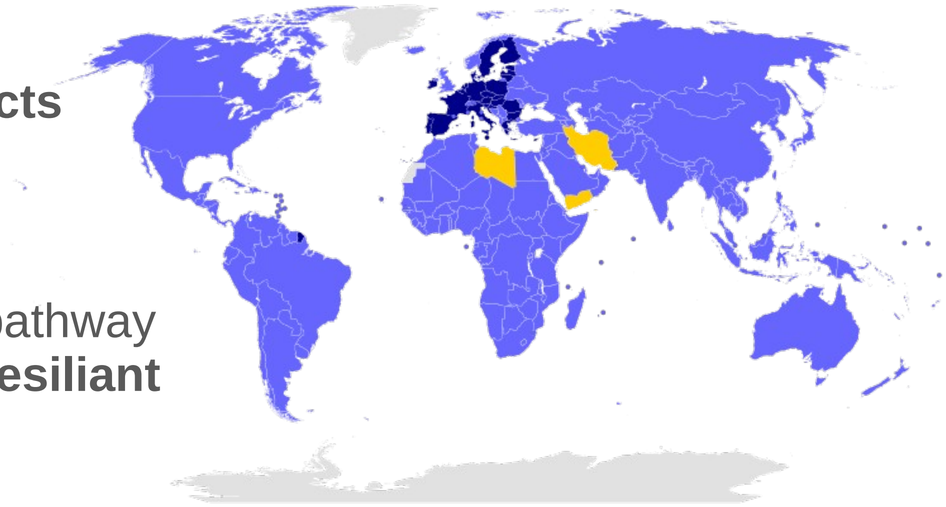
Political consequences

- **The 2015 Paris Agreement**
  → Drafted 30 November – 12 December 2015 in Le Bourget, France
  → Effective 4 November 2016 after more than 55 UNFCCC parties, accounting for 55% of global greenhouse gas emissions had ratified and acceded
  → 195 signatories

- Hold global average temperature **well below 2°C** above pre-industrial levels and to pursue efforts to **limit the temperature increase to 1.5 °C**

- Push ability to **adapt to adverse impacts and foster climate resilience**

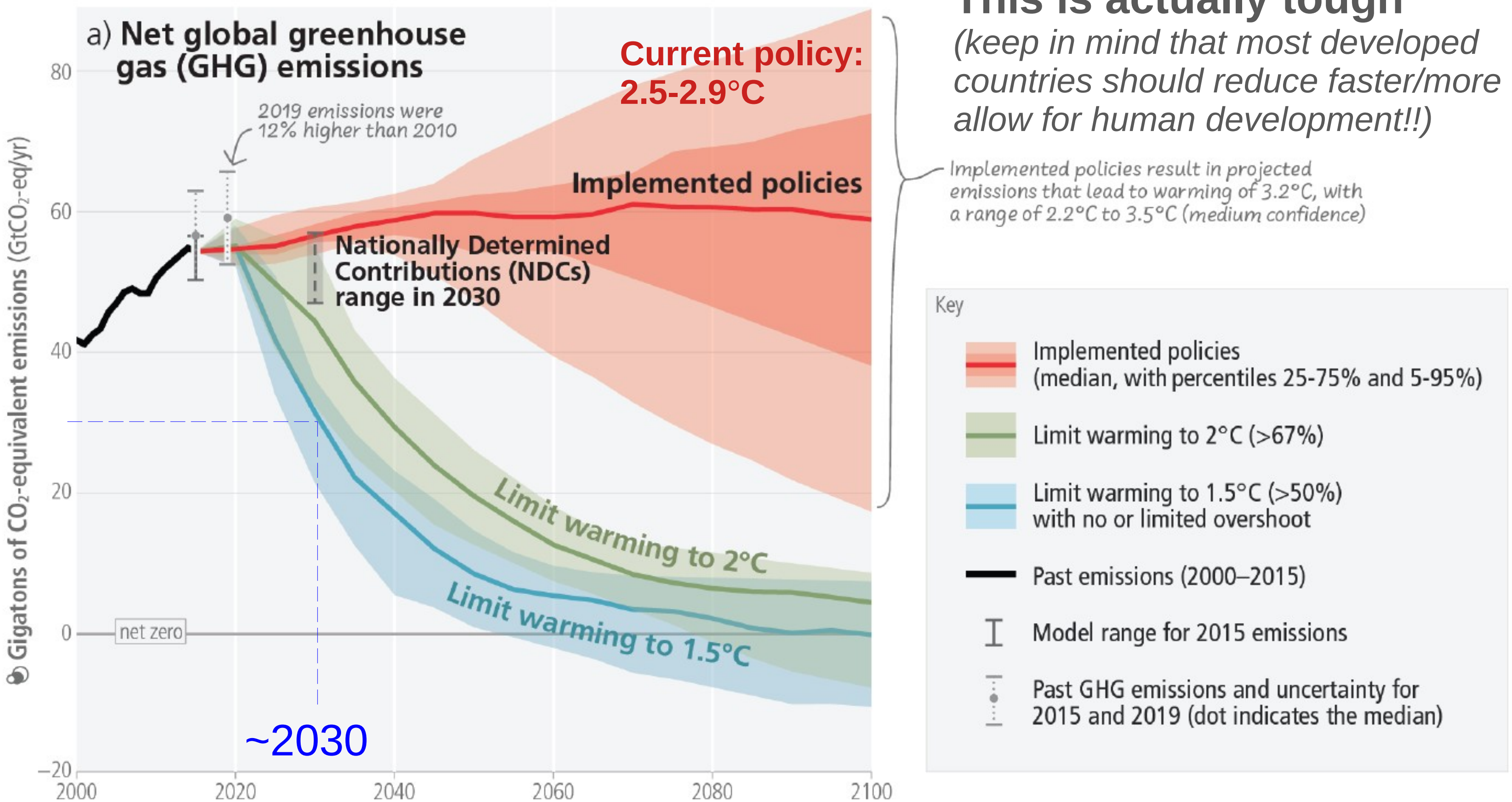
- **Make finance flows consistent** with pathway towards **low emissions and climate-resiliant developement**



Yellow: signed, not ratified

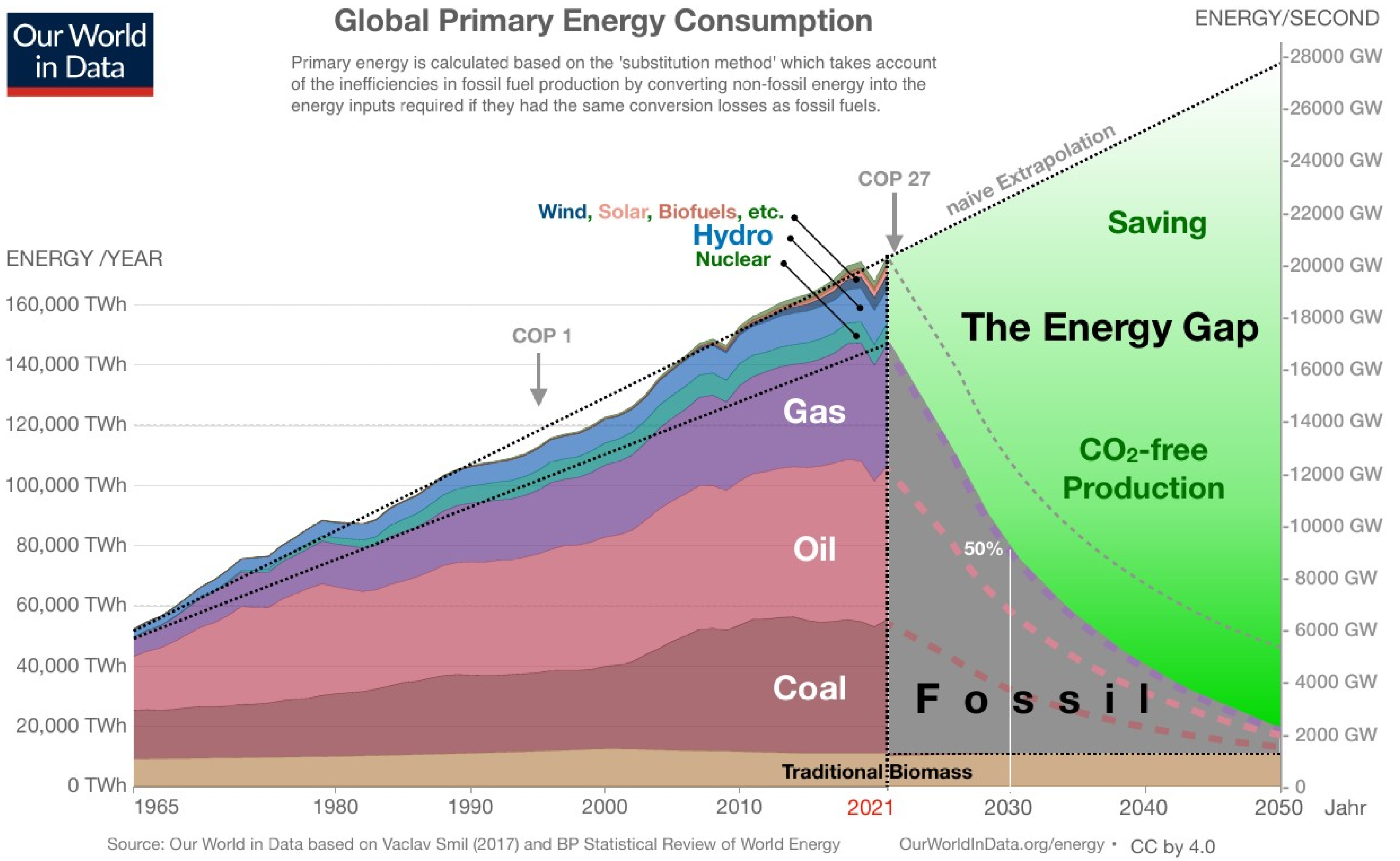
Translation of Paris into Goals

- **Reduction to zero emissions around 2100**
  → A lot of time?
  → 50% of the reduction should be achieved by ~2030 → **in 5 years**



This is actually tough
(keep in mind that most developed countries should reduce faster/more to allow for human development!!)

The energy gap



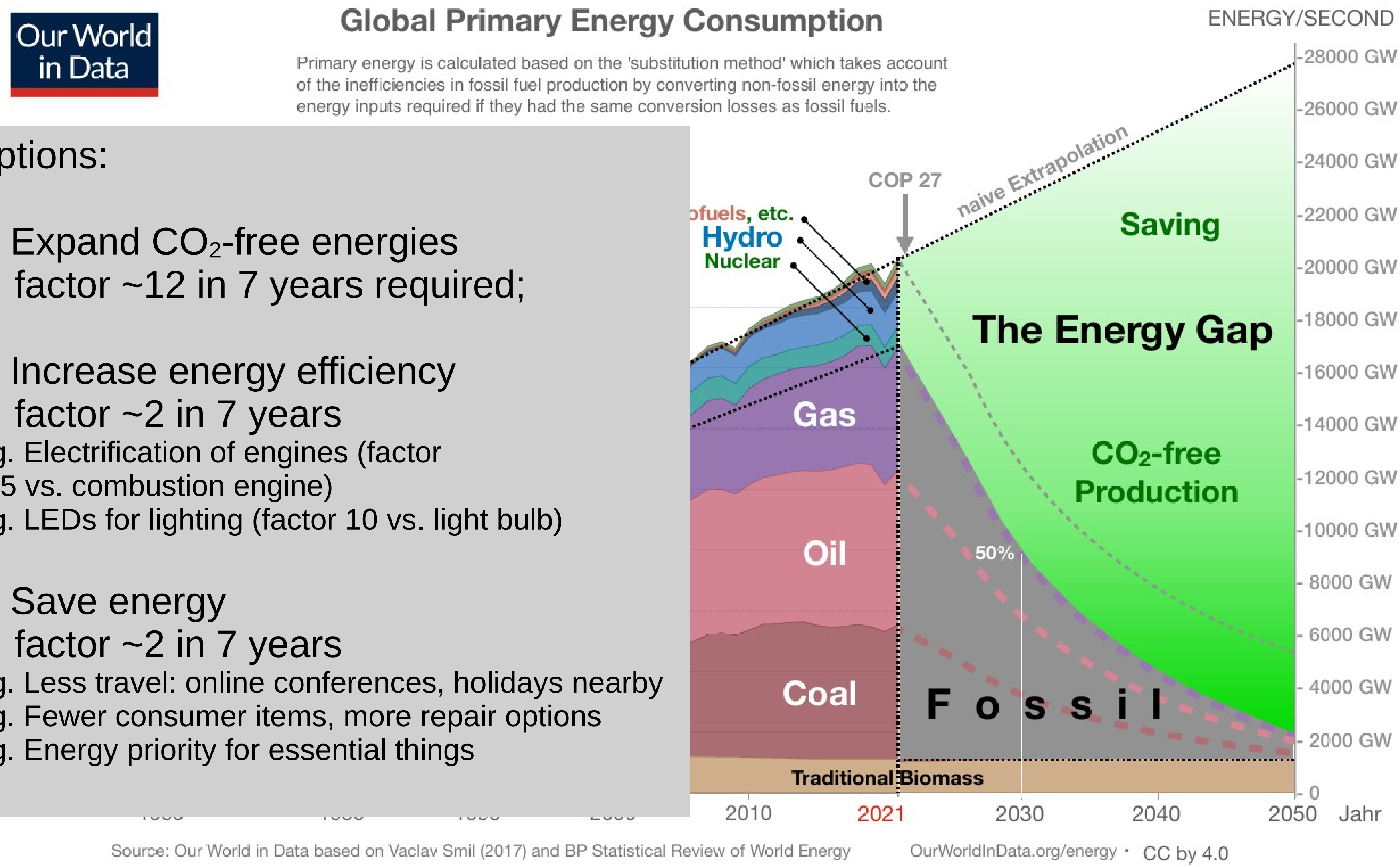
The energy gap

Options:

1) Expand CO_2-free energies
→ factor ~12 in 7 years required;

2) Increase energy efficiency
→ factor ~2 in 7 years
e.g. Electrification of engines (factor 3-5 vs. combustion engine)
e.g. LEDs for lighting (factor 10 vs. light bulb)

3) Save energy
→ factor ~2 in 7 years
e.g. Less travel: online conferences, holidays nearby
e.g. Fewer consumer items, more repair options
e.g. Energy priority for essential things



Why does sustainability matter for particle physics?

- **Legal:** e.g. German scientists self-committed to be CO_2e neutral by 2035 & many countries demand to reach the Paris agreement

- **Funding:** will (likely) be tied to sustainability in the future
  → "A detailed plan for the minimisation of environmental impact and for the saving and re-use of energy should be part of the approval process for any major project." (European Strategy for HEP 2020, Ch. 7, Paragraph A; example: LHCb phase-II upgrade TDR)

- **Outreach:** we may want to tell the world in the future how sustainable we are and how we got there

- **Society:**
  we have extraordinary many smart minds around
  we can help pioneering ideas and be a role model for society and companies
  who if not scientist will start paving the way?

Sustainability for future colliders

[…] I think the there has been growing awareness over the past years on the importance of sustainability and minimizing the impact of our research infrastructure on the environment.

I think it's very important that our field becomes again a model: […] we're model of worldwide collaboration we're model of technological development I think it would be good if you could also become a model of sustainable research and show that research can be done in a sustainable way.

[…] We should ramp up those efforts and it's clear that a future collider whichever this collider will be must be of course carbon neutral. This is a very difficult thing [...] to have an impact on the environment which is absolutely acceptable by Society otherwise this will be a show showstopper.

(Fabiola Gianotti)

Panel discussion on Future Colliders

Panelists:
Fabiola Gianotti (CERN), Lia Merminga (FNAL), Yifang Wang (IHEP), and Shoji Asai (KEK)

https://www.youtube.com/watch?v=IE3DY0dQo_I&t=5793s

Where do we stand?

- **Environmental Sustainability in basic research – A perspective from HECAP+**

  → What's the current status in our field

- **Sustainability HEP workshops**

  → What's new in our field

- **The FCC, the European strategy input, ….**

  → What's the future in our field

- **… the rest**

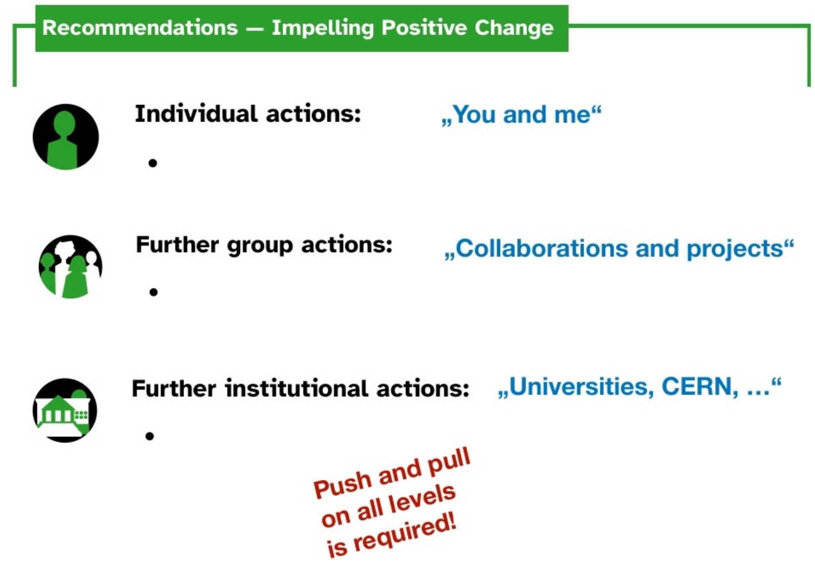
  → Other initiatives and plans

Environmental Sustainability in basic research

Gives an overview over current status of sustainability in HECAP+ (High Energy Physics, Cosmology and Astroparticle Physics + Hadron and Nuclear Physics)

Reports in alphabetical order on:

→ Computing
→ Energy
→ Food
→ Mobility
→ Research Infrastructure and Technology
→ Resources and Waste



(including also **Best practices**, **Case studies** and very general **Recommendations**)

Assessing, reporting on, defining targets for, and under-taking coordinated efforts to limit our negative impacts on the world's climate and ecosystems must become an integral part of how we plan and undertake all aspects of our research.

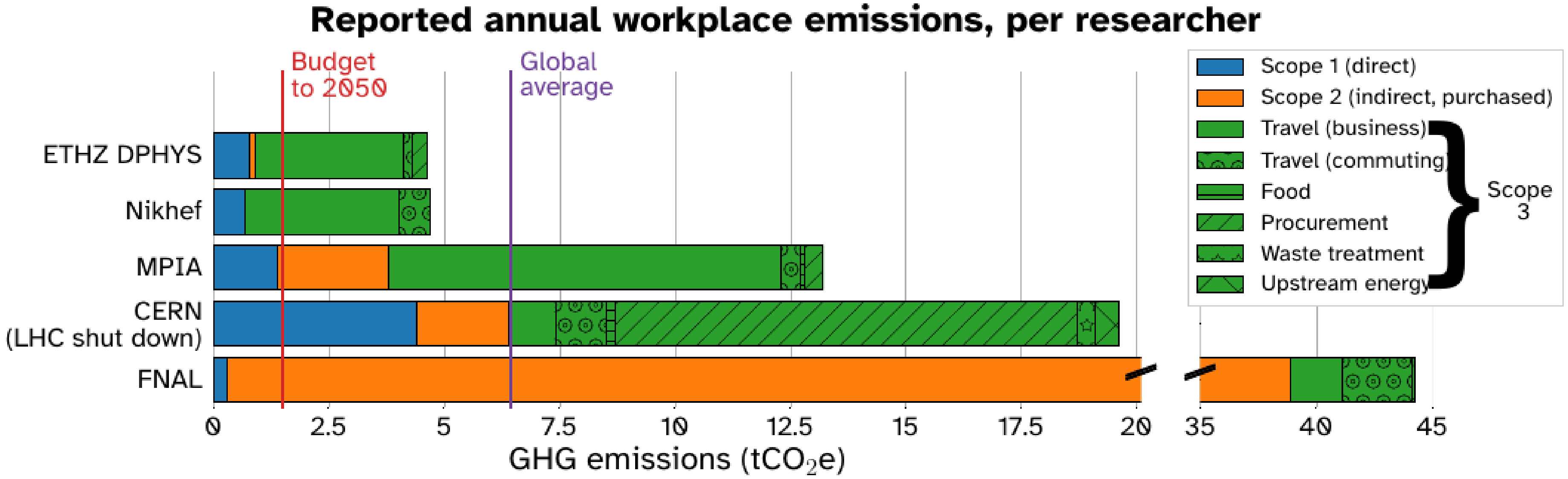
Environmental sustainability in basic research: a perspective from HECAP+
Sustainable HECAP+ Initiative Collaboration • Shankha Banerjee et al.
e-Print: 2306.02837 [physics.soc-ph],
DOI:10.1088/1748-0221/20/03/P03012 (publication)
Published in: JINST 20 (2025), P03012

https://sustainable-hecap-plus.github.io/

Workplace emissions in HECAP+

- Comparisons between institutes interesting, but also down to local and specific circumstances
  - CERN: no travel to experimental site
  - MPIA (Max-Planck Astronomy): Travel to Chile
  - Nikhef: paying for electricity from renewables (from a large provider who sells also a large amount of fossil fuel electricity)
  - Fermilab: Extremely CO_2-intensive energy sources

Scope 1: gases
Scope 2: electricity
Scope 3: the rest



2019 data, save MPIA (2018), and ETHZ business travel (average 2016-2018).

Computing

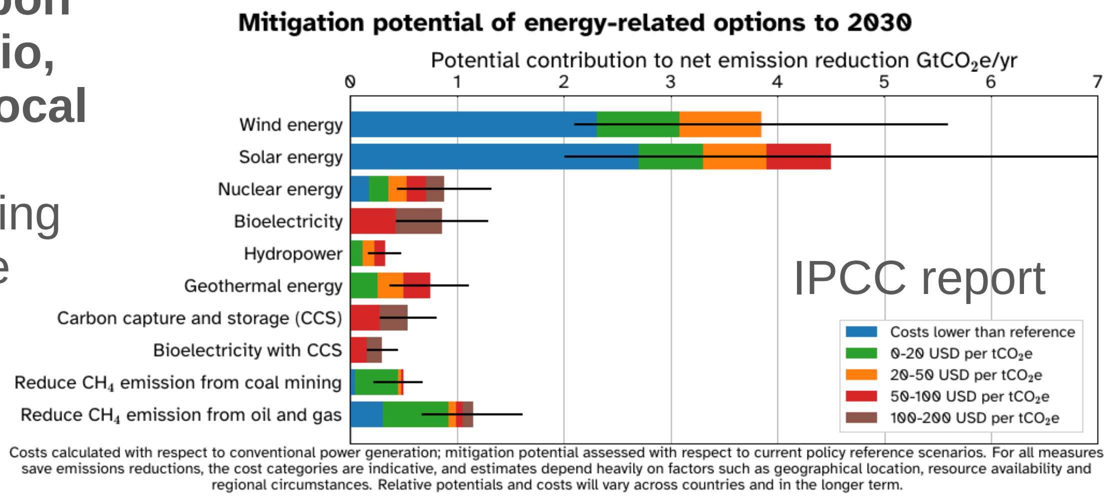
- **Hardware:**
  Manufacturing 50% - 80% of a devices CO2e footprint (server vs. laptop)
  → Infrastructure to **keep, reuse, recycle, repair**! Extend use lifecycle

- **Infrastructure:**
  Well managed, centralized systems optimized for specific (HEP) applications key to address challenges
  → Optimized PUE (=Power Usage effectiveness → Total Power/Energy used by IT)
  → Current **best centres:** 1.05-1.2 mainly due to heat recovery from cooling system for heating **(HECAP+ best practice examples: GSI green cube 1.07, CERN data centre: 1.5 (1.1 planned), Swiss National supercomputing (1.2 at 25% full load)**
  → world average ~1.55, WLCG assumed 1.45
  → well maintained data centres reacting to production and other grid loads, can help balance grid

- **Software:**
  HECAP+ Code relies on libraries and public codes, general frameworks and software infrastructure provided by experts in the experiments.
  → Likelihood Inference Neural Network Accelerator (LINNA) for efficiency saved **$300,000 in energy costs and around 2,200 tCO2** in first-year for Rubin Observatory's Legacy Survey of Space and Time (LSST) analyses (https://dx.doi.org/10.1088/1475-7516/2023/01/016)
  → **Dedicated efforts can have a huge impact and directly measurable!**

Energy: Low Carbon Sources

- **Procuring energy from low carbon sources (wind, solar, nuclear, bio, hydropower) relies heavily on local circumstances and supplier**
  → renewable energy might hit ceiling
  → sometimes unclear, if purchase indeed promotes green energy



Costs calculated with respect to conventional power generation; mitigation potential assessed with respect to current policy reference scenarios. For all measures save emissions reductions, the cost categories are indicative, and estimates depend heavily on factors such as geographical location, resource availability and regional circumstances. Relative potentials and costs will vary across countries and in the longer term.

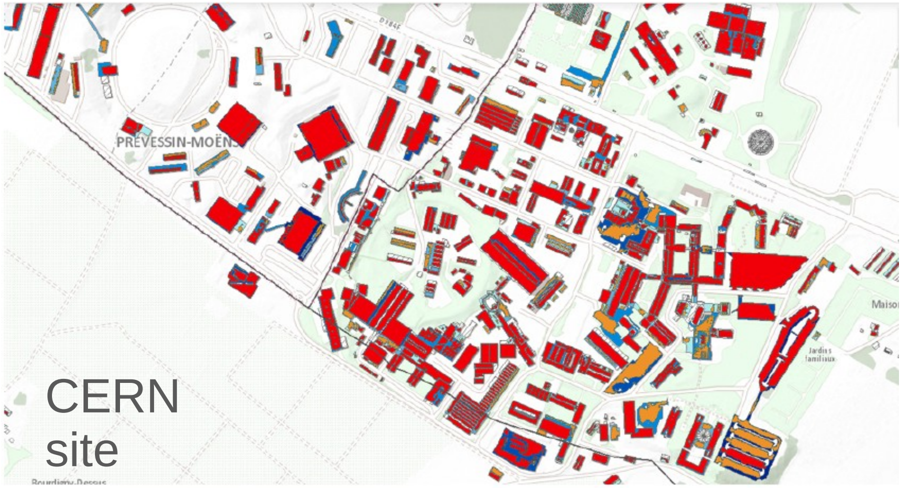
factor ~12 in 7 years required

- **Case study: Solar@CERN**
  → CERN has 653 buildings with a total roof area of 421,000 m² (red)

  → approximately 80 GWh annual electricity generation potential

  → 18% of CERN's basic (non-LHC) electricity demand could be produced locally with solar power. Other projects are conceivable

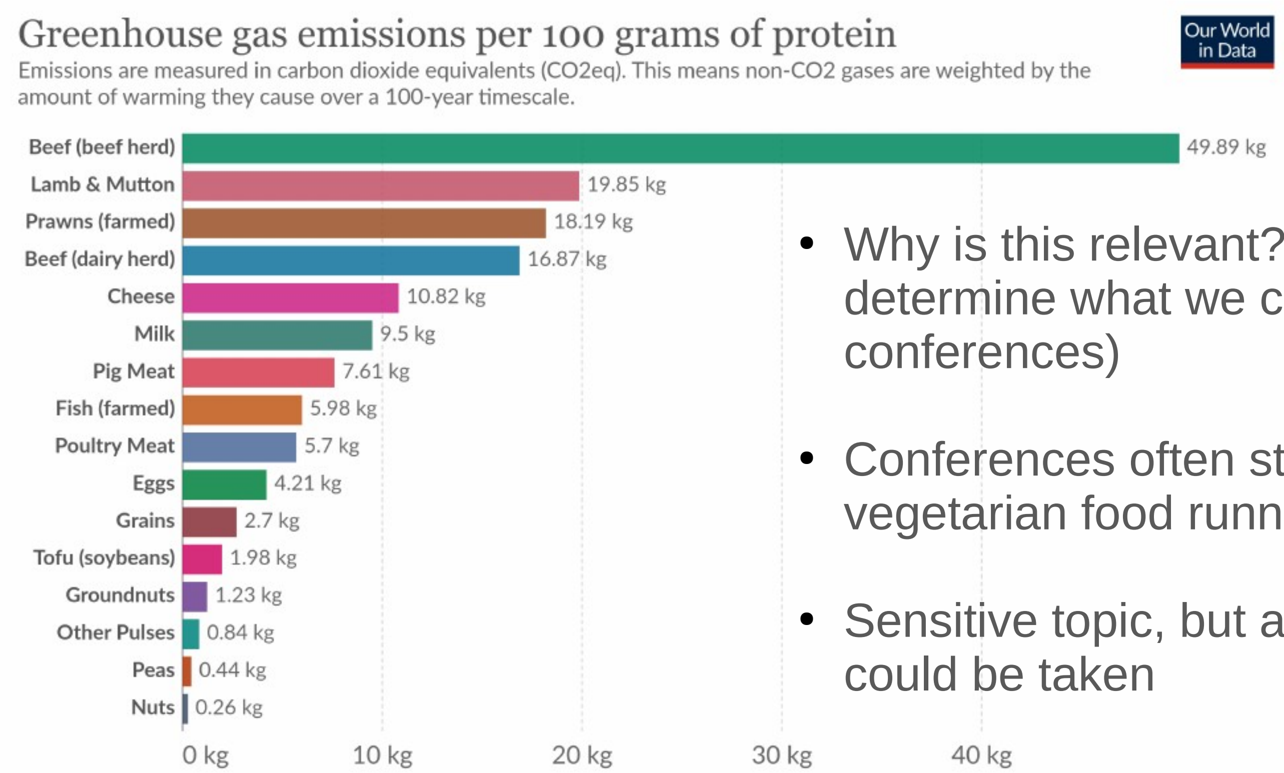
  → SESAME: fully solar powered



Food

- **Animal agriculture** responsible for just over 50% of GHG emissions from the food sector and accounts for 75% of global agricultural land use but provides only20% of world’s calories, and <40% of protein supply

- Lower meat consumption correlates with higher longevity



- Why is this relevant? What’s on offer does determine what we consume (canteen, conferences)

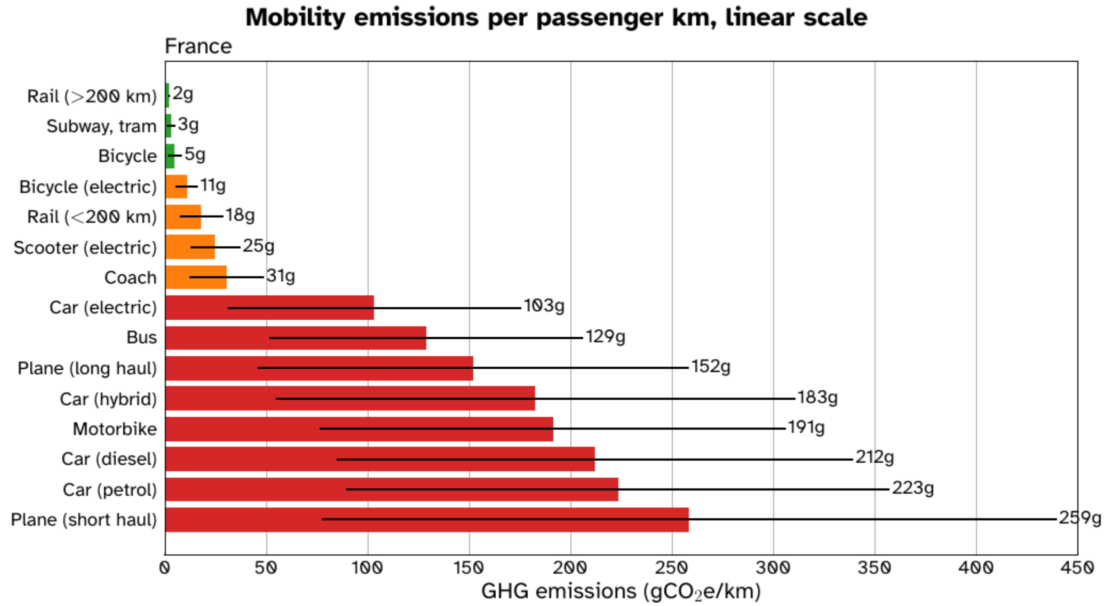
- Conferences often still meat focused, with vegetarian food running out

- Sensitive topic, but a number of soft measure could be taken

Mobility

Choice of transport is important
Choice *to* travel is important:
Work from home / remote conferences

Global scientific endeavour such as HECAP+ will always mandate some amount of long-distance travel



Downsides to hypermobility, aside sustainability concerns:
→ Visa rules and high long-haul travel costs challenging, esp. for researchers from Global South.
→ Travel difficult for people with disabilities, health impairments or caring responsibilities.

As food, it might appear small, but:
→ Air travel is ~2% of global emissions, but rising rapidly (up 32% in 5 years before pandemic)
→ Unlike electricity very hard to decarbonize
→ like food: in some cases low-hanging fruit: short-stay travel, insistence on in-person meetings or in-person contributions (e.g. instead of hiring local technicians)

Research Infrastructure and Technology

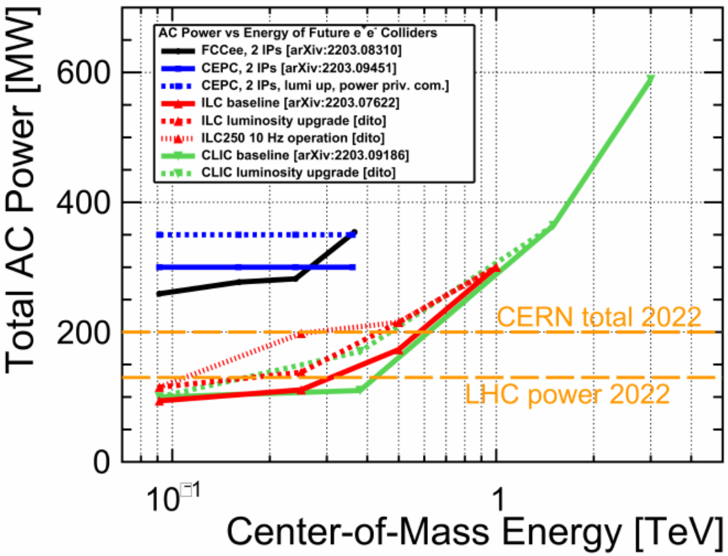
Accounting and Reporting

- Limited availability of data on emissions and resources consumption for basic research infrastructure, existing data is not standardised

  → Overall assessments of sustainability and comparisons of individual technologies challenging.

- **Implementation of effective life cycle assessment across the HECAP+ community could provide data for ongoing assessment of technologies and research infrastructure projects**

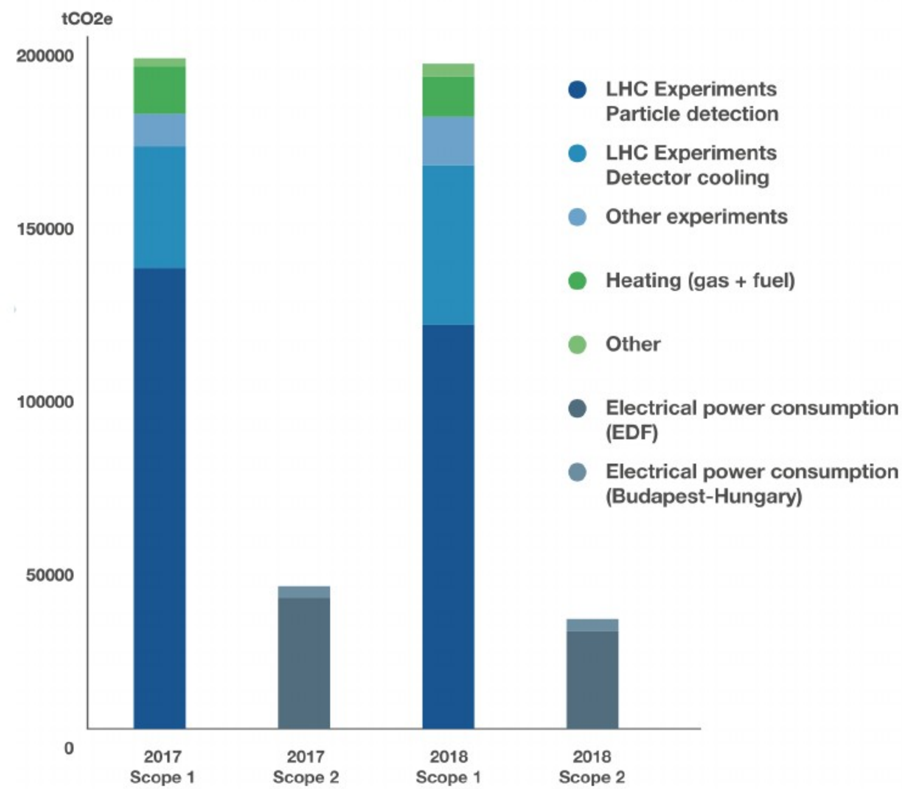
- A number of plannend and finalized assessments:
  → European Southern Observatory (ESO)
  → Giant Radio Array for Neutrino Detection
  → Relativistic Ultrafast Electron Diffraction and Imaging (RUEDI) facility (STFC)
  → Compact Linear Collider (CLIC)



- **French lab initative: https://labos1point5.org**
  German: Know your footprint **https://arxiv.org/abs/2403.03**

Research Infrastructure and Technology

- Greenhouse Gas (GHG) emissions from gases other than CO_2 are a major driver of emissions at CERN
- Main cause are RPC chambers in ATLAS and CMS as they contain HFC-134a (due to large areas, ***but also Ship and Dune plan RPC muon chambers***)
- HFC emissions are 6% of the Swiss emissions and about twice the size of Luxembourg's (201 2018) – HFC to be phased out in EU
- Future LHC detectors (Phase-II Upgrades) will switch to CO2 cooling
- Gas replacements less obvious (current candidates: equally bad forever chemicals, PFAS), but active research on replacement gase ongoing
- Not just leaks, there is a need to replenish ~10% fresh gases...



Name	Chemical Formula	Lifetime [years]	Global warming potential (GWP) [100-yr time horizon]
Carbon dioxide	CO_2	–	1
Dimethylether	CH_3OCH_3	0.015	1
Methane	CH_4	12	25
Sulphur hexafluoride	SF_6	3,200	22,800
Hydrofluorocarbons (HFCs)			
HFC-23	CHF_3	270	14,800
HFC-134a	$C_2H_2F_4$	14	1,430

Resources

- Procurement accounts for almost two-thirds of annual emissions at CERN and probably a similar size for other institutions

- **Mined materials** have largest impacts, materials used in HECAP+ experiments are produced with high environmental and societal costs (e.g., cobalt for magnets, rare earths for permanent magnets, niobium)

- Formal discussions of use and impact at recent workshop on Rare Earth Elements: iFAST - https://indico.desy.de/event/35655

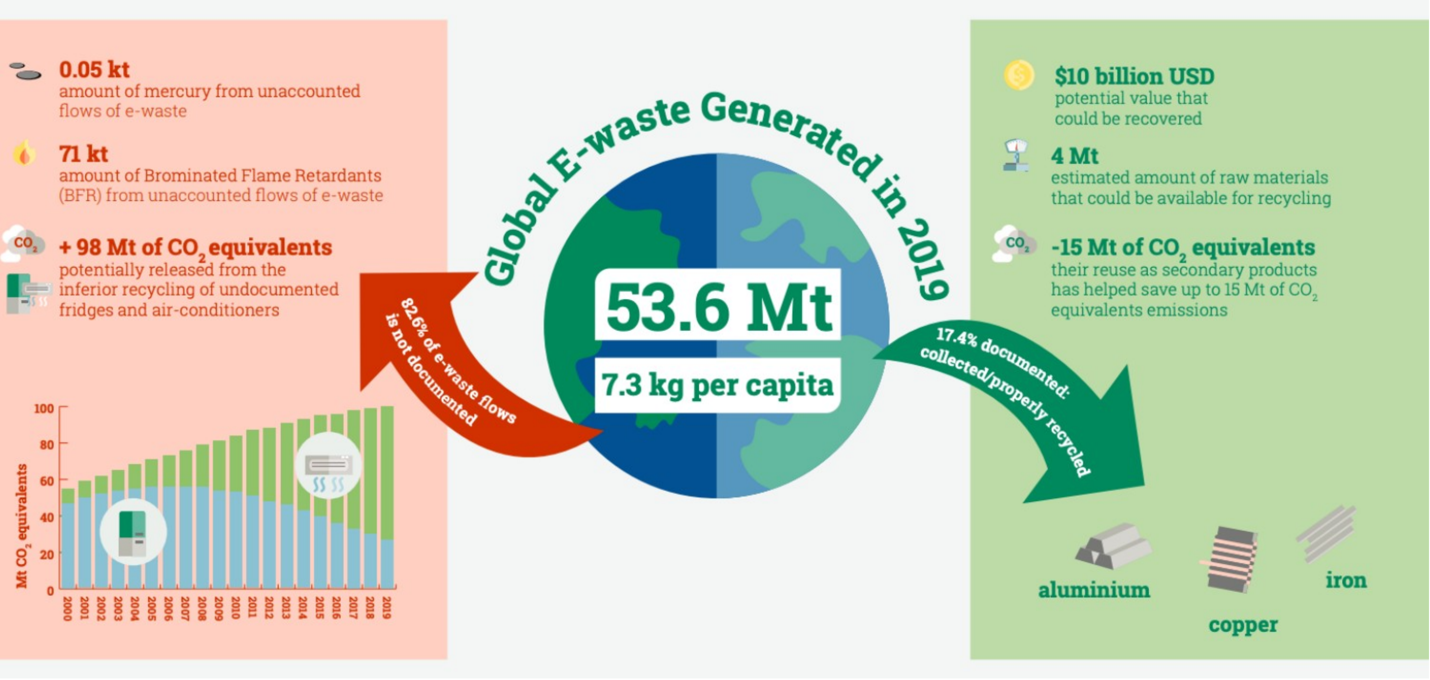
- **Best practise:**
  CERN is in the process of defining a new environmentally responsible procurement policy

- Sustainability certification from suppliers, with highest impacts

Waste

- ~3% of global GHG emissions is due to solid waste disposal despite 60% decrease in the amount of waste land-filled in the EU

- The fastest-growing portion of EU waste output is E-waste → Improving life time here is key (EU legislation incoming)



- This might also need legislation or contracts → e.g. recycling (i.e. re-use) of TDAQ computers through donations often not allowed or difficult

Sustainability HEP workshops

- **Sustainable HEP workshops kicked off in 2021:**
  free, online-only, time zone friendly,
  half-day only
- **Invited talks:**
  Keynote speech on climate change
  Towards a sustainable design of future colliders
  Sufficiency: Toward a Physics-Inspired Economics
- **Submitted talks:**
  Countering the biodiversity loss using particle physics research sites
  Sustainable Science: ATLAS Computing Practices in South Africa
  Longevity and eco-gas studies in the CMS CSC muon detector
  CEPC development towards a sustainable green Higgs factory
  Computing at the Exascale, CERN IT's Approach to Sustainability
  The future of HEP Work at the DESY data-centre
- **Talks and recordings still available:**
  https://indico.cern.ch/event/1004432/ (1st edition)
  https://indico.cern.ch/event/1160140/ (2nd edition)
  https://indico.cern.ch/event/1355767/
  https://indico.global/event/4745/

The international workshop on Sustainable HEP
Shreya Saha, Shreyasi Acharya, Juliette Alimena,
Daniel Britzger, Brendon Bullard et al.
DOI: 10.22323/1.476.1220
Published in: PoS ICHEP2024 (2025), 1220

Further Workshops and Conferences

- Seventh Workshop on Energy for Sustainable Science at Research Infrastructures

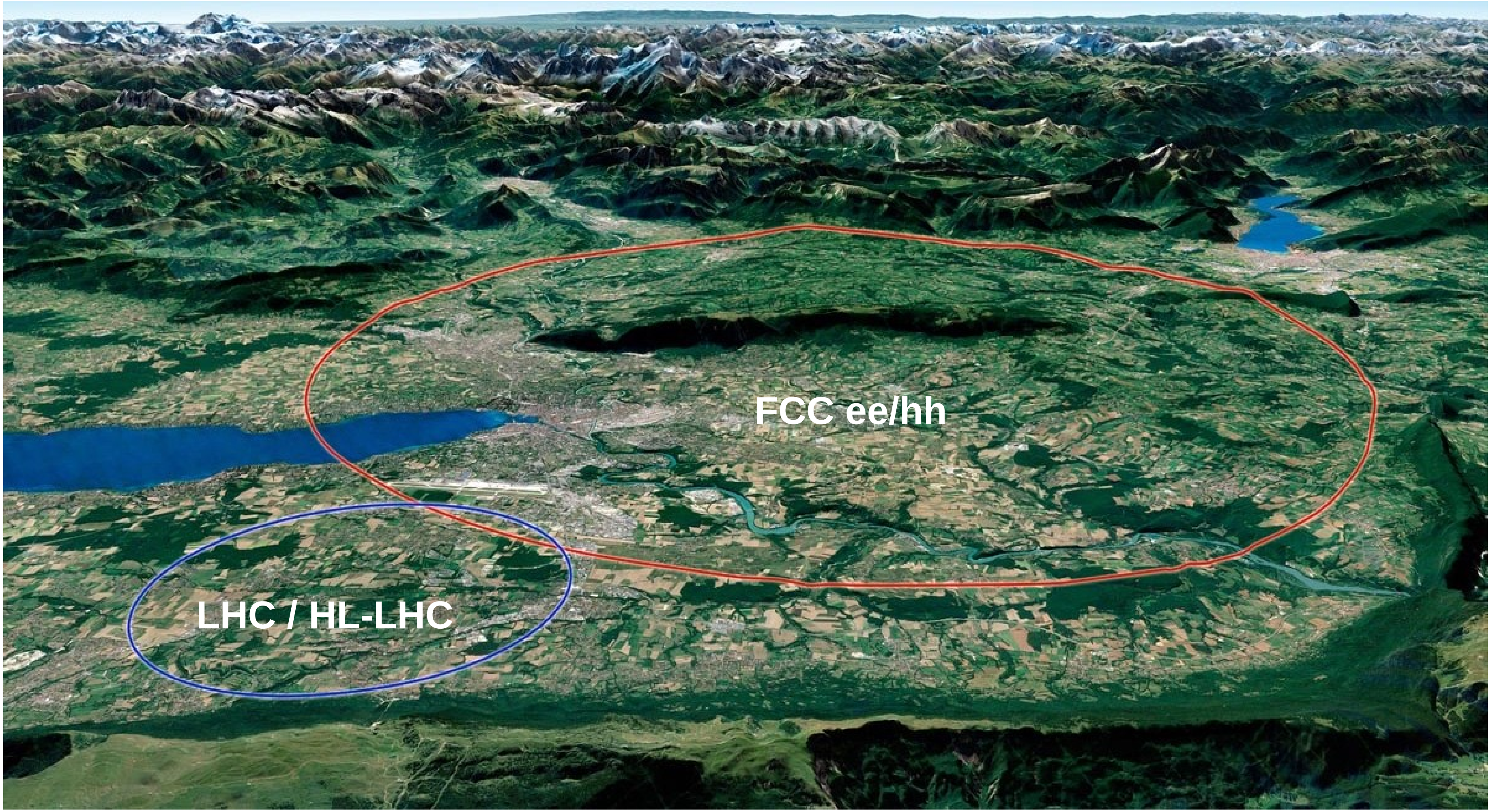
  https://agenda.ciemat.es/event/4431/ (seventh in 2024)
  https://indico.esrf.fr/event/2/ (sixth in 2022)
  Bi-annual specialized workshop for research infrastructures

- Big topic at recent CHEP conferences triggered by the 2022 energy crisis

- Now a parallel session for sustainability at ICHEP2024

  → there is growing awareness and discussions

The FCC, the European strategy input, ….

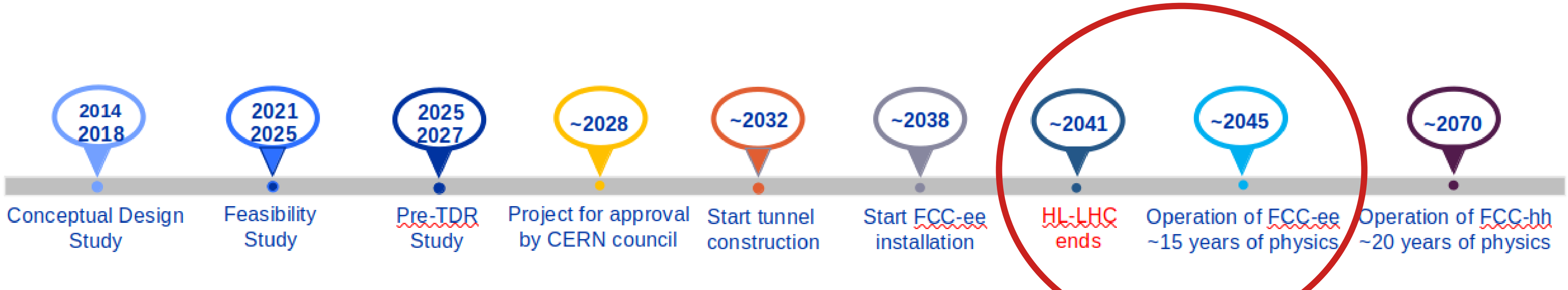


Slides taken from:
Future facilities and advances in accelerator technologies
Rende Steerenberg (CERN)

The FCC

Maximising physics opportunities:

- Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as a Higgs factory, electroweak & top factory at highest luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, proton-proton with options



- The program is highly synergetic and complementary enhancing the physics potential of both colliders
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the development of a significant new facility at CERN, within **a few years of the completion of the HL-LHC physics programme**

Slides taken from:
Future facilities and advances in accelerator technologies
Rende Steerenberg (CERN)

The FCC

Layout chosen:

- One out of ~100 initial variants, based on geology and surface constraints, environment, infrastructure

Baseline:

- 90.7 km ring
- 8 surface points
- 4-fold super-periodicity
- 4 interaction points for experiments

Integration with regional services:

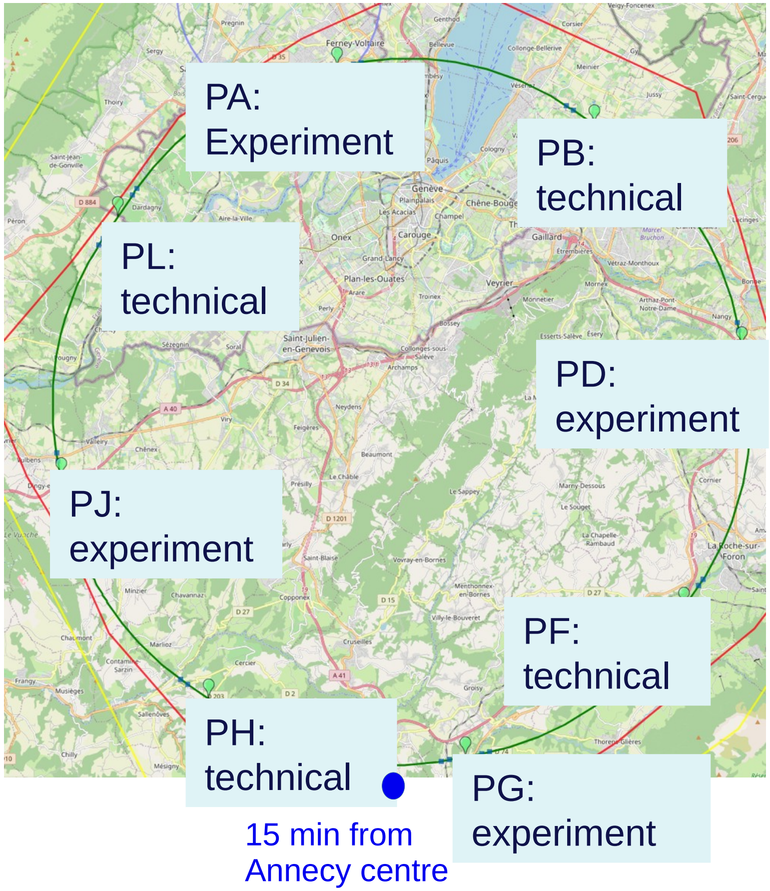
- Connections with highway network
- Electrical connection concept developed with the French electricity grid operator

Sustainability is an integral part of the study:

- Commitment to environmental protection
- Heat recuperation, reduced water consumption, etc.…

Not too far in the future:

- RF Facility for development should start in mid 2029



Summary of layout constraints and opportunities -- https://zenodo.org/records/13773120

Slides taken from:
Future facilities and advances in accelerator technologies
Rende Steerenberg (CERN)

Environmental impact of the FCC: An overview

- General overview over footprint

  Main drivers:
  → **Civil infrastructure construction**
  → **Dipoles ~7% of construction**
  → **Travel ~25% of construction**

- Computing, gases omitted
  (difficult to project,
  gases will be discontinued)

- Important to note:
  → number of full LCA and estimated numbers of e.g.CCC for other colliders agree within 10%
  → robust estimation!

  Some contributions (potentially) missing:
  extra buildings (campus on the other "pole" of the ring, up to 2500 people)

Table 1 Carbon emissions from civil construction for future colliders.

Collider	Emissions (Mt CO_2e)	Notes (see text for more complete information)
ILC (Japan) 250 GeV, 500 GeV	0.266	From ARUP report (29).
CEPC (China) 91.2 - 360 GeV	1.138	From CEPC presentation (30) which uses the factors of 7.0 kt CO_2e/km, 30% for the auxiliary buildings and 25% for A4-A5 contributions.
FCC-ee (CERN) 88 - 365 GeV	1.056	From FCC presentation (31), the deduced emissions per length of the main tunnel is 7.2 kt CO_2e/km.
CLIC (CERN) 380 GeV Drive Beam	0.127	From ARUP report (29).
CCC (USA) 250 GeV, 550 GeV	0.146	From CCC paper (32).
Muon Collider (USA) 10 TeV	0.378	Using 27 km for the sum of the accelerator and collider rings (23) and using factors of 7.0 kt CO_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 kt CO_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 kt CO_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 kt CO_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 kt CO_2e/km, 10% for the auxiliary buildings and 25% for A4-A5 contributions.

Sustainability and Carbon Emissions of Future Accelerators
Kenneth Bloom, Véronique Boisvert
e-Print: 2411.03473 [hep-ex]
DOI: 10.1146/annurev-nucl-121423-100906

Some remarks

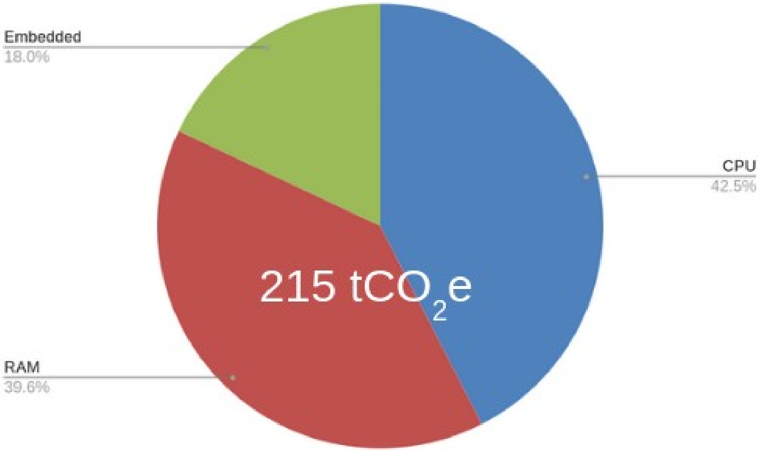
- FCC is (together with CEPC) most impactful future project (in terms of carbon footprint) and there is a competition on which collider will be built
- Project approval planned for within this ESUPP period → 2028
Potential start of construction: Within 8 years (just after having missed Paris targets?)
- General objective/goal for FCC is preservation of expertise (and jobs) in the field
- Current gap between HL-LHC and FCC-ee very small (4 years)
- Challenge: **Most carbon intensive phase is at the start of the project**
→ For other suggested projects this is delayed
- Carbon-footprint optimization ongoing, but in parts relying on very expensive / very rare materials, e.g. green cement

A comparative review of collider options:
https://indico.cern.ch/event/1439855/contributions/6542430/attachments/3076609/5444588/Future_Colliders_Comparative_Evaluation_WG_report.pdf

… and the rest: Further initiatives

Data sharing: Atlas, CMS and phenomenologists all use the same public tools to generate the same SM backgrounds **- Redundancy of effort, manpower, compute.**

ATLAS annual EvtGen emissions ~ 60M CPU hrs



Using global average carbon intensity for electricity.

Assumptions: Data storage neglected; PUE=1; CPU usage factor=1; Dell server 2x32 core, 512 GB RAM.

Total EvtGen footprint (ATLAS+CMS+pheno)

~220 return transatlantic flights

Assumptions: CMS evtgen emissions same order as ATLAS; 150 pheno papers annually, each using 10k CPU hrs on 8-core MacBook Pro; CPU usage factor = 1.

Total will scale with lumi and need for increasing precision

Numbers and Initiative:
Rakhi Mahbubani (RBI, HECAP+)

… and the rest: Data sharing

(Some) simulated data already shared between cosmologists (see e.g. Virgo database), and between lattice collaborations (International Lattice Data Grid).

International workshop on green computing in planning to discuss further examples/possibilities of data sharing

Benefits of sharing SM EvtGen:
robustness, transparency, reproducibility, equitable access.

After increasing awareness and initial discussions of the project: especially ATLAS in favour and software-wise very equipped to follow through

Project now being pursued within LHC MC Working group (https://lpcc.web.cern.ch/content/monte-carlo-wg)

Egroup for data sharing:
https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=lhc-mcwg-datasharing

… and the rest: Life cycle assessment

To understand CO_2 impacts of an experiment during its full life span, a so-called life cycle assessment (LCA) is carried out

LCA is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service. Follow ISO standards, i.e. is a standardized procedure → **comparable results.**

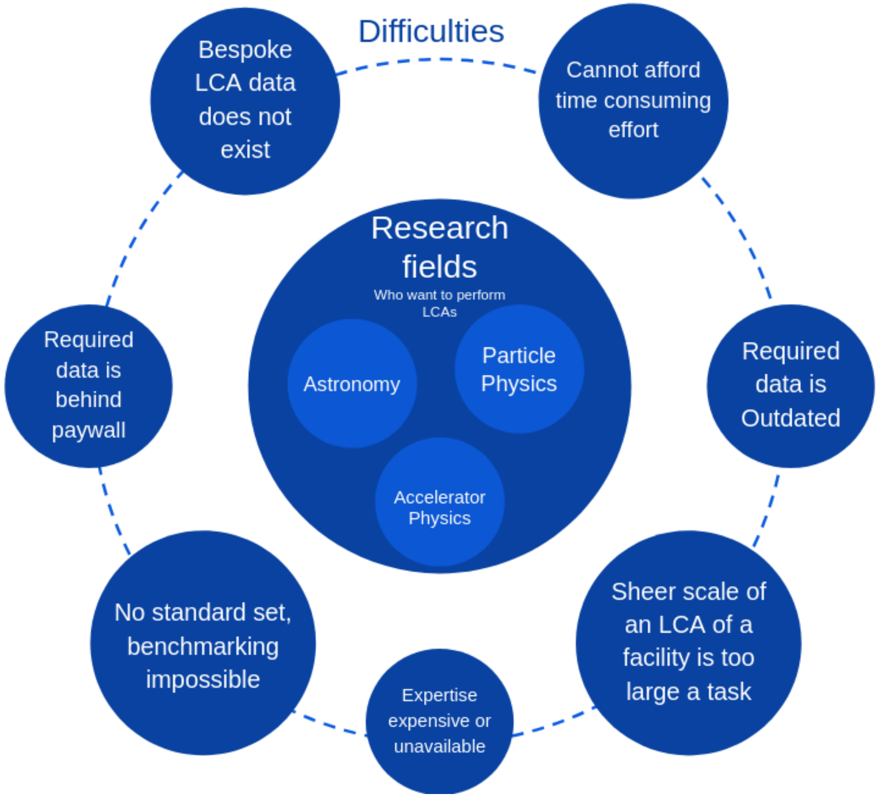
CERN has an online training on Life Cycle assessment available in its Learning hub. Anyone with a valid CERN account can subscribe.

It is organized in modules of 3 to 5 minutes, and with a short exam at the end of each module.

Additional classroom hands-on training available to learn on how to perform simple LCAs and get more acquainted with LCA software and databases. The online training is a prerequisite to follow the classroom training.
→ this is very costly (~700 CHF)

… and the rest: Life cycle assessment

Bespoke life cycle assessment for particle physics still a problem



Proposal for Open Open Research Life Cycle Assessment (ORLCA) repository

Lead: Hannah Wakeling (Uni Oxford, HECAP+)

… and the rest: HECAP+

- Sustainable HECAP+ reflection on environmental sustainability in basic research, now published in JInst.

- Interdisciplinary workshop on green computing, announcement coming soon.

- Stakeholder engagement: LDG, funders, arXiv, and other community consortia

- **Please get involved. We are looking:**

  - for anyone interested in developing the hecap.eco website.
  - for anyone interested in contributing to analyses of environmental impacts of aspects of basic research.
  - to engage with other sustainability initiatives.

- Thanks to generous support from the UK STFC, we may be able to help support and contribute to your initiative.

- Please get in touch via info@hecap.eco (or with me at kristin@hecap.eco, if you don’t like generic mailboxes).

Some conclusions

- **We (as a community) have made big progress and substantial improvements**
  (considering the constraints potentially as much as e.g. google/amazon)
- **But is it enough to achieve 50% overall reduction of CO2e?**
- **3 handles:**
  Green energy → factor of 12
  Energy efficiency → factor of 2
  Energy saving → factor of 2
- **Will need a hard look and many, many sacrifices**
- **Will require a concerted effort and dedicated funding**
  → but as a community we are certainly better placed than other fields of science (which are/will also come under scrutiny)

Need framework with benchmarks and goals and
Ability to *shape* (institutional/funding) constraints to allow achieving goals

Climate benchmarks that need to be met
(→restricted physics exploitation scenarios, what can we sacrifice?)

Reminder

Paris agreement is in principle legally binding
→ pressure on us / our savings might need to be increased
→ gives us negotiating power if we have a clear plan and strategy with demonstrable impacts and realistically achievable objectives in line with 1.5°C
→ There will be no (fundamental) science if climate breaks down*

Assessing, reporting on, defining targets for, and under-taking coordinated efforts to limit our negative impacts on the world's climate and ecosystems must become an integral part of how we plan and undertake all aspects of our research.

* „We predict with high confidence the [Atlantic Meridional Overturning Circulation (AMOC)] tipping to happen 2025 – 2095 (95% confidence range, 15 Feb 2024)
https://www.nature.com/articles/s41467-023-39810-w

Thank you

Who are the emitters?

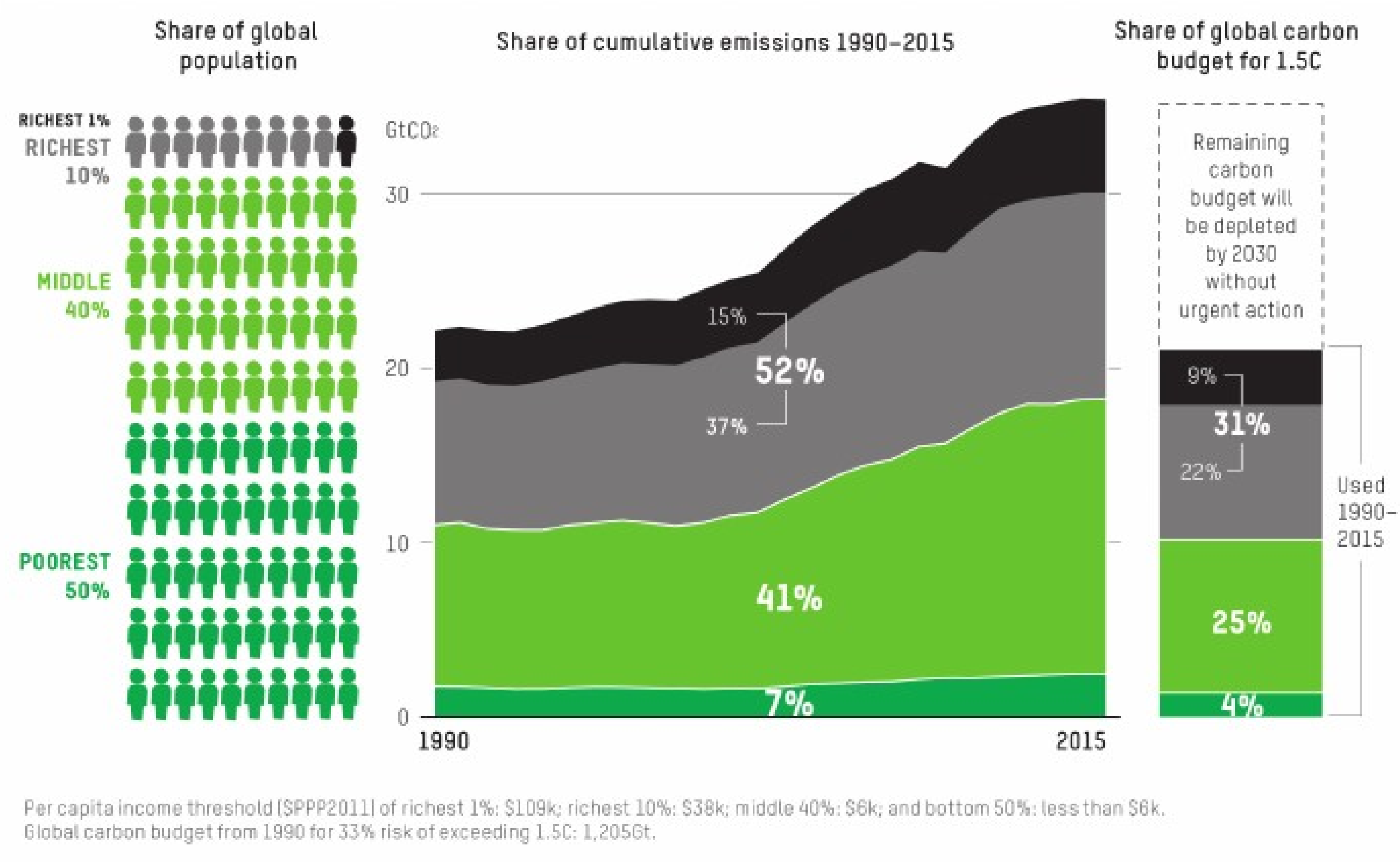


Figure 1.2: Share of cumulative emissions from 1990 to 2015 and use of the global carbon budget for 1.5°C linked to consumption by different global income groups. Figure reproduced from Ref. [9] with the permission of Oxfam.[a]

What does this mean for particle physics?

Options:

1) Expand CO2-free energies (factor 12)
Renewable power for computing: processors and cooling;
Consider district heating and site selection;
Job scheduling according to energy availability; ...

2) Increase energy efficiency (factor 2)
Optimised processors (clocks, GPUs),
architecture, cooling system,
software, ...

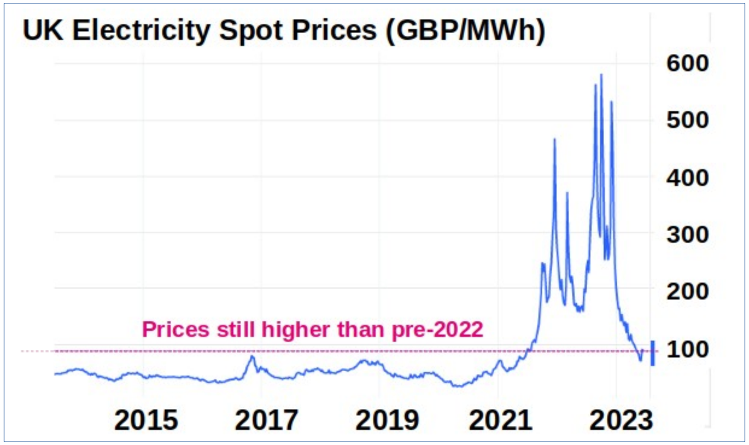
3) Save energy (factor 2)
Prioritise research questions
Optimise debugging, statistics and precision;
Modular and reusable software;
Modular and repairable hardware, reduce purchases;

Can’t we just use green energy and not do anything?

- **Electricity prices are volatile**

- **EU projections from 2016 predict about 25% rise of prices (consumer)**
  → Cut 25% of the physics?

- And it’s not just electricity prices but also hardware



- **Costs of computing infrastructure evaluation 2032 (with 2021 as index)**

- Installed hardware based on computational requirements (15-20% increase/yr), Unit costs (10-20% decrease/yr), 5 years of lifetime
  → **Costs could rise between 0.5 – 5.5 (best vs. worst case scenario)**

- Electricity costs (based on average) consider inflation, power efficiency (30% decrease → no improvement), high prices+high inflation versus both dropping
  → **Costs could rise ranging by 1.6 – 3 – 7 (based on mid capacity)**

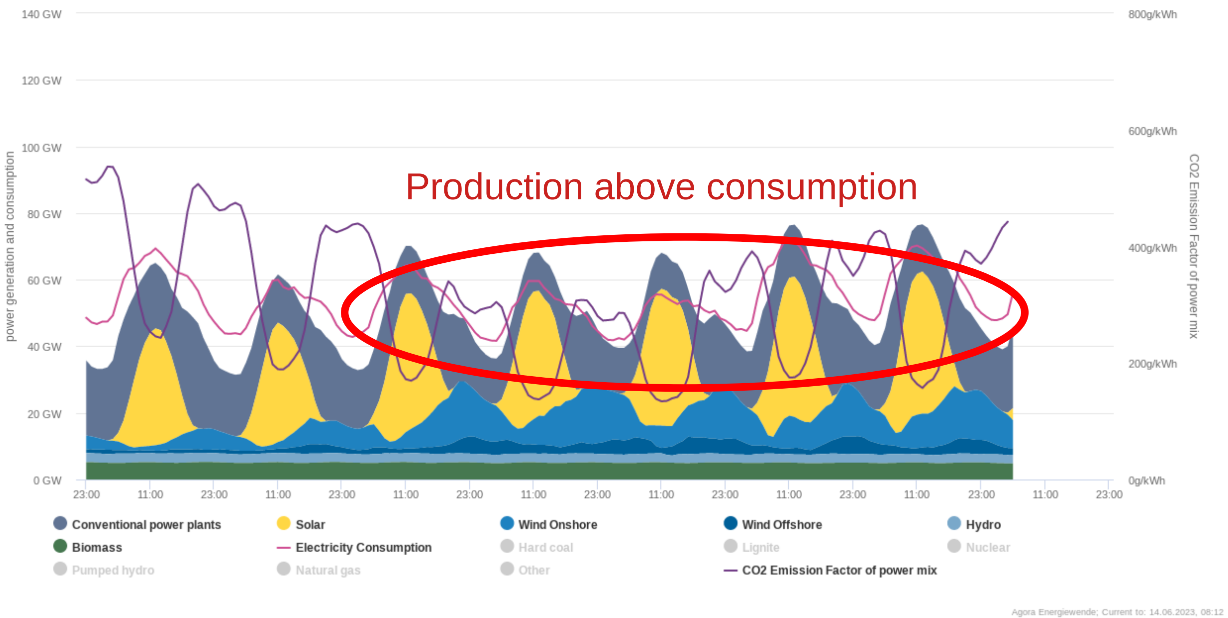
Chris Brew (RAL)

Infrastructure

- **Usage of carbon-free energy paramount**

  → "Own" production (requires investment into solar + potentially storage)

  → Regulation of load according to prices ("Follow the money" – R.W.), prices can be negative, but requires special tariff that can be used → well maintained data centres reacting to production and other grid loads, can help balance grid



Lancium Computing centre
https://indico.desy.de/event/37480/contributions/138296/attachments/82407/108618/2023-05-30%20Concrete%20Action.pdf

“Classical” Software sustainability

- General sustainability => Re-useability and training

  → Institution for Research and Innovation in Software for High Energy Physics (IRIS-HEP) [44]

  → HEP Software Foundation

- **May provide an important platform for accelerating the inclusion of environmental considerations in software development. (examples e.g. are Sherpa speedup!)**

- Underwriting of FAIR principles: software (and data) should be Findable, Accessible, Interoperable and Reusable

- Sharing optimization workflows, **consulting services** for smaller experiments

Agriculture impact

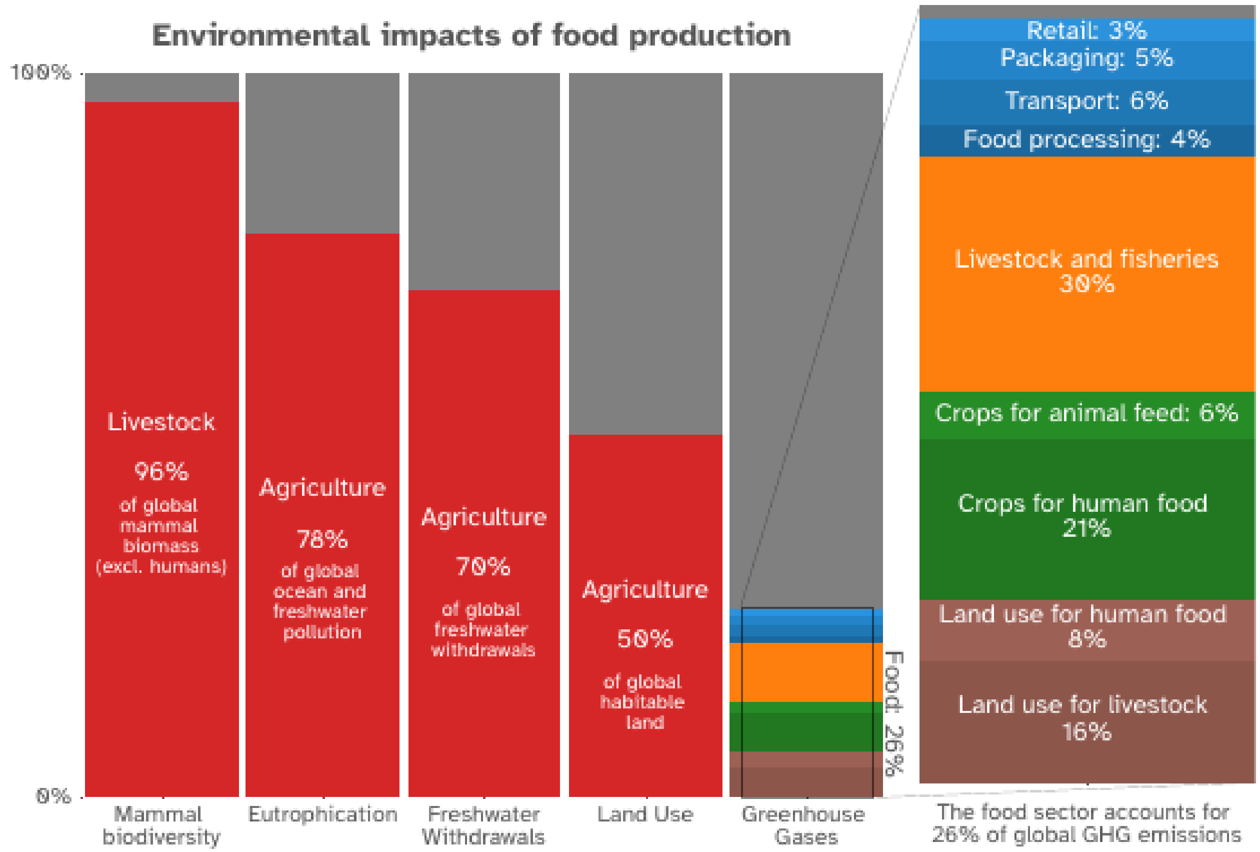


Figure 4.1: Environmental impact of food production, with fine-grained partitioning of GHG emissions by food sector. Figure modified from Ref. [119] under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0) license, based on data from Refs. [114] and [120].