WG5: Sustainability & Environmental Protection

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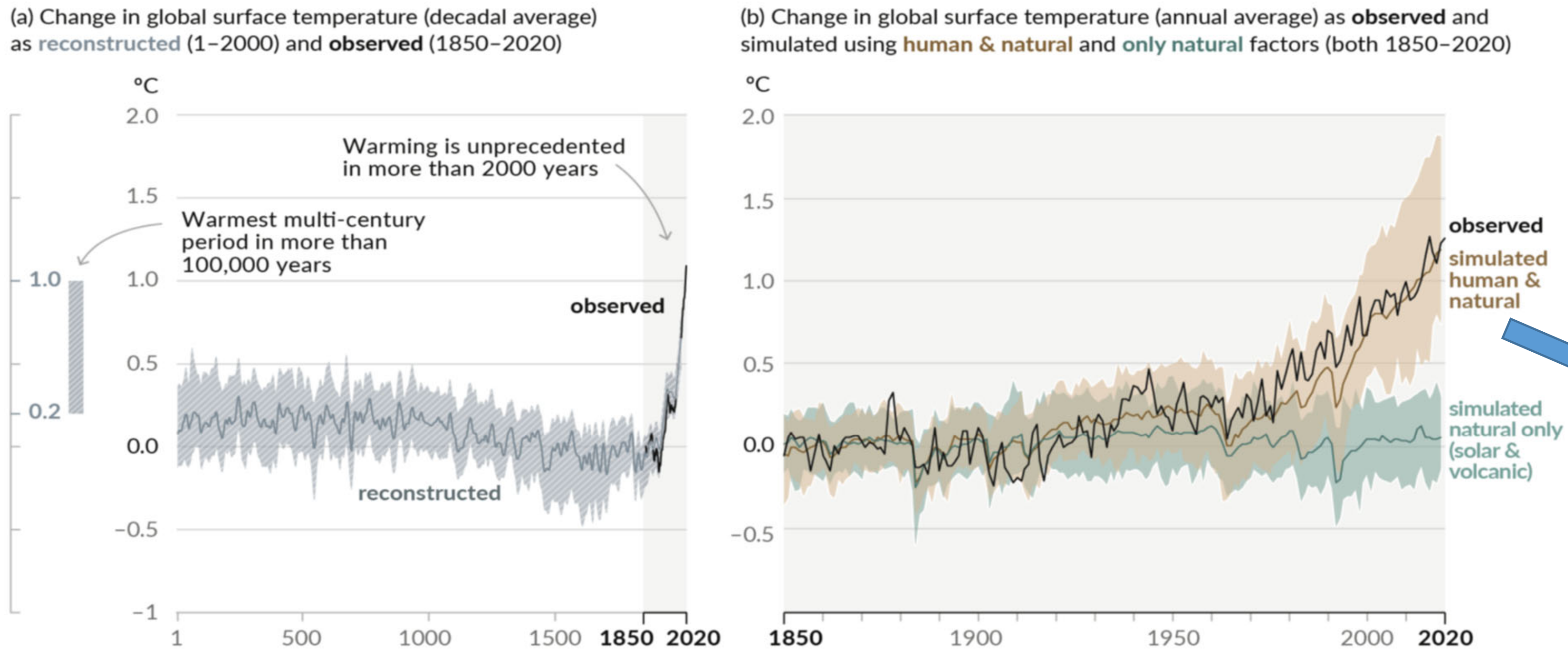
Climate Change is Real…

Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

Paris agreement: reduce by half the net total CO_2 emissions by 2030

Changes in global surface temperature relative to 1850–1900



[Ken Bloom, Workshop Sustainable HEP 2025]

(IPCC AR6)

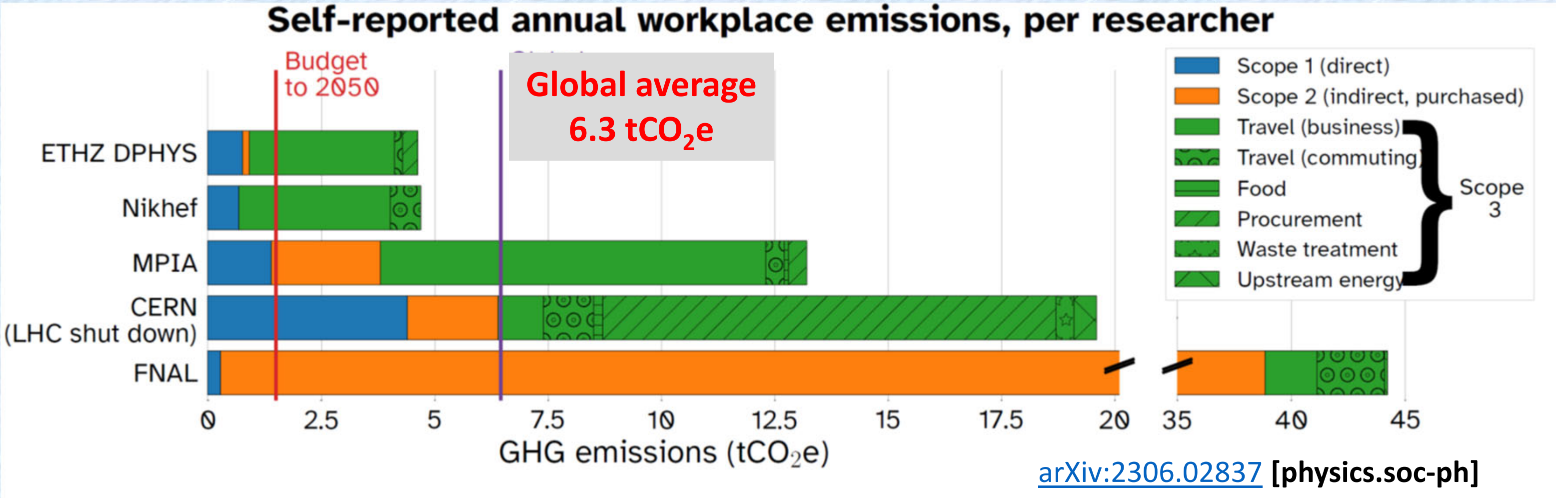
Strong call for responsability and actions at each level of the society:

- individuals
- collective projects,
- institutions
- ….
- governments

There is a risk that the societal challenges arising from „climate emergency" could draw resources away from fundamental research

…and Particle Physics is also Responsible and Should React Accordingly

- ✓ **The current (future) projects of particle physics will create greenhouse gas emissions (GHG) well surpassing that of a typical citizen, and thus well above the per-capita emissions expectations**



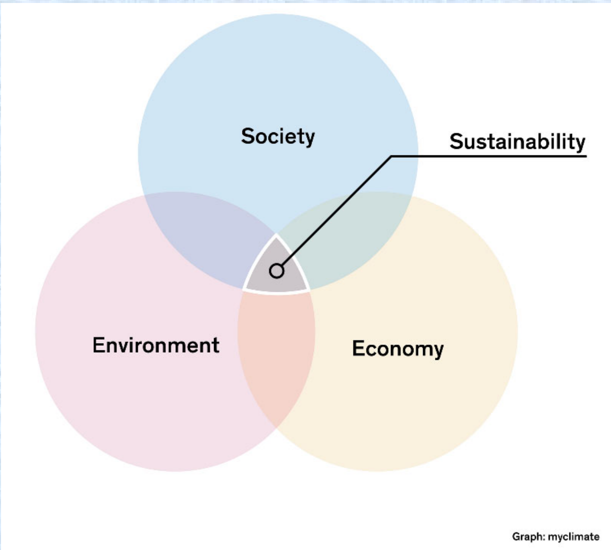
arXiv:2306.02837 **[physics.soc-ph]**

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

- ✓ **Every new project should be carefully assessed a.f.a. its GHG emissions are concerned**
- ✓ **Every possible measure should be taken by particle physics community to mitigate GHG emissions**
- ✓ **Our community must be very well prepared to justify the relevance of a project and communicate its sustainability actions**
- ✓ **Our community should also look for opportunities to develop new technologies/applications revolving about mitigation of GHG emissions**

Sustainability of a Science Project

Sustainablity assessment of a project is based on the analysis of the three main pillars: **society, economy and environment**



A comprehensive, recommended by the relevant bodies **assessment of sustainability of particle accelerator-based research project should be based on quantitative Cost-Benefit-Analysis (CBA):**

Direct cost
- Construction
- Operation
- Maintenance

Shadow CO_2 cost
- Construction
- Equipment
- Energy consumption

Revenue
- Research and industrial services
- Space rental

Carbon Tax
- Construction
- Manufactures
- Electricity

Indirect cost
- Land and forest consumed
- Environmental pollution
- Air quality depletion
- Impact on local life quality (noise, vibration, traffic)
- Biodiversity depletion
- Loss of cultural and natural heritage
- Loss of agricultural income

Benefit value
- Scientific knowledge
- Tech Spin-offs
- Education and training impact on careers
- Economic growth from procurements
- Open data / open source software
- Licences and patents
- Web / social media impact
- Cultural activities
- Newly created land
- Heat supply
- Avoided carbon emissions
- Newly created / reinforced public infrastructures / services
- Increased life expectancy (medical procedures / devices)


Guide to Cost-Benefit Analysis of Investment Projects
Economic appraisal tool for Cohesion Policy 2014-2020
December 2014

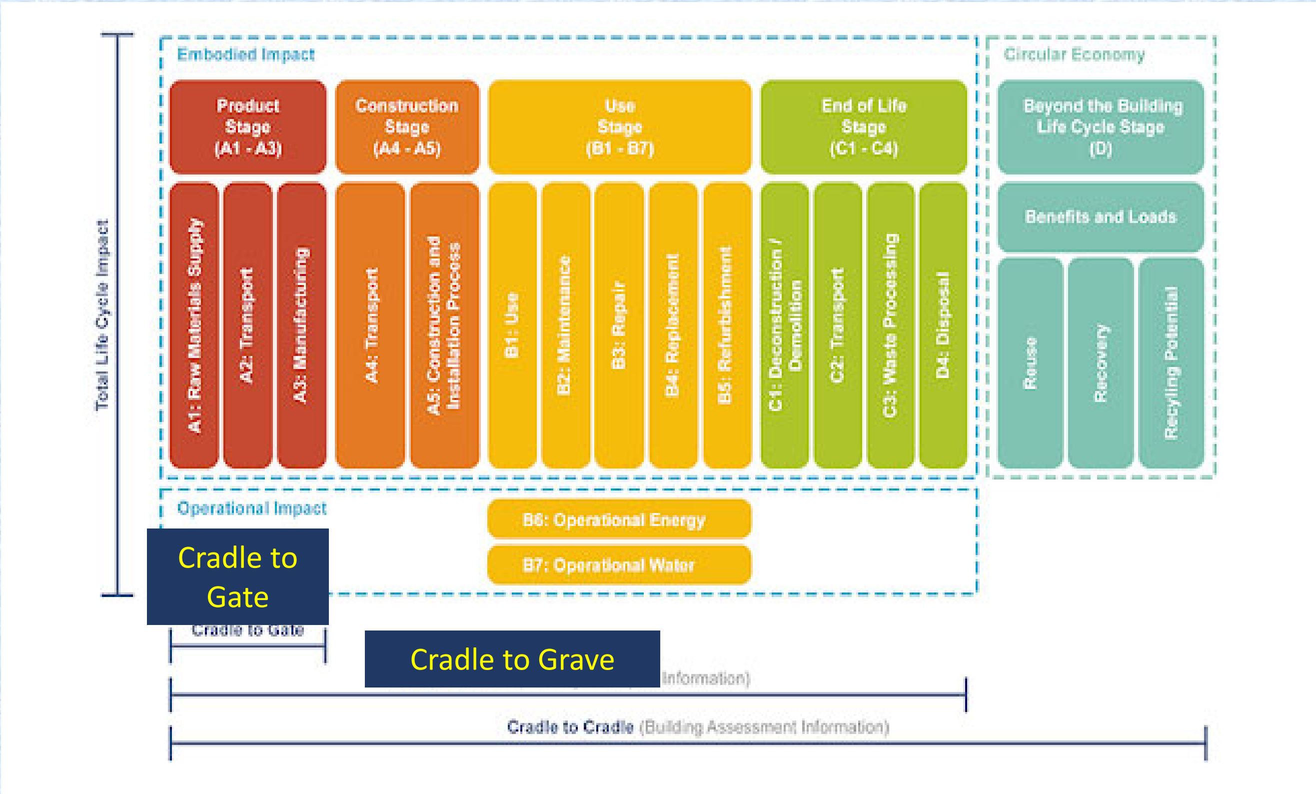
ESPP Contribution #162

ESPP Contribution #220

ESPP Contribution #265

Sustainability & Environmental Issues of HEP Accelerators

Life Cycle Analysis (LCA) as the approach to quantify the environmental impact of a Research Infrastructure (RI) in terms of:



- **Energy efficiency & Green House Gases (GHG) emissions footprint**
- **Civil engineering work** (concrete, tunnels, caverns, excavated material etc…)

- **Accelerator construction** (components, materials ...) → Investment in R&D for new technologies (e.g. high efficiency klystrons, thin film SC RF cavities, permanent magnets, high temperature superconductors, …)
- **Accelerator operation** (power for operation, carbon intensity of electricity…)

- **Reuse of excavation material and other waste**
- **Impacts on biodiversity**

- **Decommisioning** (material recycling, site infrastructure and tunnel reuse, radioactive waste…)

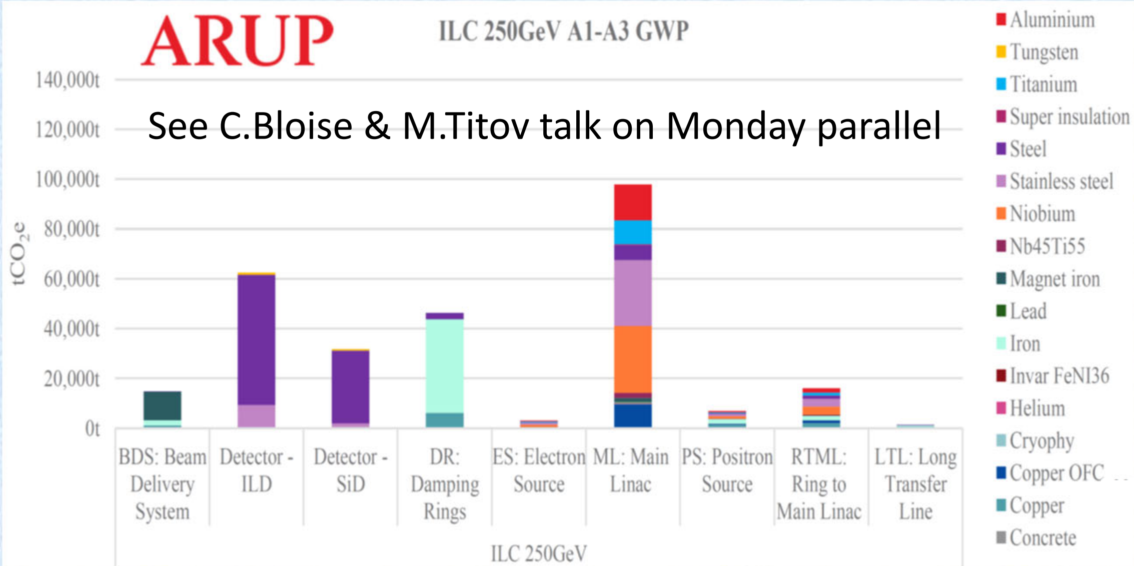
[LDG WG on Sustainability Assessment of Accelerators] [High-level environmental sustainability guidelines for large accelerator facilities] [ESPP Contribution #162] [ESPP Contribution #220]

Sustainability & Environmental Issues of HEP Accelerators

Significant effort on Life Cycle Assessment (LCA) already carried out by many of the future collider projects

Civil engineering is largest single impact and so has been studied in greatest detail by projects:

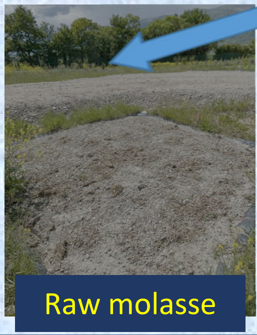
- **Surface and underground infrastructure: in both cases manufacture of cement and steel gives the biggest impact**
- **Civil Engineering is broadly equivalent in impact to the full lifetime of operations for future collider**
- Options which reuse the existing LHC tunnel are therefore lower impact (LEP3, LHeC)
- Consumption of land has also been assessed

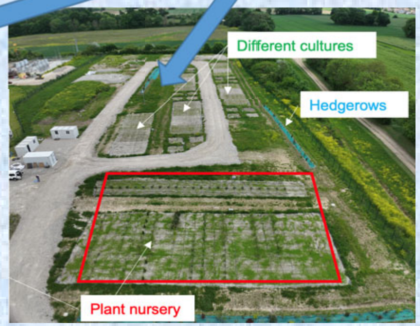


There are common strategies for reduction of impacts in most aspects of the projects, examples being:

- **Alternative cements**
- **Local production of construction materials**
- **Use of recycled materials**
- **Material efficiency**
- **Adopting green energy**
- **Waste heat recovery**
- **Ecosystem and biodiversity protection**
- **Water conservation**

OpenSkyLab @ CERN: Molasse → fertile soil (can be also utilized by other tunnels)





<u>FCC: estimate of reuse of excavated soil:</u>
40% refill of quarries (~ 7.5 Mt)
25% reconstituted soil (~ 4 Mt)
30% deposit (~ 5 Mt)
5% other reuse

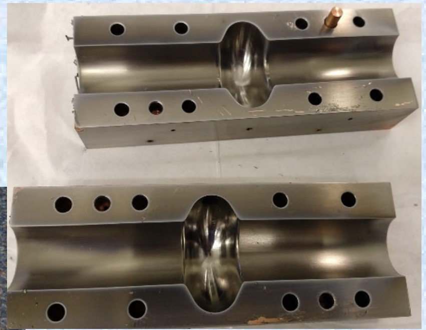
Sustainability & Environmental Issues of HEP Accelerators

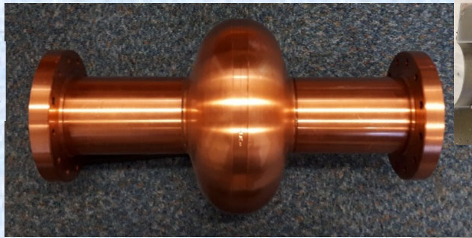
Intense R&D on accelerator systems can provide a major reduction in carbon impact (most impontant factors are RF systems and magnet systems)

Some examples are listed below, they do not all apply to every project:

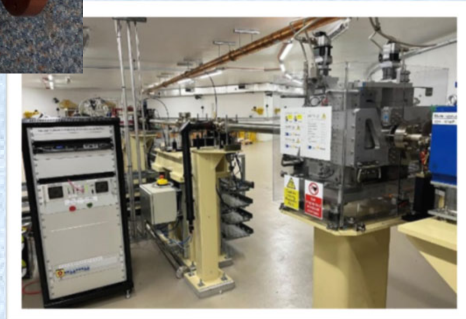
- **Thin film coated superconducting cavities** – reduction in rare materials, increase of operating temperature (e.g. Nb_3Sn-on-Cu at 4K instead of 2K → 3x energy saving on cryogenics)
- **Cryogenic systems with *eco-mode*** offering reduced power consumption during non-operational periods
- **Permanent magnets** instead of electromagnets
- **Energy recovery linac technology** enabling recycling of particle beam power
- **Higher efficiency power sources:** (two-stage) klystrons and tristrons
- **High temperature superconducting magnets**
- **Plasma acceleration** as a potential road towards more compact and sustainable colliders

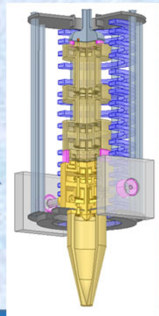
Prototype split cavity coated in niobium and copper cavity waiting to be internally coated with Nb_3Sn



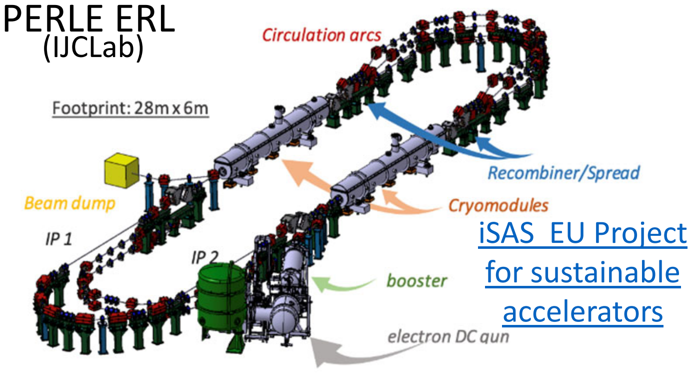


Permanent magnet quadrupole installed in Diamond Light Source as a replacement for an electromagnet





PERLE ERL (IJCLab)



[iSAS EU Project for sustainable accelerators]

Sustainability & Environmental Issues of HEP Accelerators

Comparison of Future ee Collider options at CERN (table 4.2 from ESPP Contribution #281)

- This table compares CLIC-380, FCCee, and LCF-250:

	CLIC (2 IPs)	FCC-ee (4 IPs)				LCF (2 IPs)		
						250 LP	250 FP	
c.o.m. energy [GeV]	380	91.2	160	240	365	250	91.2	250
Civil engineering (A1 – A5)								
Underground [kt CO_2 eq.]	134 – 268	480 – 1000				206 – 411[a]		
Surface sites [kt CO_2 eq.]	59 – 118	50 – 184				N/A		
Total GHG emissions from CE [kt CO_2 eq.]	193 – 386	530 – 1184				>206 – 411		
Operation period with CE infrastructure [years]	20[b]	39[b]				20[b]		
Accelerators, technical infrastructure, detectors								
Accelerators (A1 – A3) [kt CO_2 eq.]	105 – 140	N/A[c]				169 – 225	+18 – +24 [d]	
Technical infrastructure (A1 – A3) [kt CO_2 eq.]	14 – 19	N/A[c]				24 – 32 [e]		
Detectors (A1 – A3) [kt CO_2 eq.]	71 – 94	142 – 186[f]				71 – 94[g]		
Total GHG emissions for accelerator, TI and detector HW [kt CO_2 eq.]	190 – 253	N/A				>264 – 351	>282 – 375	
Number of years of physics operation	10	4	2	3	5	5	1	3
Electricity consumption								
Carbon intensity of electricity generation [g CO_2 eq. per kW h]	14 – 18							
Accelerators and detectors [TW h/y]	0.82	1.2	1.3	1.4	1.9	0.8	0.7	1.0
Off-line computing [TW h/y]	0.07 – 0.14	0.14 – 0.28				0.07 – 0.14		
GHG emissions/year of physics operation [kt CO_2 eq./y]	12 – 17	18 – 26	20 – 29	22 – 31	29 – 40	13 – 17	10 – 14	15 – 20

- **The ranges provide an indication of possible reductions achievable**
- LCA for accelerator and technical infrastructure systems having largest impact for FCCee is underway

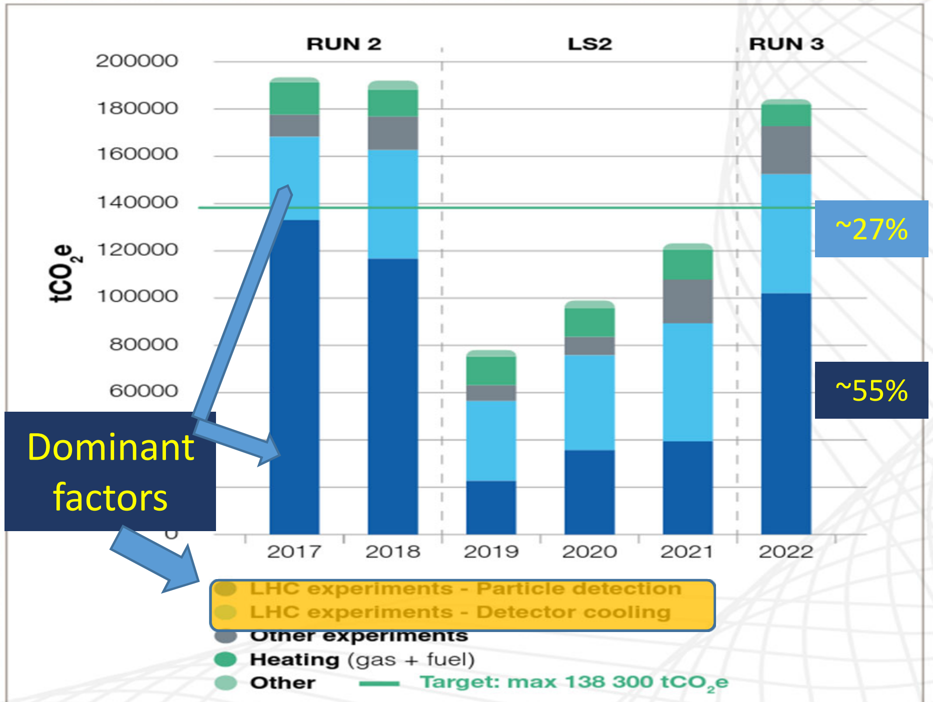
Sustainability & Environmental Issues of HEP Detectors

Dominant factor: CO_2e emissions from the detectors: leaks of gases

- **Particle detection: gaseous detectors** like RPC, CSC and RICH containing Green House Gases (GHG), **and detector cooling**
- **Air conditioning systems: HFCs** (hydrofluorocarbons)
- **Gases used for electrical insulation in power supply systems**: **SF_6**

Name	Chemical Formula	Lifetime [years]	Global warming potential (GWP) [100-yr time horizon]	
Carbon dioxide	CO_2	–	1	arXiv 2306.02837
Dimethylether	CH_3OCH_3	0.015	1	
Methane	CH_4	12	25	
Sulphur hexafluoride	SF_6	3,200	22,800	RPC
Hydrofluorocarbons (HFCs)				
HFC-23	CHF_3	270	14,800	
HFC-134a	$C_2H_2F_4$	14	1,430	RPC
Perfluorocarbons (PFCs)				
PFC-14	CF_4	50,000	7,390	MPGD, RICH
PFC-116	C_2F_6	10,000	12,200	cooling, RICH
PFC-218	C_3F_8	2,600	8,830	cooling
PFC-3-1-10	C_4F_{10}	2,600	8,860	RICH
PFC-5-1-14	C_6F_{14}	3,200	9,300	cooling

- **CERN example: considerable emission of GHG/F-gases from particle detection and detector cooling (90 km of gas pipes; 30 systems)**



CERN SCOPE 1 EMISSIONS FOR 2017–2022 BY CATEGORY
"Other" includes air conditioning, electrical insulation, emergency generators and the fuel consumption of the CERN vehicle fleet.

Sustainability & Environmental Issues of HEP Detectors

Mitigation measures / Recommendations:

- **Move to the new gas mixes for the detectors („eco-gases”) - intense R&D effort ongoing and needed**
  - **RPC detectors – research on “eco-gases”, possibly retrofitting existing systems**

    Pros (of RPCs): good timing, reasonable position resolution, cost efficient

    Cons: standard gas contains $\mathbf{C_2H_2F_4}$ (GWP 1300) and SF_6 (GWP 23500), both “F-gases” to be phased out

    Extensive R&D ongoing on „eco-friendly” gases: DRD1
    Example: RPC ECOgas@GIF++
  - **Cherenkov detectors – the current gases with a high GWP are well optimized to maximize the overall performance of the spectrometer, but „eco” alternatives are being researched** (a good radiator gas must be transparent over a broad wavelength (up to UV region), well controlled refractive index, low scintillation)
  - **Cooling** – **high GWP gases to be replaced or improvements of the current systems and/or work on the „eco” ones**

- **Optimization of operation costs and CO_2 load of the experimental setups**
- **Improved monitoring and automatic warning systems**
- **Sustainable cooling: CERN switches to CO_2 cooling during LS3** (ATLAS and CMS inner trackers)
- **CERN objections for 2030:**

Domain	Value in reference year (2018)	Current status	Target for 2030
Scope 1 emissions (tCO_2e)	192 100	170 100 (2023)	➢ Reduce by 50% w.r.t. 2018
Electricity consumption (GWh)	1252	1142 (2023) 1290 (estimation 2024)	➢ Max 1500 ➢ 10% renewable
Gas consumption (GWh)	61 (average 2016-2018)	39 (2024)	➢ Reduce by 60% w.r.t. 2018

Sustainability & Environmental Issues of HEP Detectors

Mitigation measures / Recommendations:

- **If an immediate replacement of a gas unrealistic → move to recirculation and recuperation (avoid, reduce, compensate)**
- **Highly successful efforts at CERN, with the aim to approach the 100% limit of recirculation and recuperation:**

LHCb RICH recovery system: CF_4 and C_4F_{10}; recovery on the level of 80%

CMS RPC recovery system: R134a and SF_6 ; recovery above 80%

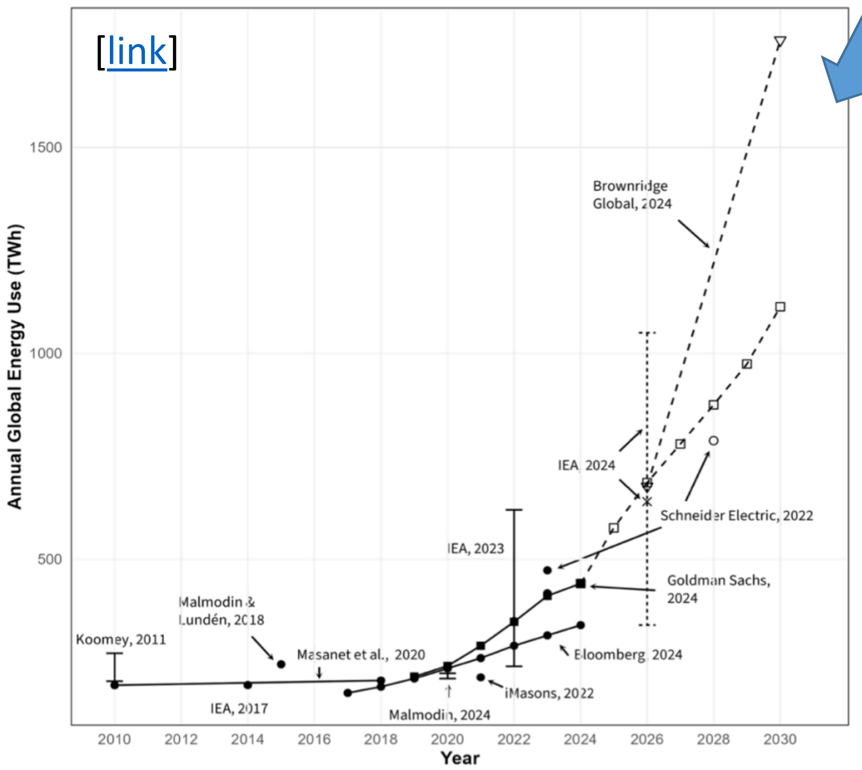
CMS CSC recuperation system of CF_4: efficiency about 70%

Sustainability & Environmental Issues of HEP Computing

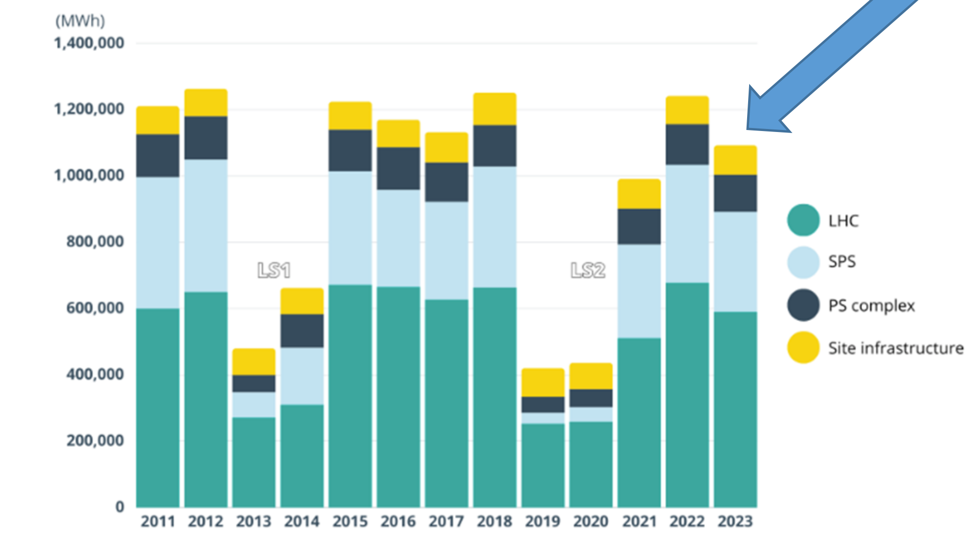
The energy / CO_2 impact of computing

- **Computing centers are a major consumer of energy, and the trend is skyrocketing (AI has a role here….)**

[link]



- **In our environment, Computing Centers are a fraction of the total impact**
  - At CERN, IT < 5% of the total (a fraction of the "Yellow")



CERN's electricity consumption 2011-2023.

- CERN → Global WLCG scales up ~5x
  - So energy used by the Global WLCG ~ 20% of CERN
  - Global WLCG: 164 sites, 42 countries

Sustainability & Environmental Issues of HEP Computing

Strategies to reduce CO_2 impact of computing

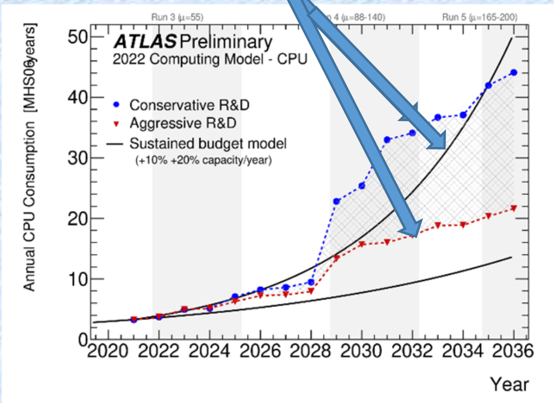
1.Needs from the experiments [increasing CO_2 impact]

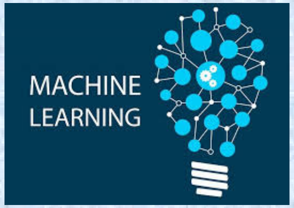
- **Can be mitigated with AI, GPUs, faster algorithms, more efficient programming languages …**

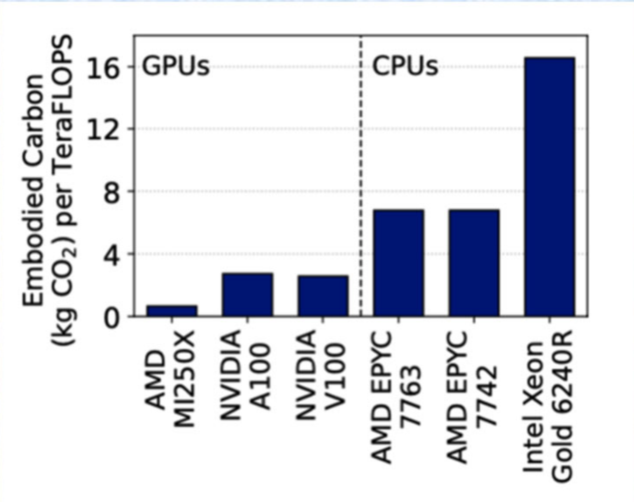
2.Higher efficiency resources [decreasing CO_2 impact]

- **More modern CPUs, GPUs, …**

Effects of R&D







Advertised PPA Improvements of New Process Technologies

Data announced during conference calls, events, press briefings and press releases

	TSMC						
	N7 vs 16FF+	N7 vs N10	N7P vs N7	N7+ vs N7	N5 vs N7	N5P vs N5	N3 vs N5
Power	-60%	<-40%	-10%	-15%	-30%	-10%	-25-30%
Performance	+30%	?	+7%	+10%	+15%	+5%	+10-15%
Logic Area					0.55x		0.58x
Reduction %	70%	>37%	-	~17%	-45%	-	-42%
(Density)					(1.8x)		(1.7x)
Volume Manufacturing				Q2 2019	Q2 2020	2021	H2 2022

- Computing is getting less and less energy hungry due to the progress in fabrication process: **generation over generation the power goes down a lot (-10% to -60% ….)**

ESPP inputs # 9, 12, 18, 47, 53, 67, 73, 107, 121, 124, 127, 147, 171, 176, 180, 187, …

A holistic study of the WLCG energy needs for the LHC scientific program

David Britton[1], *Simone* Campana[2*], and *Bernd* Panzer-Stradel[2]

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[2] CERN, Esplanade des Particules 1, 1211 Geneva 23, Switzerland

Sustainability & Environmental Issues of HEP Computing

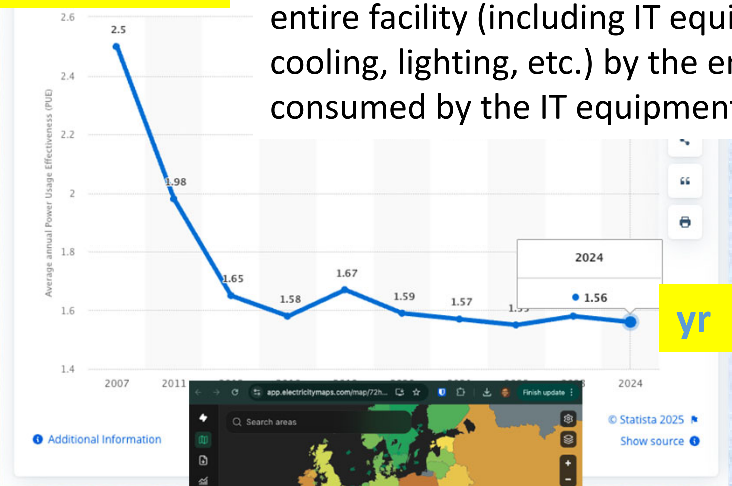
Strategies to reduce CO_2 impact of computing:

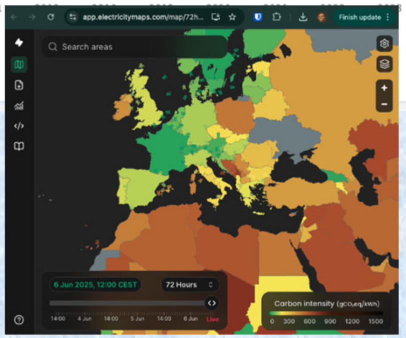
3. Higher efficiency data centers [decreasing CO_2 impact]

- Lower Power Usage Effectiveness (PUE)
- Choice of energy source [and location?]

Average PUE

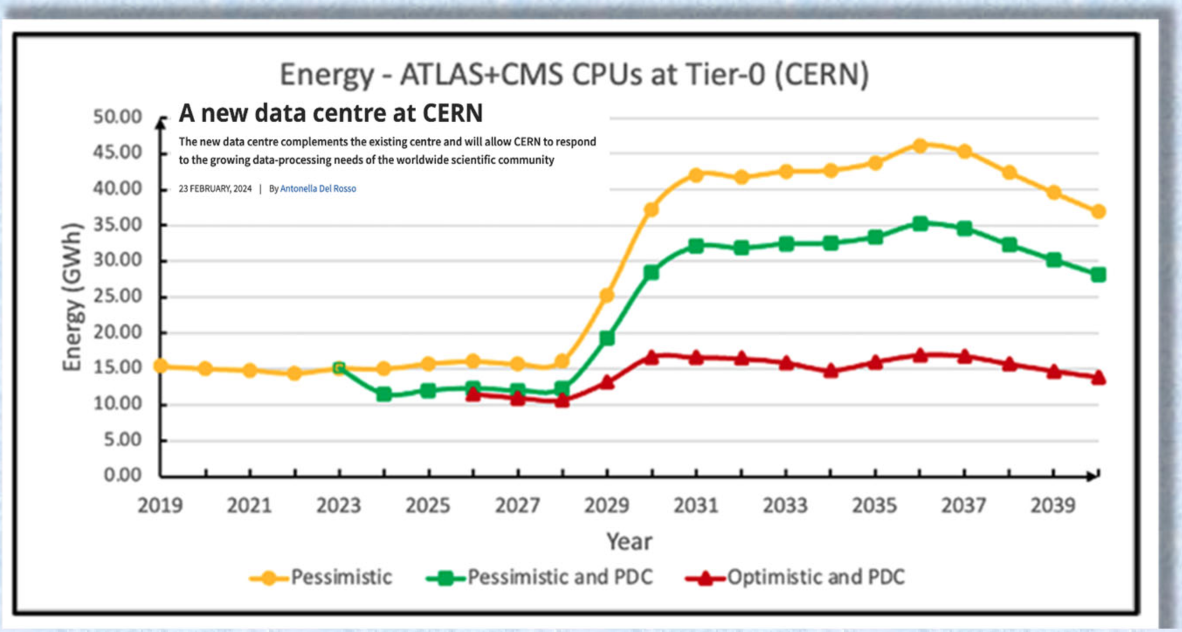
PUE - the total energy used by the entire facility (including IT equipment, cooling, lighting, etc.) by the energy consumed by the IT equipment alone





A good example of the current best extrapolation (CERN only)

HL-LHC Computing aims to be in the same energy envelope as today's …
.. pending the planned R&D programs from the experiments
[the yellow line is no more relevant:
the Prevessin Data Center is now operational]

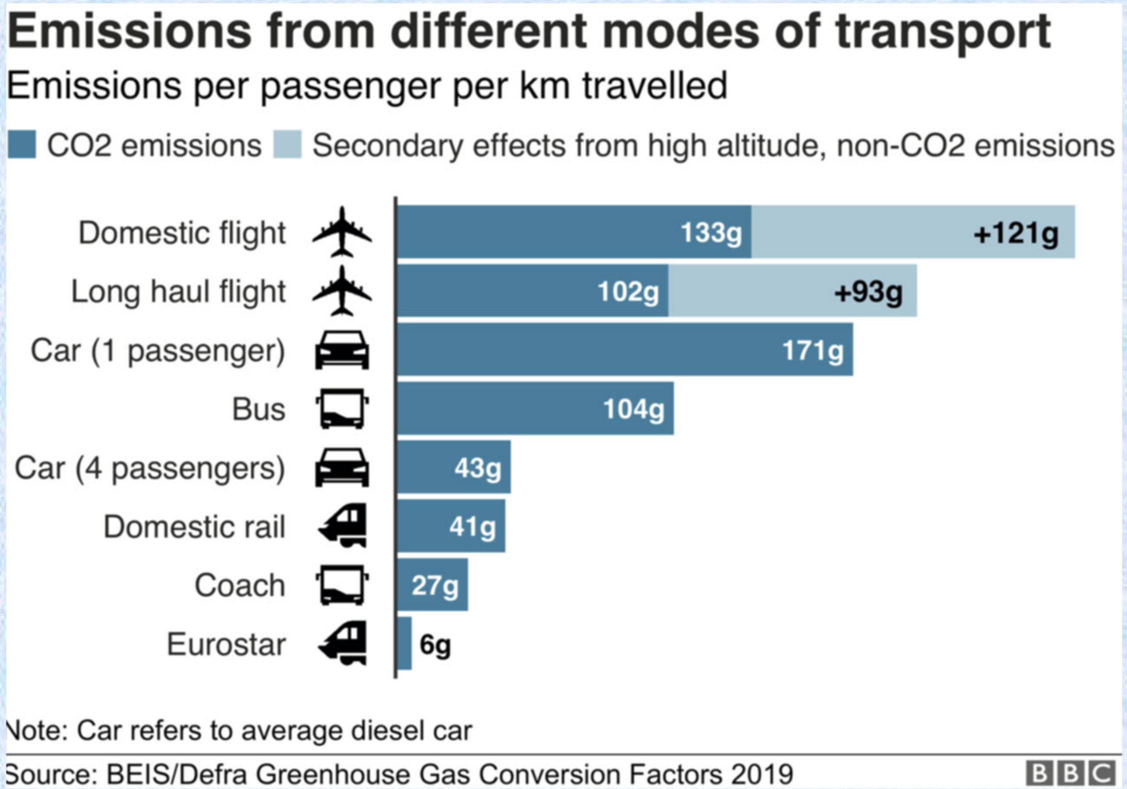


Sustainability & Environmental Issues of HEP Travel

Particle physics business travels produce a lot of CO_2e

Potential mitigation measures:

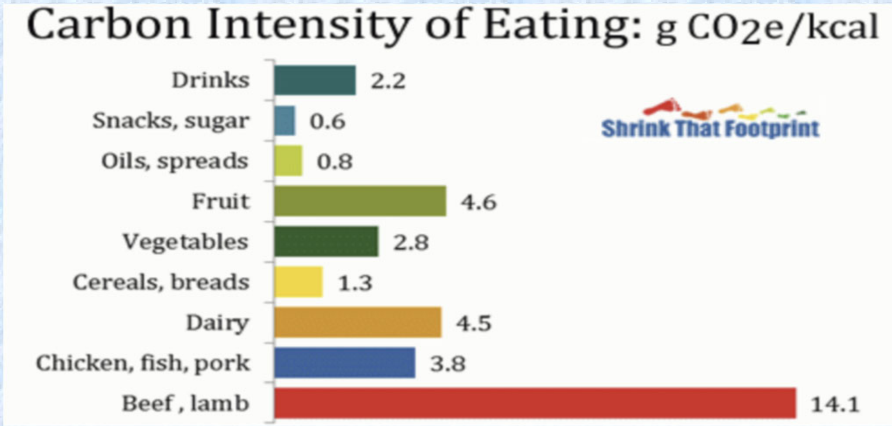
- Land-based travels to greater extend
- Balance of remote vs. in-person meetings
- Regional centers of big collaborations
- Remote operation of experiments
- Conferences: regional, virtual etc.
- Conference catering
- Ways to commute to the lab
- Quantitative measures of CO_2 load of a researcher, collaboration, conference



However, there is **a need for a balanced approach**, weighing appropriately the mitigations of travel (environment footprint) vs. the benefit of human exchanges (professional, social …)

Other Sustainability Issues

- **CERN specific actions revolving around sustainability** e.g. Environmentally Responsabile Procurement Policy
- **FCC sustainability plans** → ESPP Contribution #233, ESPP Contribution #247
- **Biodiversity** → ESPP Contribution #12
- **Mitigation of carbon intensity of eating**
- **Methods of HEP wastes disposal**
- **Laboratory site organization** (e.g. heat recovery at CERN)
- **Carbon footprint offsets**
- **Negative emission technologies** (nature based, CO_2 capture…)
- **Education** oriented towards sustainability and env. issues
- ……



Recovered heat from LHC cooling towers supplies heating to a nearby residential area in France (Ferney-Voltaire ~ 8000 households)

Summary (part 1)

- The WG welcomes and underlines many good examples of R&D efforts of HEP community revolving around technological advances (accelerators, detectors, computing…) towards mitigating CO_2 emissions as much as possible; these efforts should be continued and strenghten
- The evaluation of future HEP projects should take into account principles of environmental sustainability
- In particular, future projects need to compute the full Life Cycle Analysis (LCA) of all accelerator and detector components
- The lab environmental reports/strategies should be periodic, public and envision ambitious emissions targets
- CERN, with its global status and visibility, should seize the opportunity and be an international role model by achieving emissions reduction beyond its current targets, demonstrating our field's commitment; in particular, pursue active sustainability actions (buildings, heat reutilization…) with adequate funding
- Laboratories and funding agencies should be proactive in encouraging and providing opportunities for their staff members to contribute to addressing and communicating the environmental crisis

European Strategy Update

Summary (part 2)

- The WG will consider the proposal of a „sustainability charter" that could be voluntarily included in institutions' rules and regulations

- HEP detectors: all efforts aimed at implementation of „eco" gases in our detectors and cooling systems, should be supported

- HEP computing: sustainability should be integrated into hardware and software practices

- We should enable and encourage environmentally friendly business travel, commuting, and methods of collaboration by reorganizing them in more environmentally friendly ways, while not neglecting the advantages of direct interactions between researchers

- Enable and encourage practices that minimize food-related negative environmental impacts

- Existing research sites be managed and future sites designed to enhance habitat diversity, halt local biodiversity loss, minimize water use, and encourage natural water cycles

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