TRIUMF

Sustainability in HEP (accelerators, detectors, computing)

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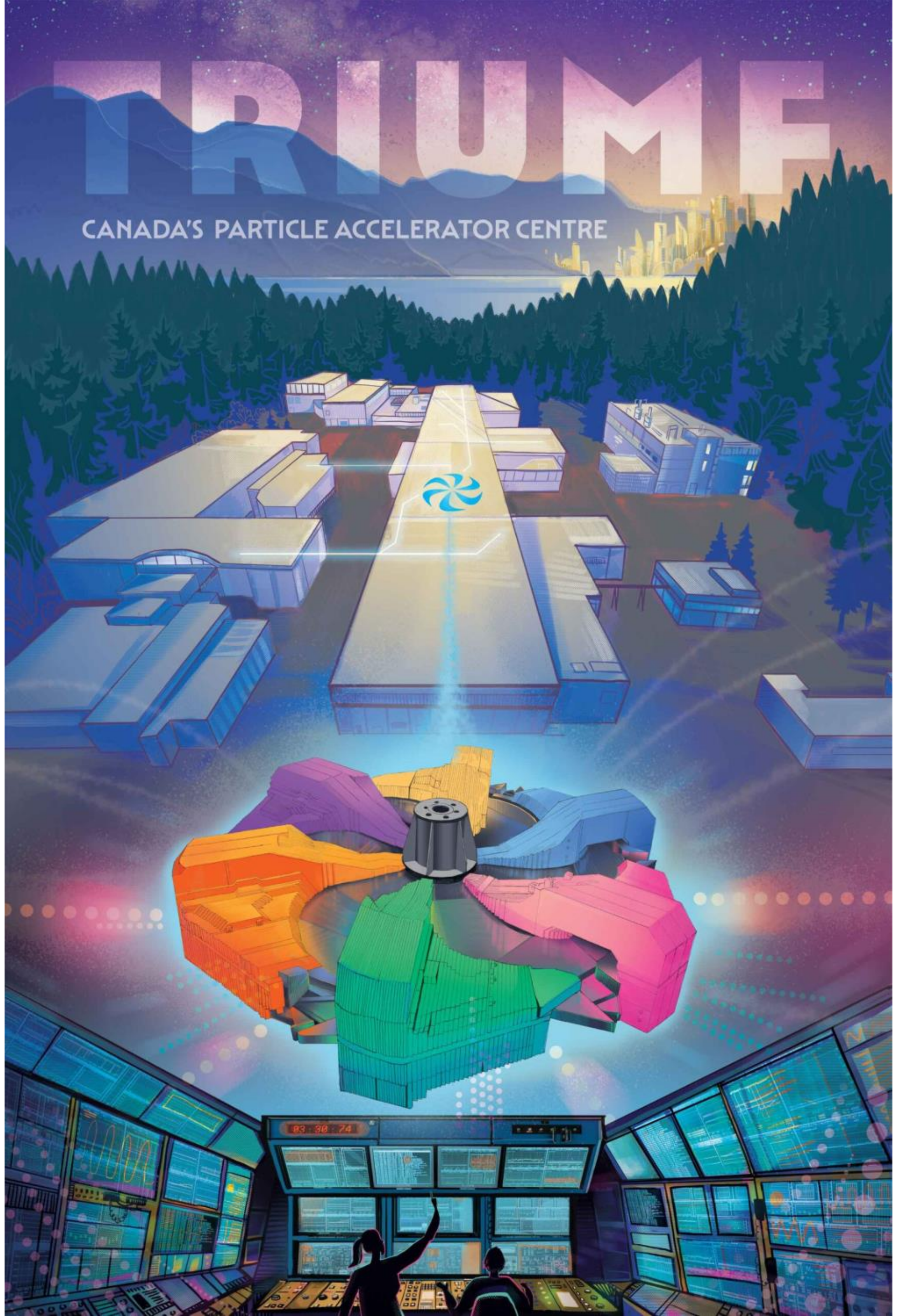


Discovery,
accelerated

2020 European Strategy for Particle Physics

The environmental impact of particle physics activities should continue to be carefully studied and minimized. A detailed plan for the minimization of environmental impact and for the saving and re-use of energy should be part of the approval process for any major project.

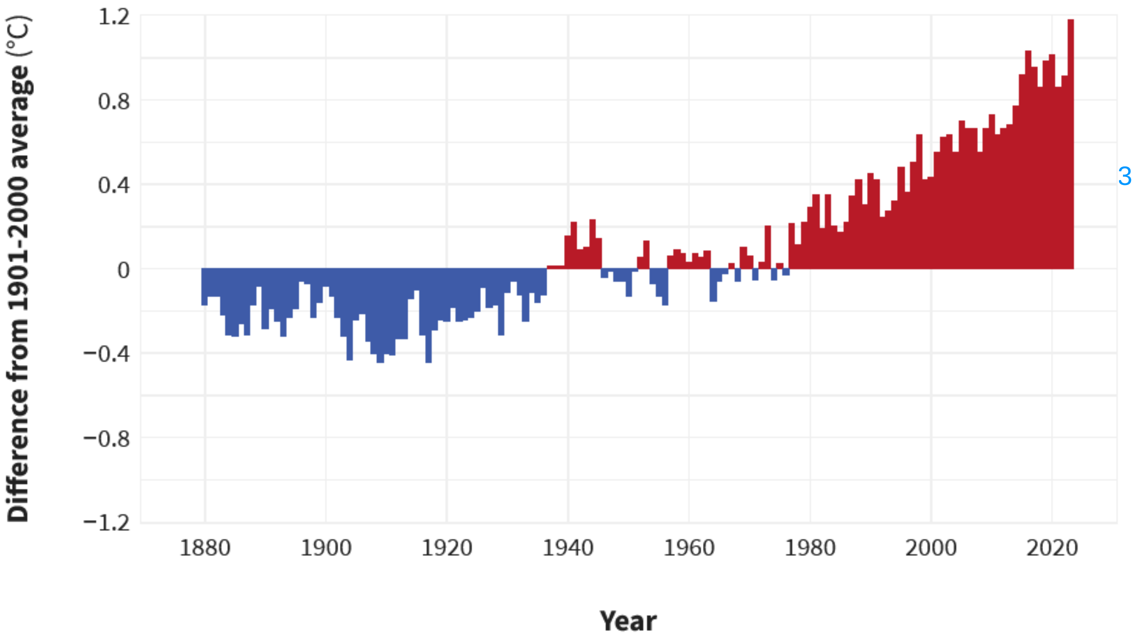
Report of the US 2023 Particle Physics Project Prioritization Panel (P5)

Commitment to sustainability is a high priority for particle physics activities. This includes energy and carbon management, energy efficiency and savings, and environmental impact. It concerns present and future accelerators as well as testing and computing facilities.

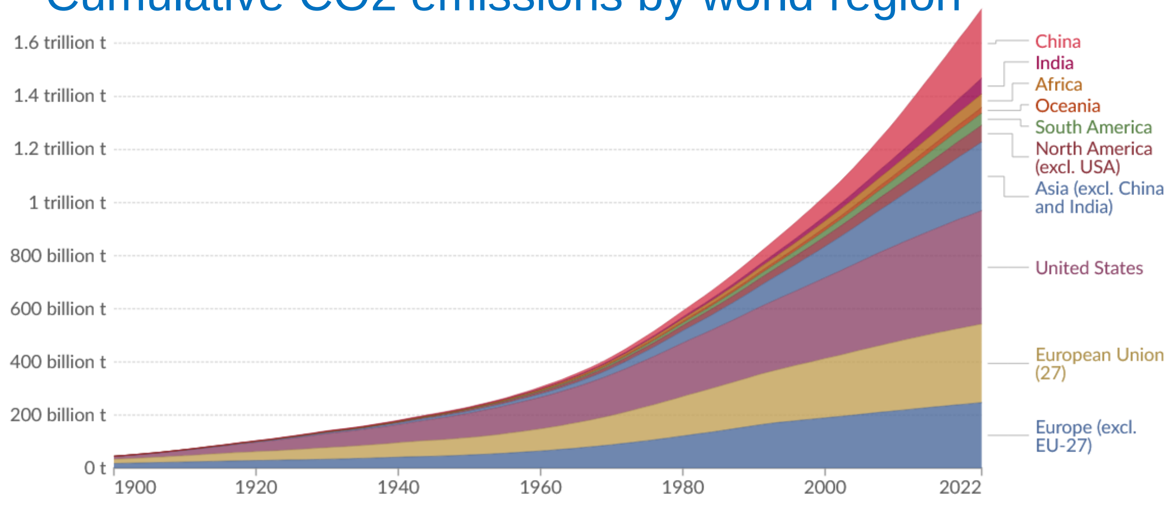
An existential threat

- Human life on earth as we know it is endangered by the unsustainable exploitation of many natural resources.
- One of the most urgent issues: CO2 from burning fossil fuels accumulates in the atmosphere. CO2 in the atmosphere is the primary determinant of the earth's average surface temperature.
- Present large HEP facilities have a significant carbon footprint - consumption of electrical energy, green house gases from detectors, heating of buildings, procurements, travel/commuting and waste.
- Present operation and future accelerator projects need justification not just in terms of scientific output vs effort (cost/resources) but also vs overall electricity consumption and carbon footprint.

Global average surface temperature

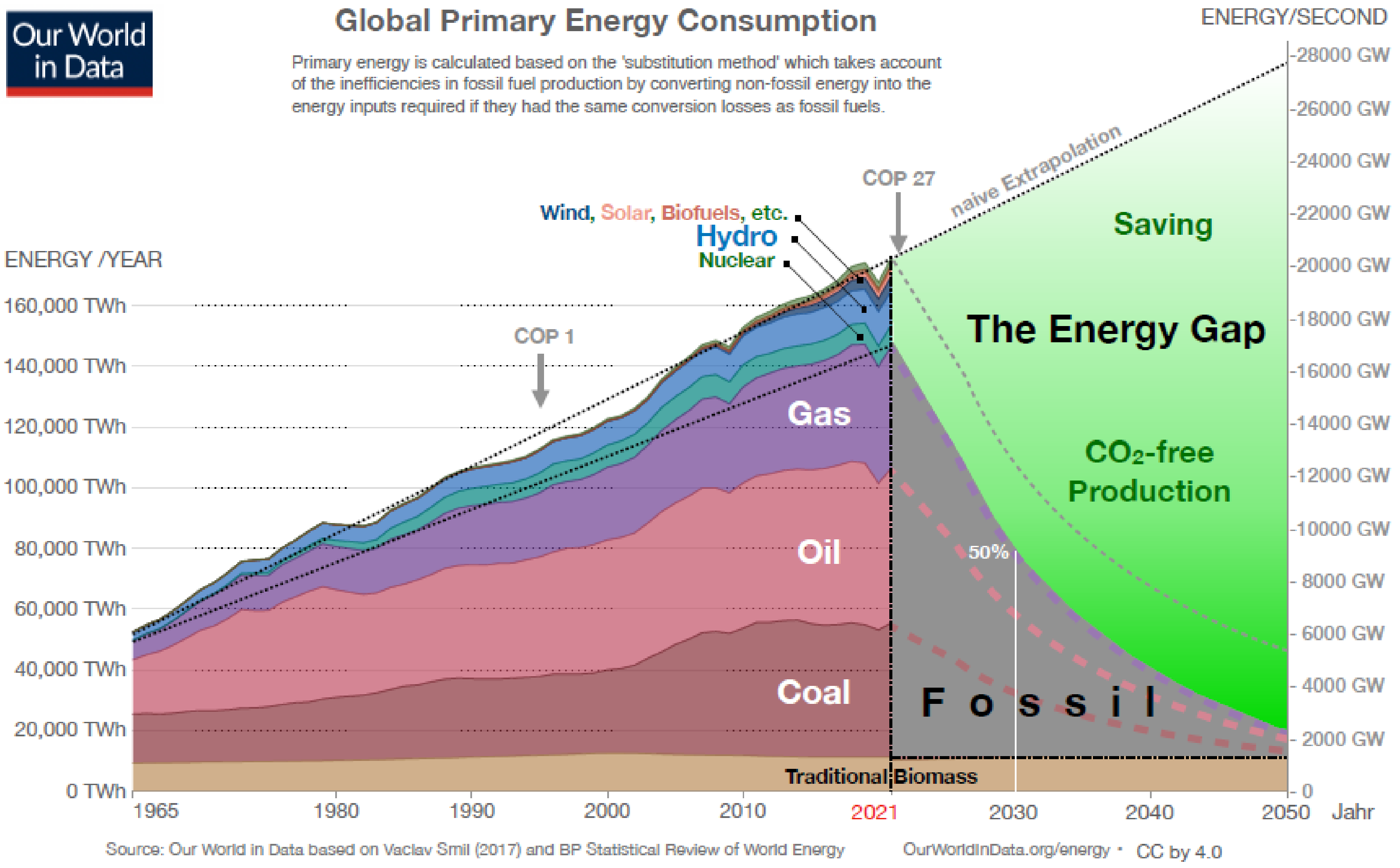


Cumulative CO2 emissions by world region



Global primary energy consumption

- Present global energy production is dominated by fossil fuels
- To reach climate change targets fossil fuel consumption requires dramatic reduction that will create an energy gap
  - Requires rapid rise of climate neutral power generation
  - Energy costs will rise
  - Requires energy savings and recuperation
- Rising costs and enhanced scrutiny will challenge HEP accelerators, experiments and data analyses centres both present and in the future



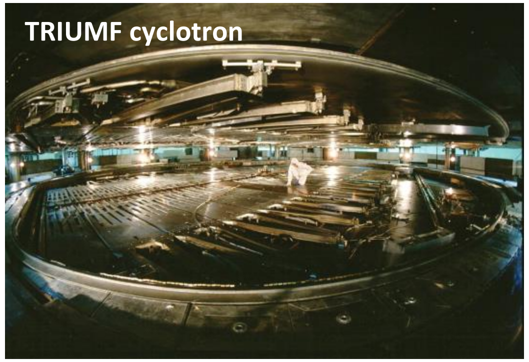
Definitions

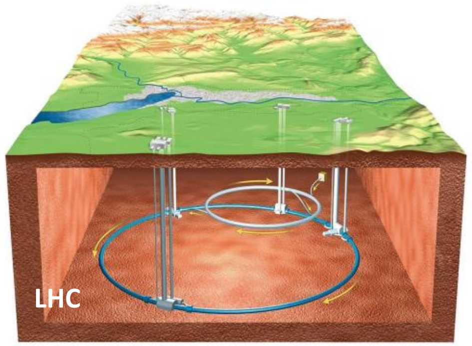
- **Carbon footprint** - the amount of green house gases (GHGs), expressed as CO2 equivalents, that are generated either directly or indirectly from a specific activity
  - Measured in kgCO2equivalent -> kgCO2e
- **Global warming potential** (GWP) - a measure of how much energy the emissions of 1 kG of a gas will absorb over a given period of time, relative to the emissions of 1 kG of carbon dioxide (CO_2)
  - Example: @100years GWP_{CH4}=21, GWP_{SF6}=23000
- **Carbon intensity -** is the carbon footprint embodied in a process
  - given in kgCO2e/kg for material and kgCO2e/kWh for energy and depends on the method of production
  - Aluminum - 7kgCO2e/kg from Europe and 20kgCo2e/kg from China
  - Concrete – 0.1-0.2kgCO2e/kG

Power comparisons

Large accelerator complexes require significant electrical power

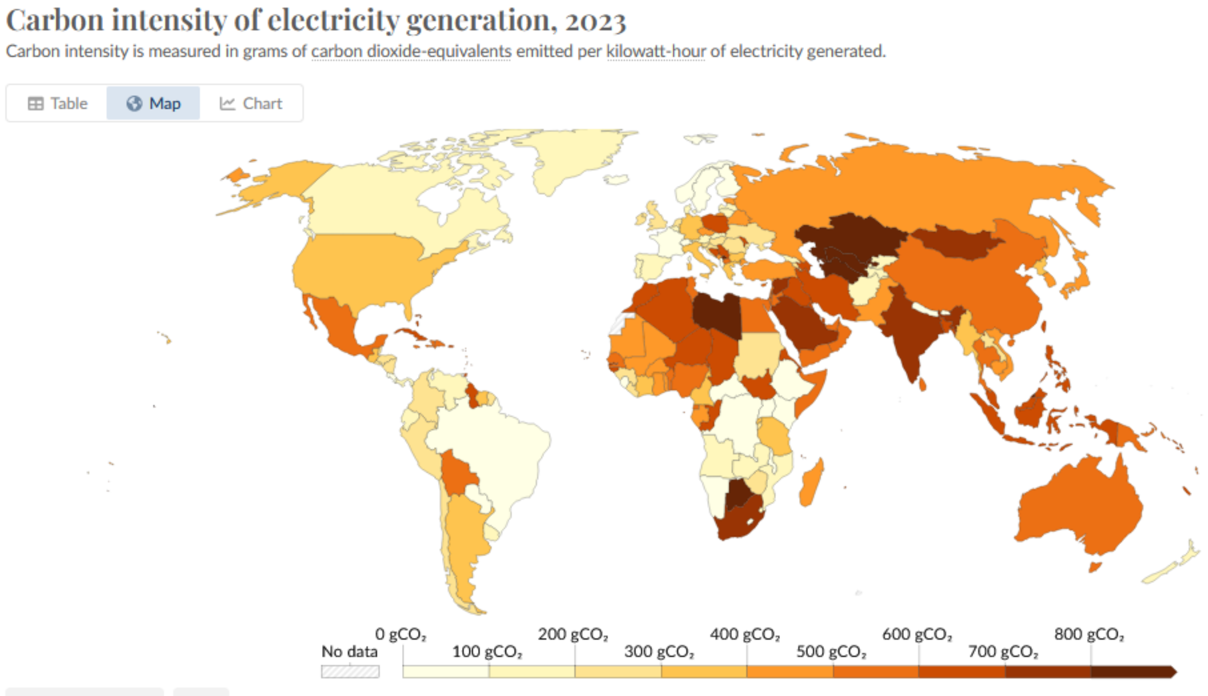
Cyclist	0.4 kW
PET cyclotron	60 kW
TRIUMF 500MeV cyclotron	2.6 MW
Large Hadron Collider	120 MW
FCC-ee, @ Higgs Energy	282 MW
Nuclear Power Station	1.3 GW
BC Hydro Revelstoke Dam	2.5 GW
Mankind Total (all sources)	19 TW

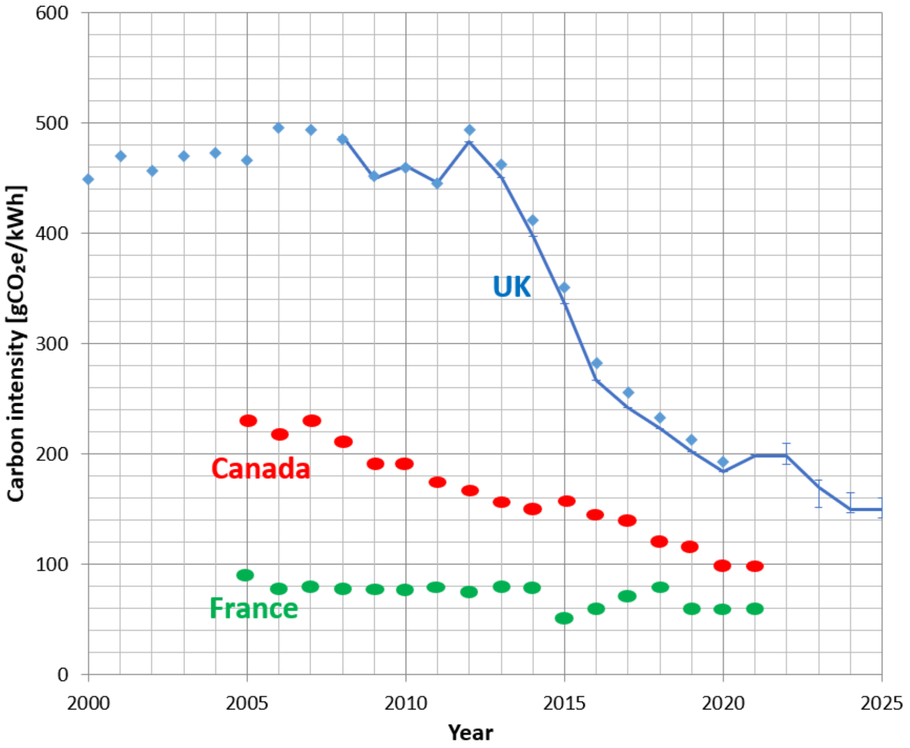




Carbon intensity of electricity production

- The carbon intensity depends on the process used to produce the energy and is improving with time as more green energy is brought on-line
- French, Canadian and UK electricity produces 60, 100 and 200 gCO2/kW-h respectively
- Regardless of the power source laboratories should aggressively seek ways to reduce power consumption as the globe transitions to low carbon solutions



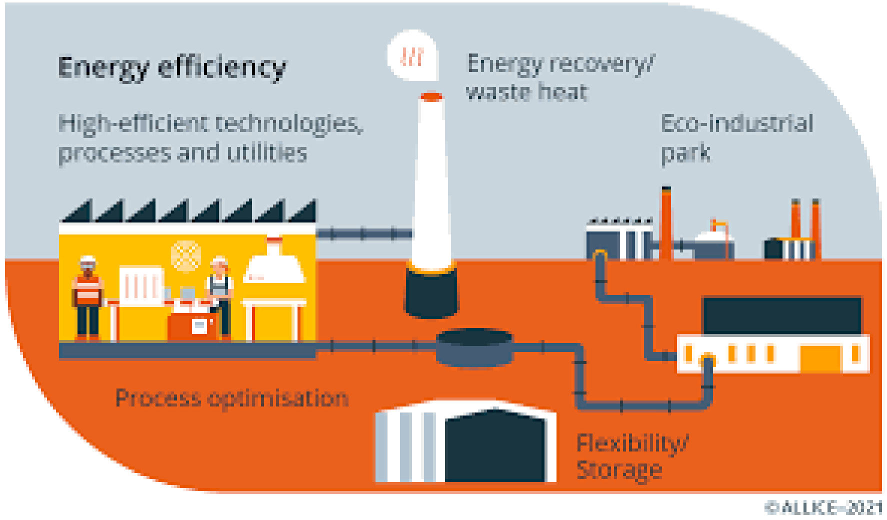


https://ourworldindata.org/grapher/carbon-intensity-electricity

Required community actions

- Reduce energy consumption per person by increasing energy efficiency and modifying culture while transitioning away from carbon fuel sources
  - **Example: “2000W Society” in Switzerland**: Numerical goal for primary power consumption of 2.0kW per person (Now: US: 9.0kW, Europe: 4.4kW, China: 3.6kW, India: 0.8kW, World:2.4kW, required food for humans: ~ 100W)

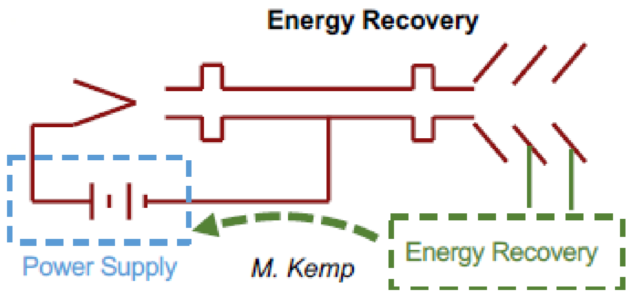
- The Accelerator community needs to evolve to more efficient technologies and support R&D to reduce total energy consumption.
  - Requires change in culture - we need to focus on energy efficiency with the same priority as achieving higher performance.
- Like the 2000W Society idea, a numerical goal for the energy consumption of accelerator-based user facilities could be beneficial.
  - For example, a goal for the maximum power consumption per user could be defined (i.e. 5 kW per user). (LHC: 12000 users, 120 MW, 10 kW/user; NSLS II (light source): 2000 users, 6 MW, 3 kW/user ; RHIC: 1000 users, 25 MW, 25 kW/user)
  - At any rate each lab should set interim targets with budgets and resources to reduce yearly consumption



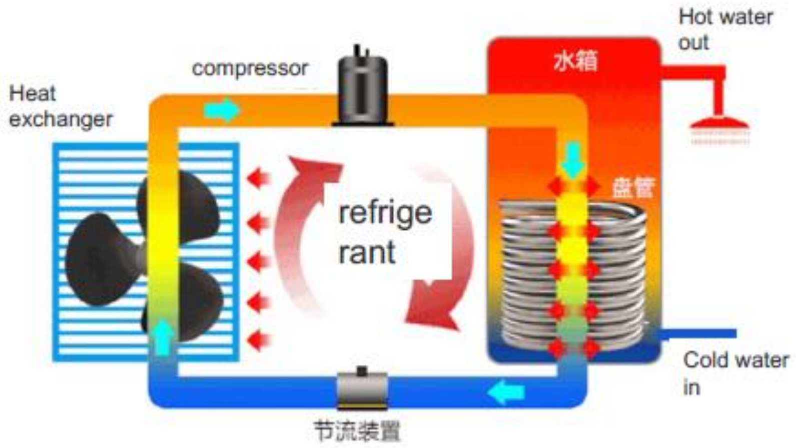
R&D to reduce energy consumption

Efficiency gains can come from improved technology or some form of energy recovery.

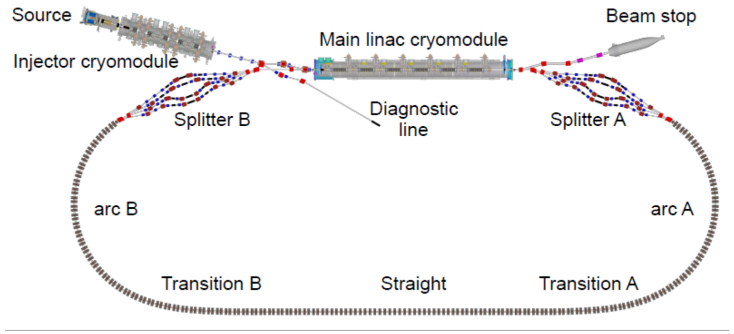
- Reduce
  - Develop more efficient power converters to DC and RF
  - Develop more efficient He refrigerators (presently 3 – 4 times worse than Carnot efficiency!)
  - Develop superconducting technologies – High Temperature Conductors (HTC) for DC applications and new SRF materials for higher Tc
  - Deploy more permanent magnets
  - Develop more compact accelerators to reduce construction footprint (muon collider, wake field accelerators)
- Recover
  - Employ energy recovery linacs where possible
  - Develop energy recovery for pulsed systems
  - Recover process heat using heat pump technology



Energy recovery in RF sources - SLAC



Heat pump - CEPC



C-Beta (Cornell) – 4-turn ERL

Carbon emissions production in HEP

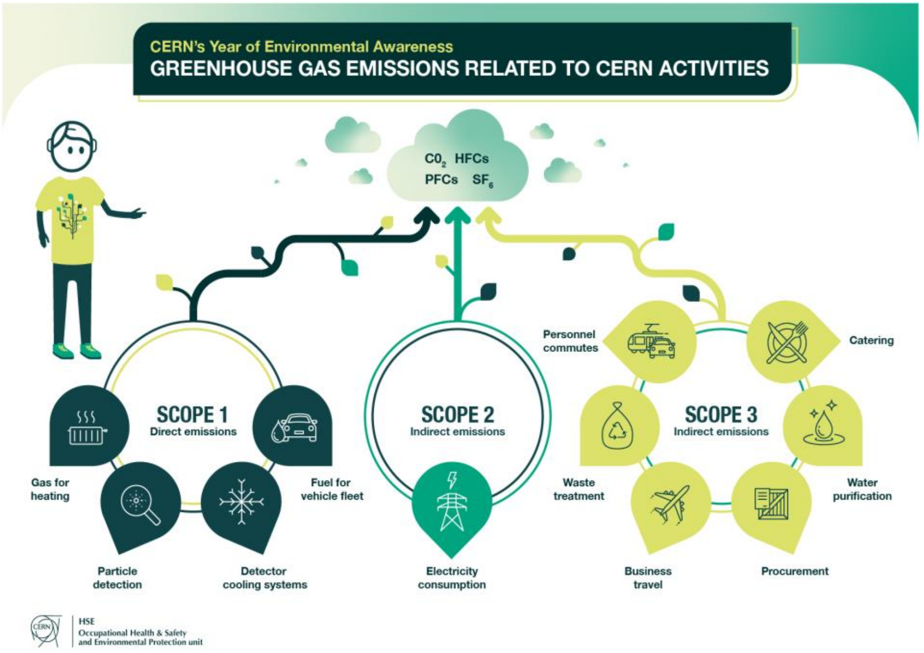
Beyond electricity consumption, HEP facilities produce considerable CO2 emissions.
Methodologies are being developed to help better compare and guide facilities in operation.

Recent analysis within HEP categorized production of CO2 emissions from three main research areas:

- Large particle accelerator installation and operation
- Large particle detectors for colliders and neutrino physics
- High-performance computing infrastructures that support science

Each area can be analyzed in terms of three common categories or scopes:

- **Scope 1**. Emissions from a source that an organization owns or controls directly, i.e. gas used in organization's cars, or leaked gases from detector systems.
- **Scope 2**. Emissions associated with energy purchased and used by the organization, i.e. gas burned in power stations connected to the electrical grid
- **Scope 3**. Everything else. Emissions associated with the manufacture and disposal of products used by the organization, commuting, business travel.



HEP computing – scope 2,3

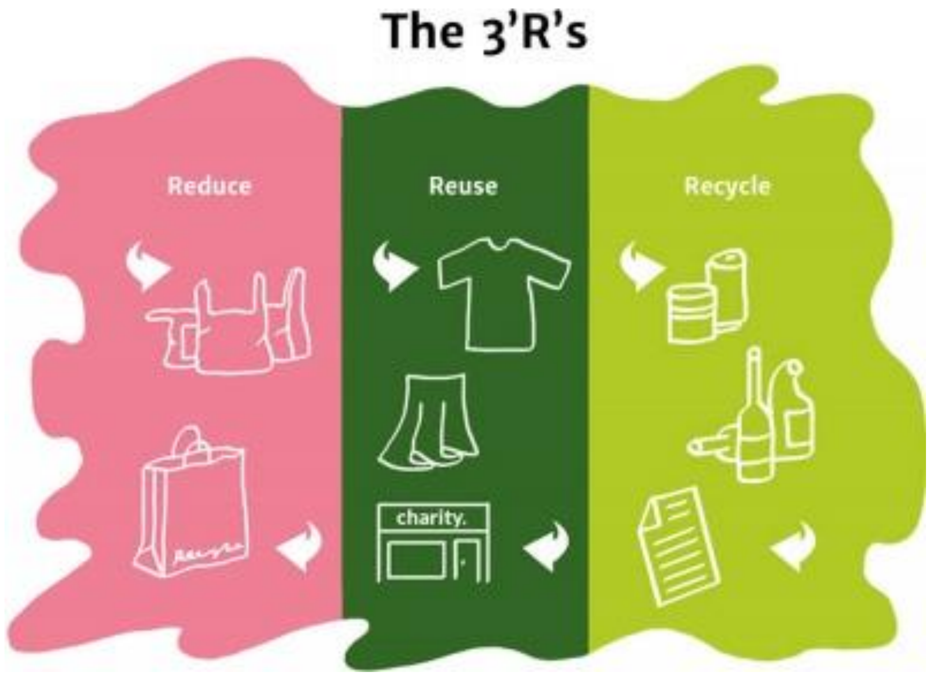
- Large computer data centers are power hungry – computation and cooling
- Across all sectors, data centers and computing already contribute approximately 2-4% of global GHG emissions, and that fraction is only predicted to grow in the next 10 years.
- the power usage effectiveness (PUE) and water usage effectiveness (WUE) are key performance indicators for data center efficiency
- Mitigations
  - Continually upgrade software for more efficient algorithms
  - Set targets for PUE and WUE – continuous improvement
  - Promote R&D towards efficient computer hardware
  - Coordinate power loads with their electricity suppliers, to reduce consumption during peak hours
  - Implement plans for waste heat recovery in design phase for new computing centres
  - Provide information on the GHG intensity of the computation in a standardized transparent format to help gauge progress

Direct green house gases – scope 1

- HEP particle detectors and detector cooling systems use significant quantities of GHGs with high GWP (1000 to 10000 times CO2) – SF6, PFC, HFC
- Escaping gas presents a serious risk for adding to a facility's yearly carbon footprint
  - Responsible for 40% of CERN's total annual carbon footprint in 2022
- European regulations will target research institutes more stringently in the future
  - Will significantly impact cost and availability of these gases
- Mitigations:
  - Reduce yearly GHG consumption of operating systems and develop new systems for better retention through the detector life cycle https://indico.fnal.gov/event/51385/contributions/226556/attachments/149100/191804/Snowmass_CERN_GHGStrategies_BMandelli.pdf
  - Research new environmentally friendly gas mixtures https://doi.org/10.1088/1748-0221/17/05/P05005

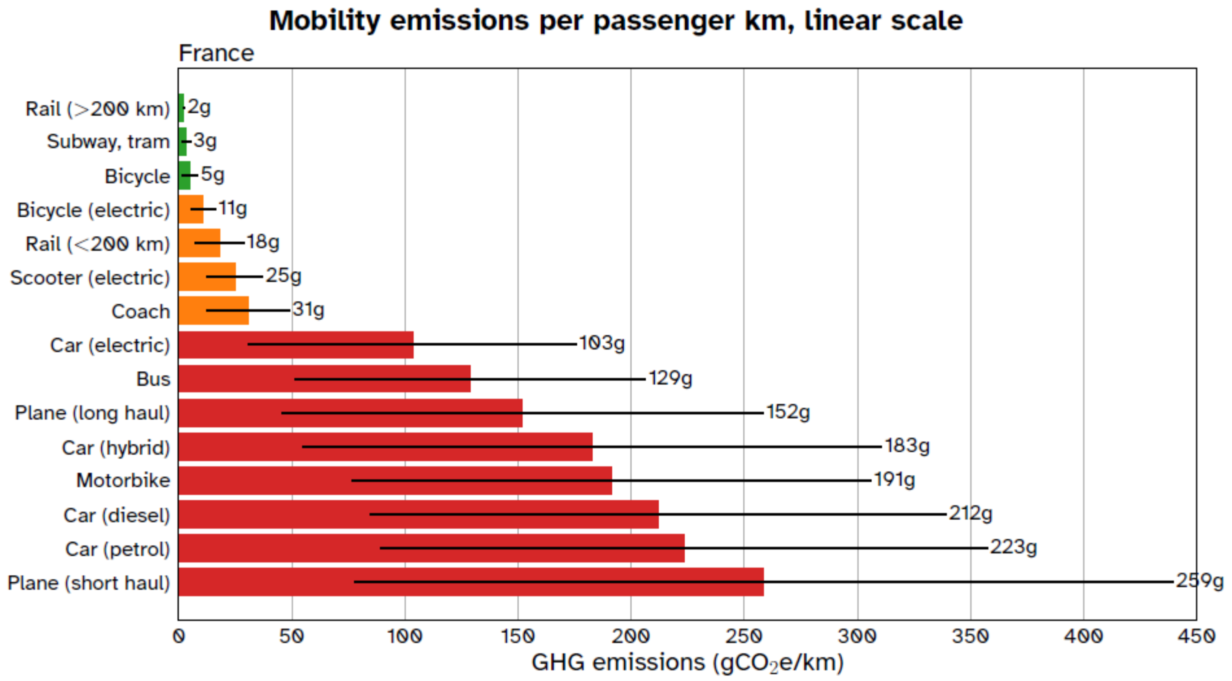
Procurements – scope 3

- HEP facilities require significant procurements to maintain and develop scientific infrastructure and support on-site activities
- Each procurement is associated with a certain carbon footprint required to produce the raw material or part and can be a significant fraction of the facility's yearly output
- Mitigations:
  - Reduce, reuse and recycle
  - Adopt sustainable procurement policies
    - Consider the full life cycle of the procurement, the carbon cost of production and the carbon footprint of operation and disposal and not just capital cost
    - Develop a vendor data base in collaboration with other labs that rewards good practice



Travel – scope 3

- HEP participants tend to travel frequently for collaboration meetings or conferences
  - One transatlantic flight -> 1 tCO2e
  - One domestic flight -> 0.2-0.4 tCO2e
- Commuting also adds to GHG emission
  - Car commute (gas) 100km/week produces 1 tCO2e annually
- Mitigations
  - Provide incentives for public transport and environmentally friendly transport
  - Incentivise the reduction of business air travel – set personal and lab goals while considering inclusion
  - Community: develop better hybrid approaches to meetings

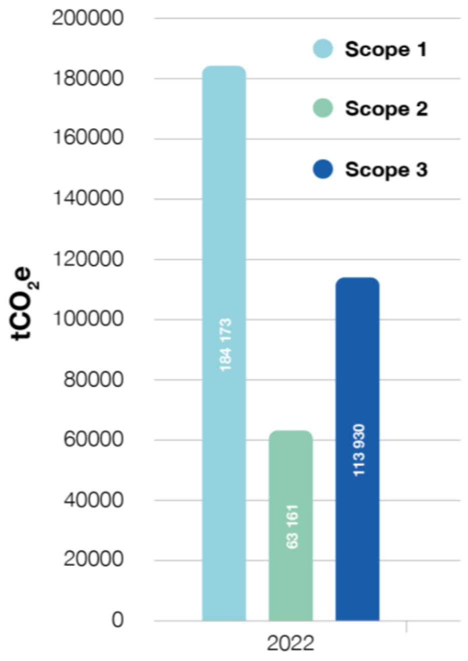


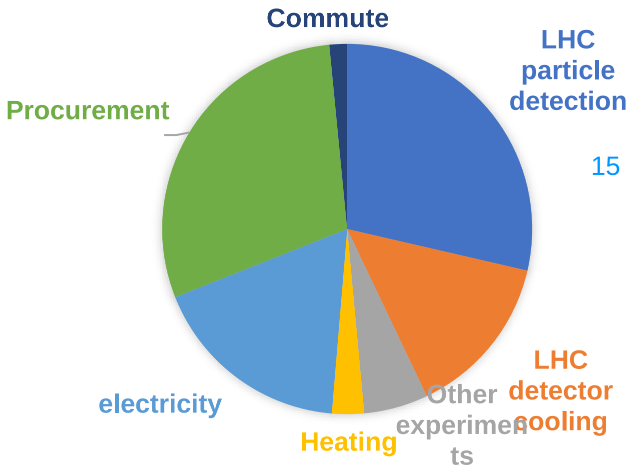
The total carbon footprint of Nikhef in the Netherlands in 2019 was ~1 ktCO2e with 75% from air travel of staff.

Facility GWP examples

CERN 2022 – Total GWP was 350ktCO2e

- To put in context assuming 12200 users this corresponds to 30tCO2e per user or roughly 5x the average individual annual carbon footprint in Europe
- More than 78% of CERN's scope 1 emissions are due to detector gases, some of which have very high GWP
  - CERN's goal is to reduce the scope1 CO_2e emissions by 28% by the end of 2024





CERN CO2e Emissions 2022

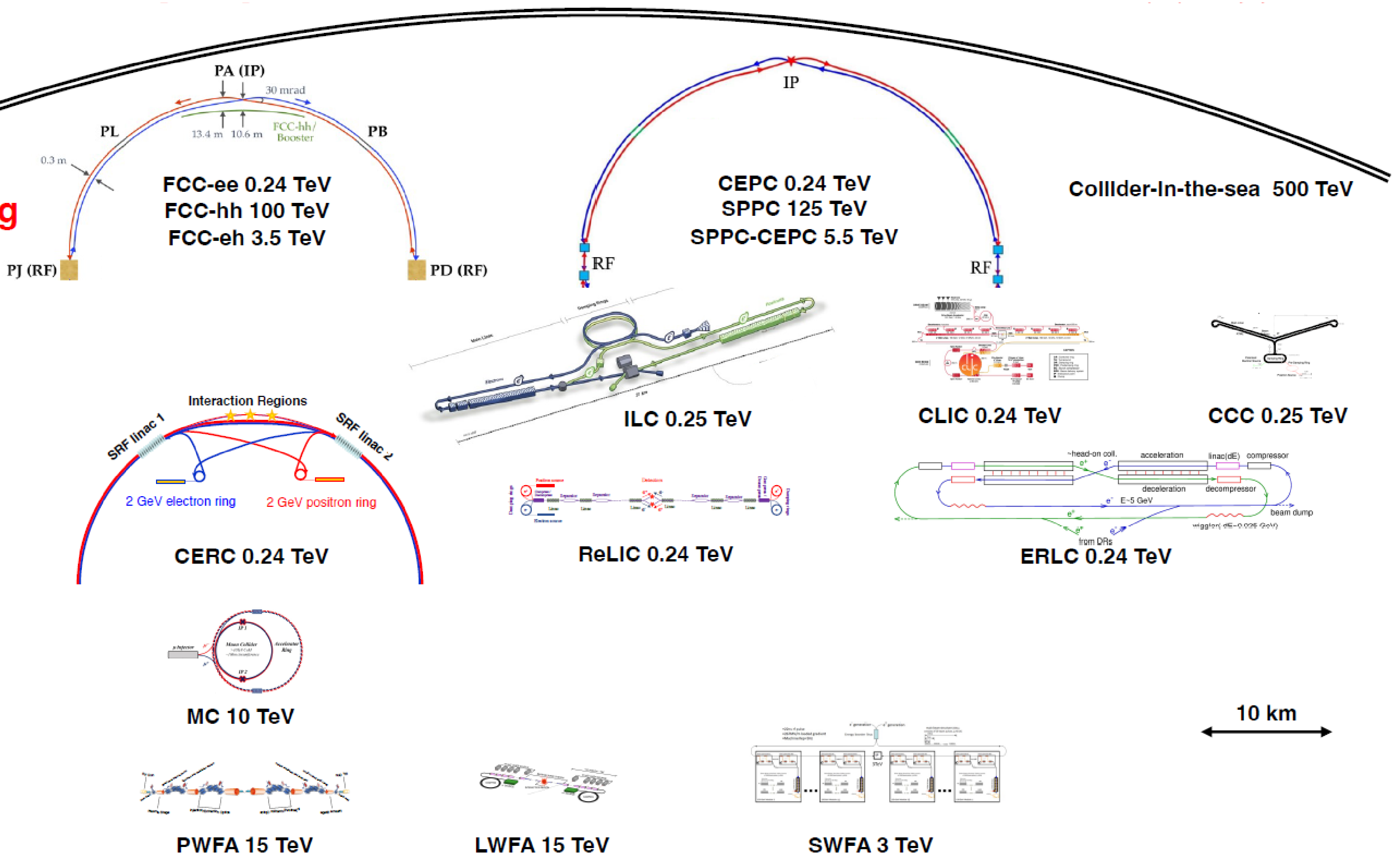
- More than 90% of scope 3 emissions are from procurements (includes life cycle of production)
- Despite the relatively high electricity draw, 1.2TW-h, the GWP (scope 2) is 60ktCO2e due to relatively low carbon power from France with a carbon intensity of 50ktCO2/TW-h

STFC 2022 – Total GWP was 29ktCO2e

- This corresponds to 17tCO2e per staff member or 4 times national average of 4.7tCO2e
- STFC facilities consumed 107 GW-h with a GWP of 22.1ktCO2e given the UK carbon intensity of 200ktCO2e/TW-h (4x CERN)

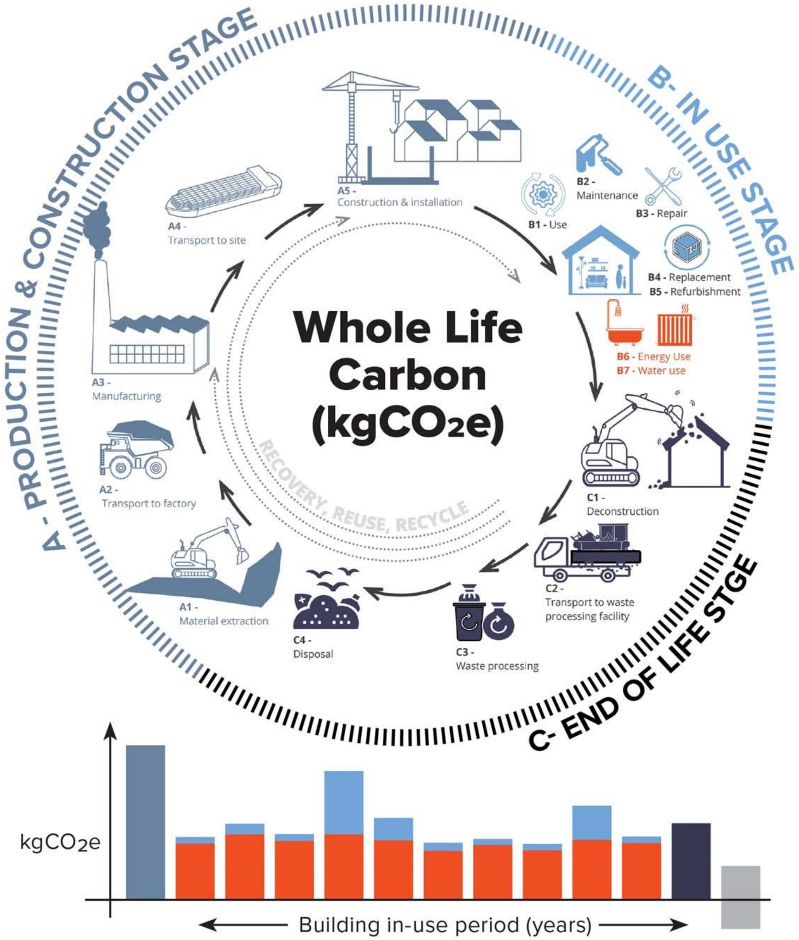
Future HEP projects and sustainability

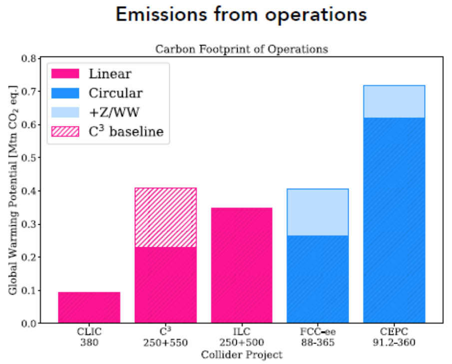
- Storage ring colliders
- Linear colliders
- ERL colliders
- Muon collider
- Wakefield colliders

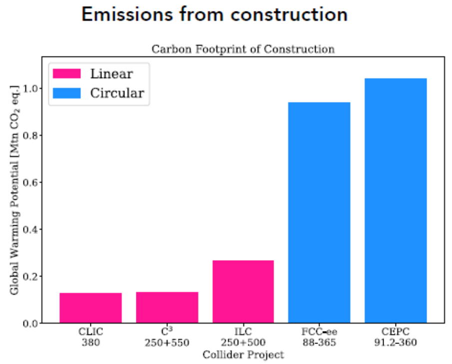


Lifecycle analysis (LCA)

- For new project proposals a full life cycle analysis methodology is being developed. The goal is to enhance scrutiny on projects beyond cost and effort.
- Such analyses estimates the total energy and carbon footprints over the full life cycle and should play an important role, maybe defining role, in selecting the next project.
- The LCA includes both the construction and operation phase with CO2 emission and energy consumed per ton of concrete, steel, and aluminum, as well as CO2 emission during operation and decommissioning
- Some large collider proposals (FCC, ILC, CLIC, CCC) have already prepared such lifecycle analyses. (Recent reports: [Life Cycle Assessment for CLIC and ILC, July 2023]; [M. Breidenbach et al., PRX Energy 2, 047001]; also, [RUEDI, Daresbury])







Community engagement

- ICFA panel on sustainable accelerators, chair: Thomas Roser (BNL)
- https://icfa.hep.net/icfa-panel-on-sustainable-accelerators-and-colliders/

Energy for Sustainable Science at Research Infrastructures (ESSRI) - workshop series – Sept. 25-27, 2024, Madrid

2021–25: I.FAST, Work Package WP-11 Sustainable Concepts and technologies

https://ifast-project.eu/index.php/wp11-sustainable-concepts-and-technologies

Sustainability for Particle Accelerators: RUEDI - A Case Study – Ben Shepherd UKR1-STFC Daresbury https://www.astec.stfc.ac.uk/Pages/Sustainable%20Accelerator%20Review%202024.pdf

SustainableHECAP+ Initiative, **“Environmental sustainability in basic research: A perspective from HECAP+”,** 2023, available at: https://sustainable-hecap-plus.github.io/.

Summary

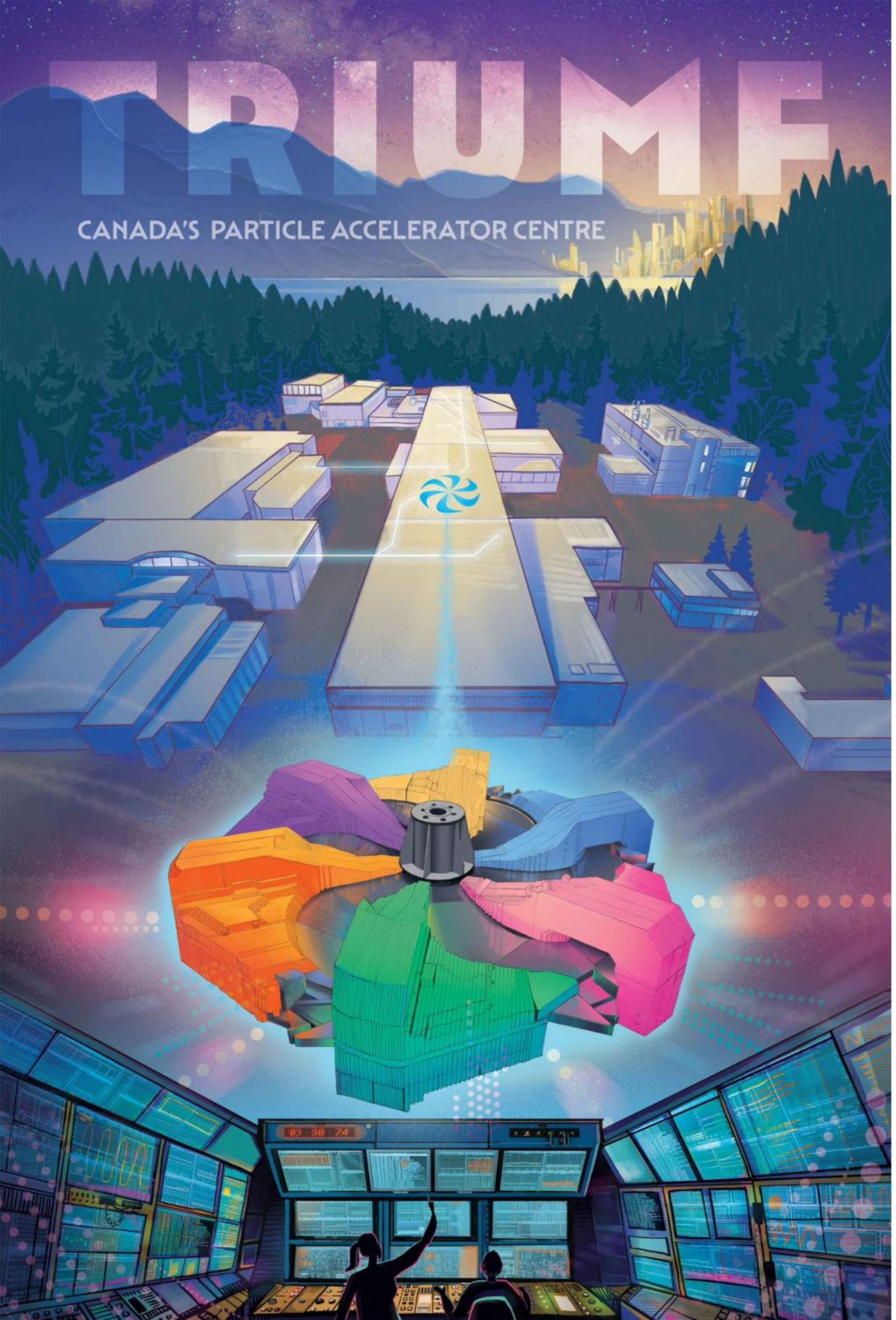
Present large HEP facilities have a significant carbon footprint from consumption of electrical energy for accelerators and data centres, green house gases from detectors, heating of buildings, procurements, travel/commuting and waste.

The worldwide “Climate Emergency” requires everybody to take urgent action, including the HEP community.
Future accelerator projects will need to minimize resource use, especially energy consumption and reduce CO_2 emissions throughout their lifecycle from construction, operation, to decommissioning.

Proposed actions include:

- Support the completion of comparative lifecycle analyses of total energy and carbon footprint for all future accelerator projects
- Support R&D of increased energy efficiency and reduced carbon emissions with a priority at least as high as performance and cost reduction R&D.
- Advocate low impact commuting and remote or hybrid meetings to reduce air travel in our community
- Reward industrial partners who exemplify best practise in sustainability
- Consider carbon cost in addition to capital cost in procurement decisions
- Establish and report key performance indicators regularly and transparently with concrete goal setting.
- Consider a community-based approach to neighbourhood energy efficiency through transformation of waste heat to energy

https://indiancc.mygov.in/activity/fiza-khan/poster-on-energy-conservation/



Thanks
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