Sustainable Science: a path to reducing the environmental footprint of research

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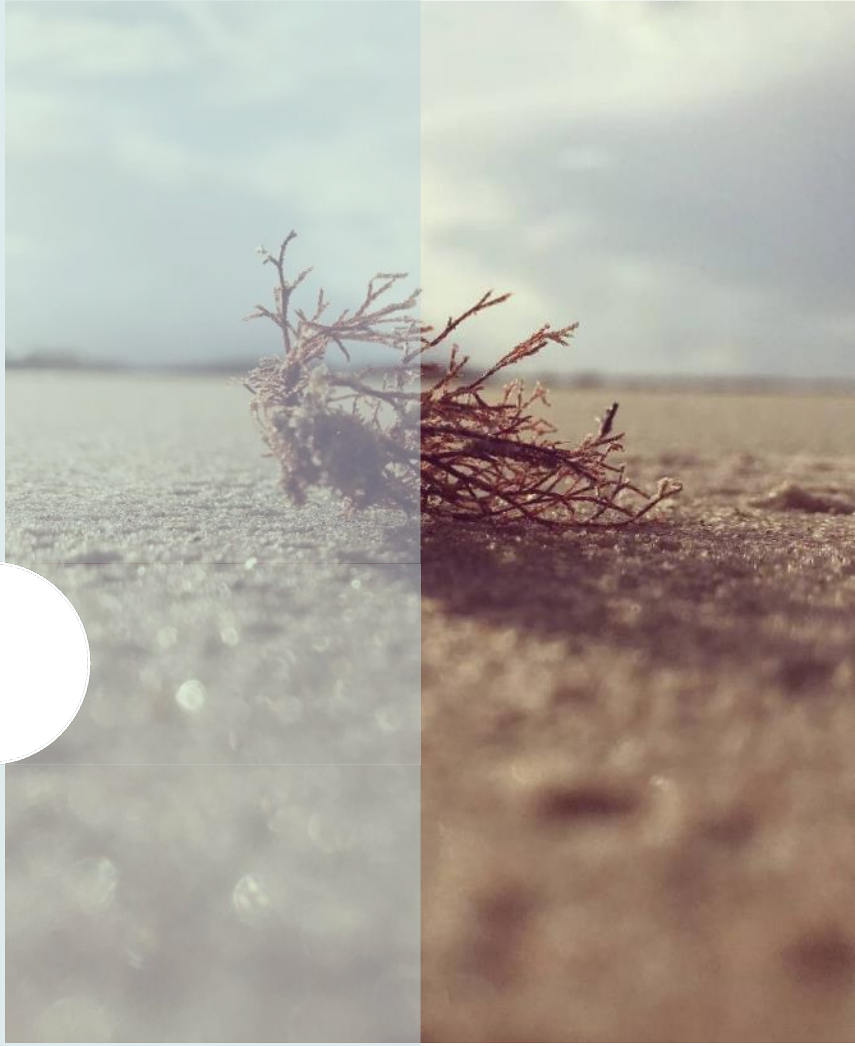

- PhD, Theoretical Particle Physics, 2012
  - University of Notre Dame du Lac, USA
- Postdoctoral Fellow, 2012 – 2017
  - INFN, Sezione di Roma, Italia
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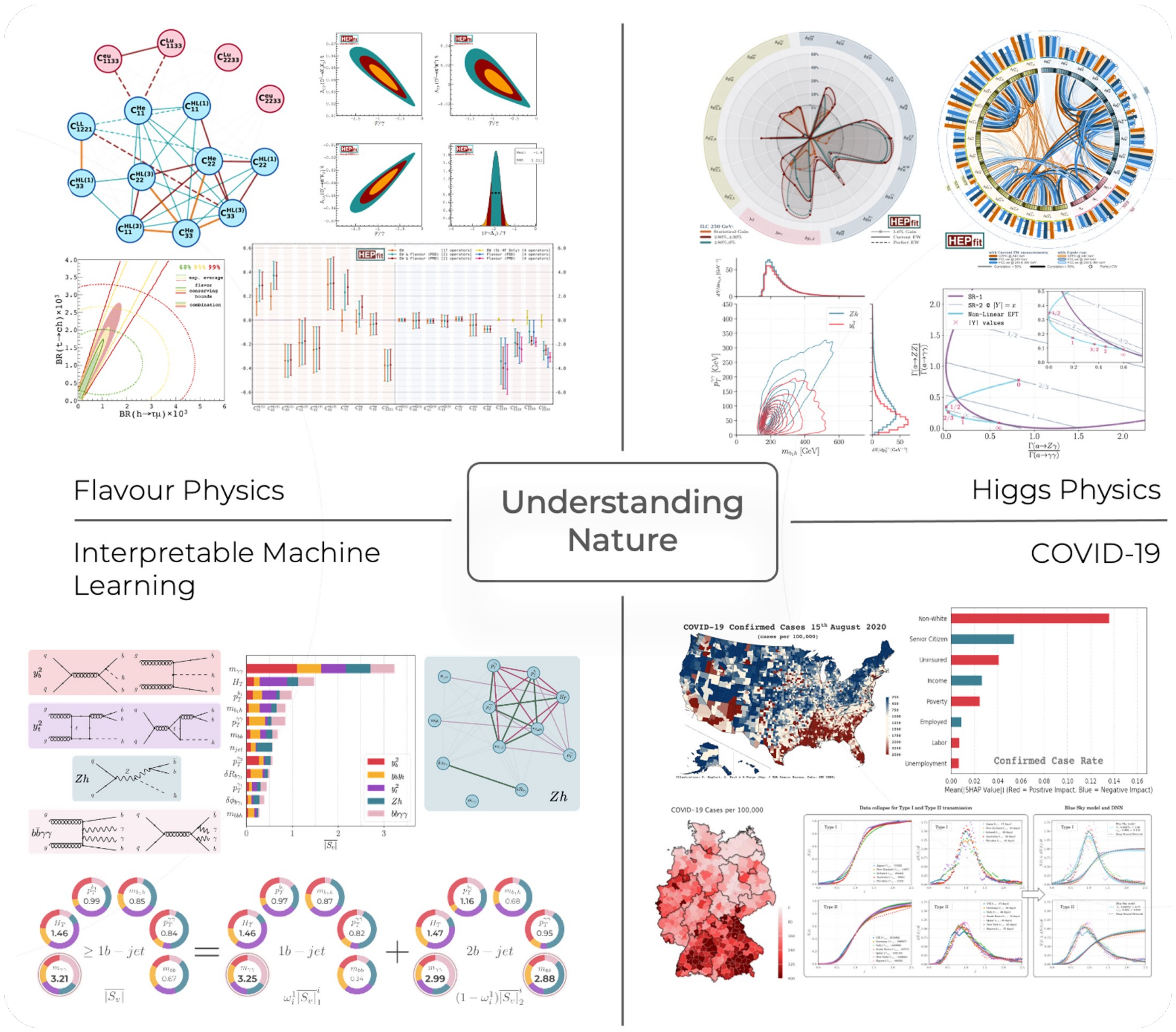


Sustainable HECAP+ Reflection Document

The climate crisis and the degradation of the world's ecosystems require humanity to take immediate action. The international scientific community has a responsibility to limit the negative environmental impacts of basic research. The **HECAP+ communities** (**High Energy Physics, Cosmology, Astroparticle Physics, and Hadron and Nuclear Physics**) make use of common and similar experimental infrastructure, such as accelerators and observatories, and rely similarly on the processing of big data. Our communities therefore face similar challenges to improving the sustainability of our research. This document aims to reflect on the environmental impacts of our work practices and research infrastructure, to highlight best practice, to make recommendations for positive changes, and to identify the opportunities and challenges that such changes present for wider aspects of social responsibility.

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

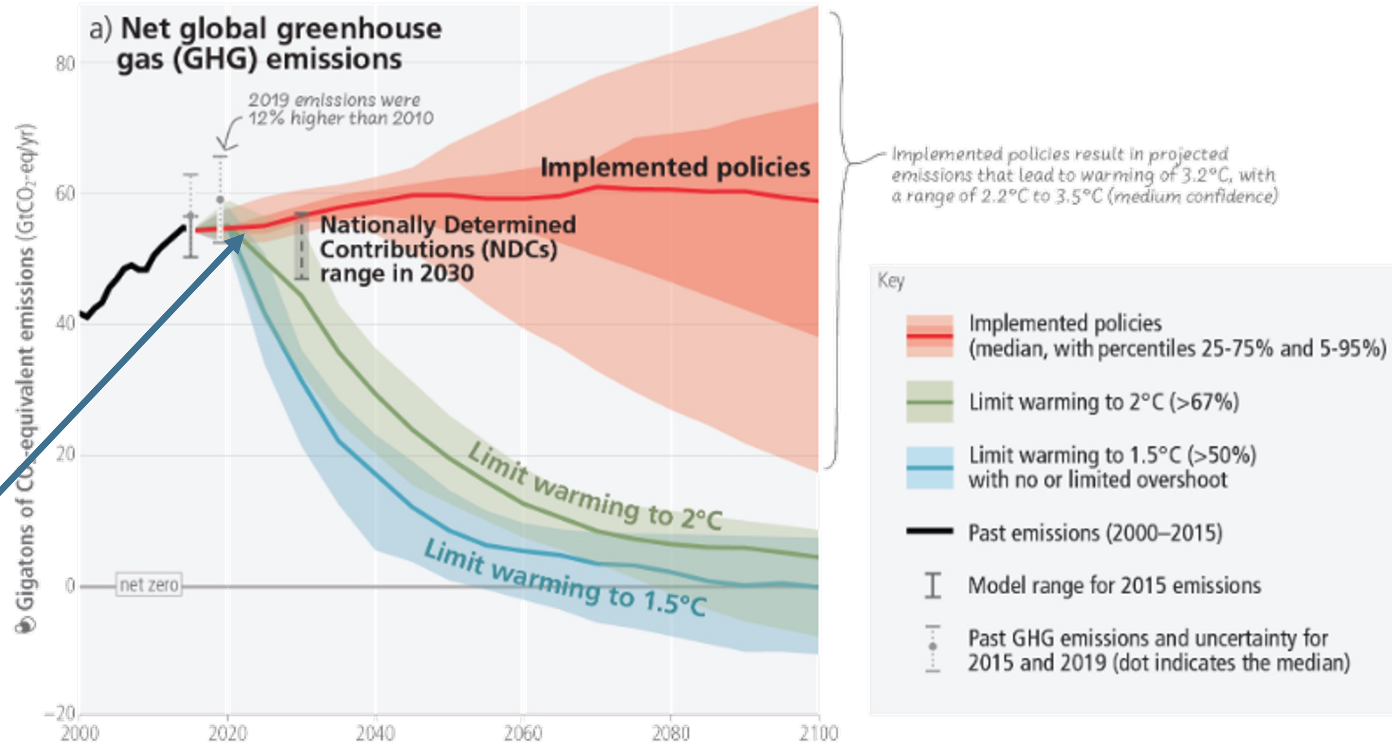
Intergovernmental Panel on Climate Change

It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. […] **Human-induced climate change is already affecting many weather and climate extremes in every region across the globe.** Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since [the Fifth Assessment Report in 2014].

Global surface temperature will continue to increase until at least mid-century under all emissions scenarios considered. **Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades.** […] Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, heavy precipitation, and, in some regions, agricultural and ecological droughts; an increase in the proportion of intense tropical cyclones; and reductions in Arctic sea ice, snow cover and permafrost.

Current policy implementations are not sufficient to reduce GHG emission to the required extent.

We are here



[7] IPCC, 2023: Summary for Policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001.

Figure 1.1: According to the IPCC, the global net greenhouse gas emissions have to come down to zero to limit global warming. To avoid irreversible tipping points, mitigation pathways should limit warming to 1.5°C, which requires deep, rapid and sustained emissions reductions. Pledged policy changes announced up until October 2021 by nations party to the Paris Climate Agreement, known as Nationally Determined Contributions, are insufficient to meet this goal. Figure excerpted from the IPCC 2023 Synthesis Report, Ref. [7].

the harsh reality

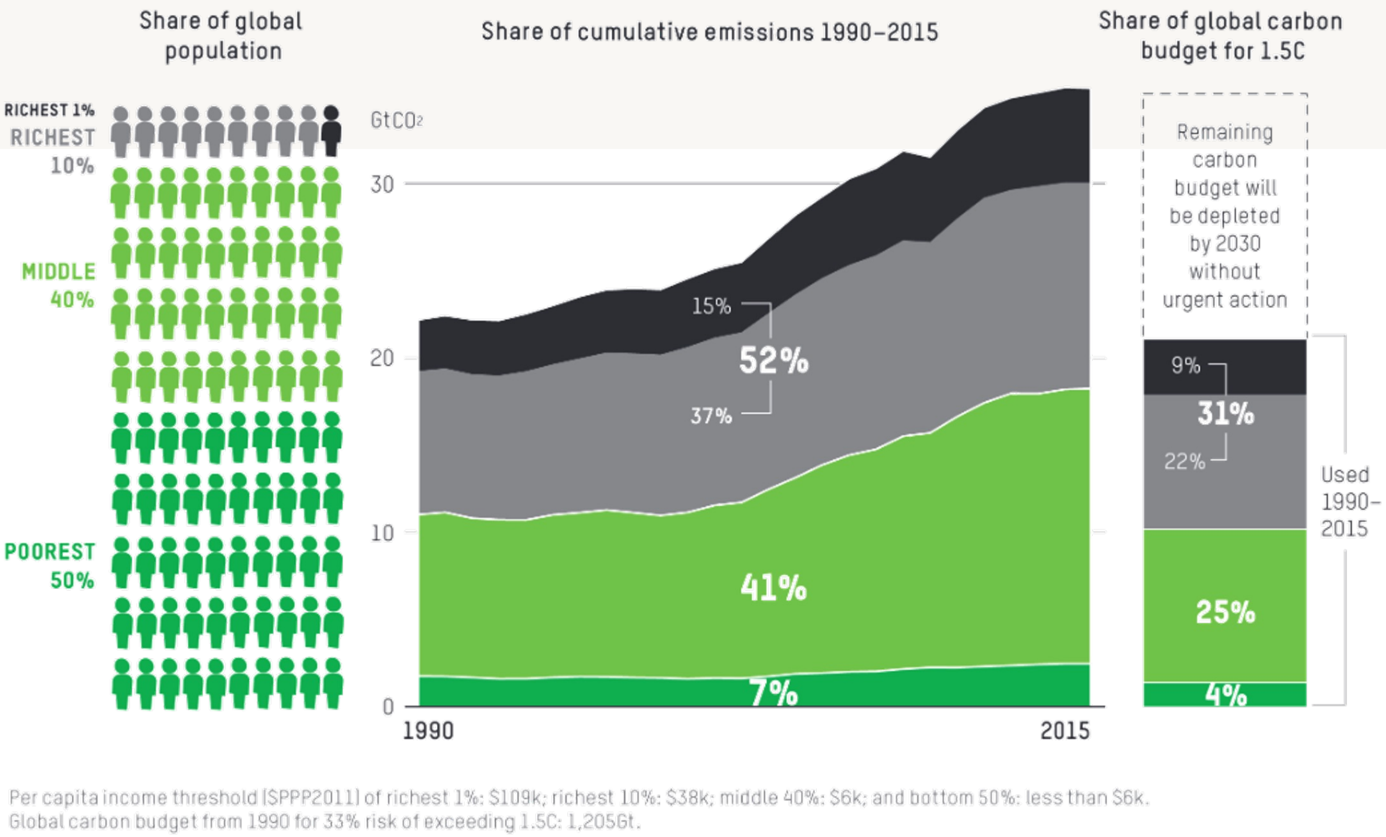
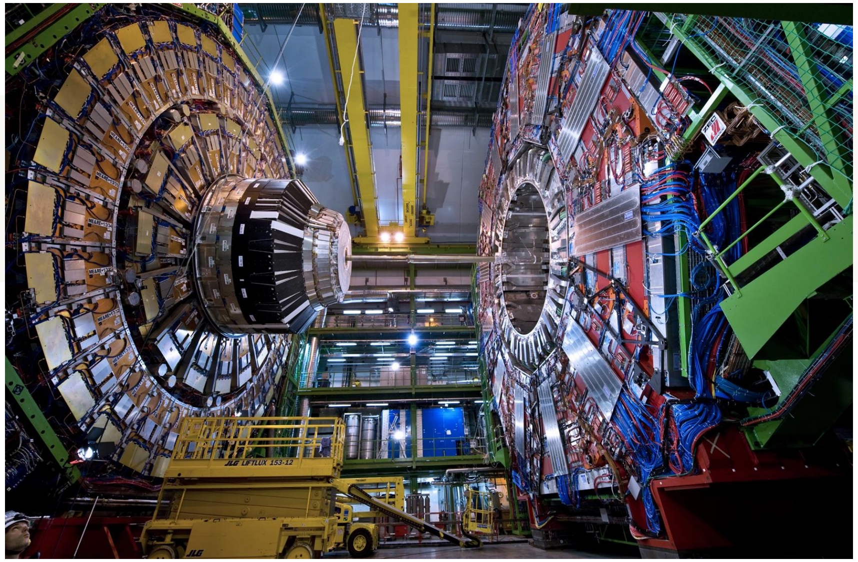


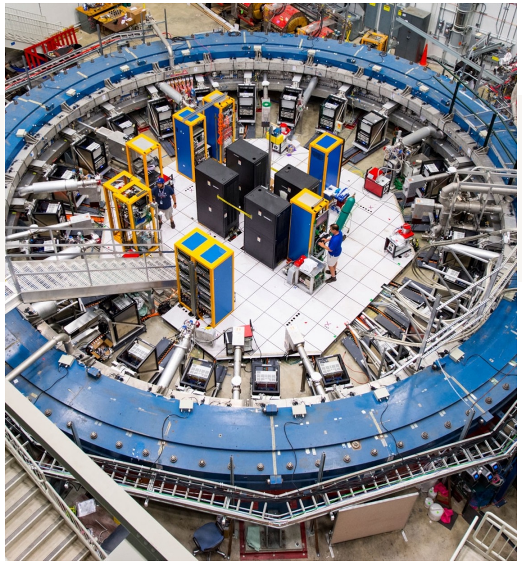
Figure 1.2: Share of cumulative emissions from 1990 to 2015 and use of the global carbon budget for 1.5°C linked to consumption by different global income groups. Figure reproduced from Ref. [9] with the permission of Oxfam.[a]

[a] Oxfam House, John Smith Drive, Cowley, Oxford OX4 2JY, UK, https://www.oxfam.org.uk/. Oxfam does not necessarily endorse any text or activities that accompany the materials.

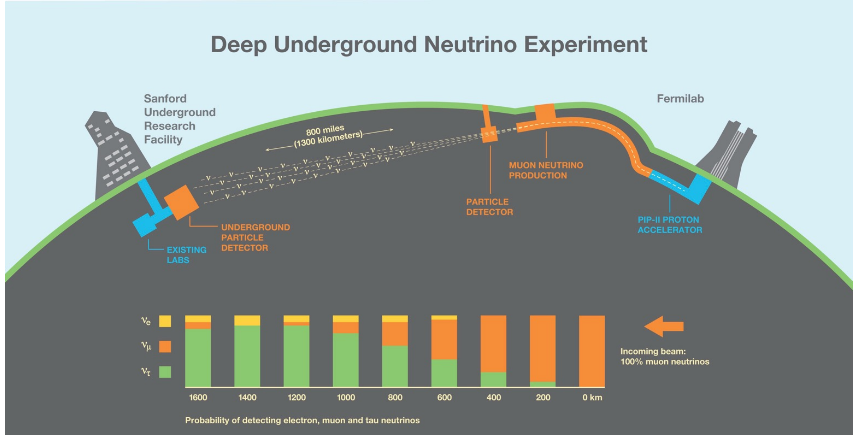
Richest 10% of the world's population means **annual income > €34,000.**

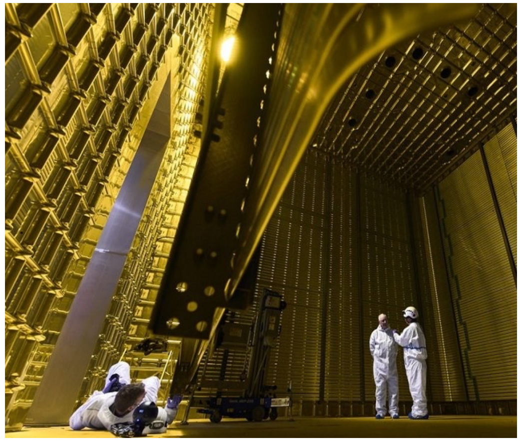
[9] T. Gore, "Confronting carbon inequality," Geneva, 2020. https://oxfamilibrary.openrepository.com/bitstream/handle/10546/621052/mb-confronting-carbon-inequality-210920-en.pdf. Accessed on: 2 June 2023

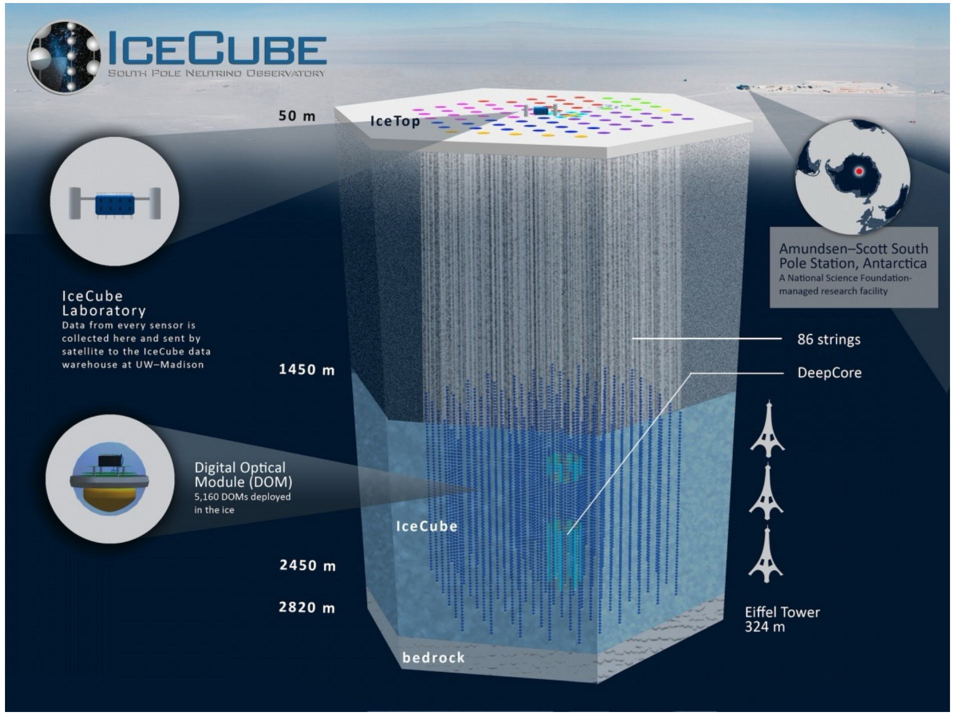


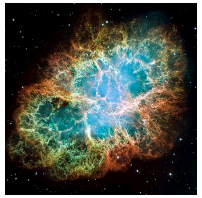


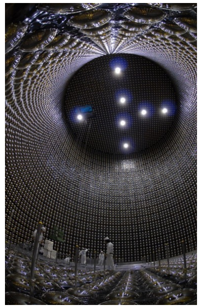
the science we do

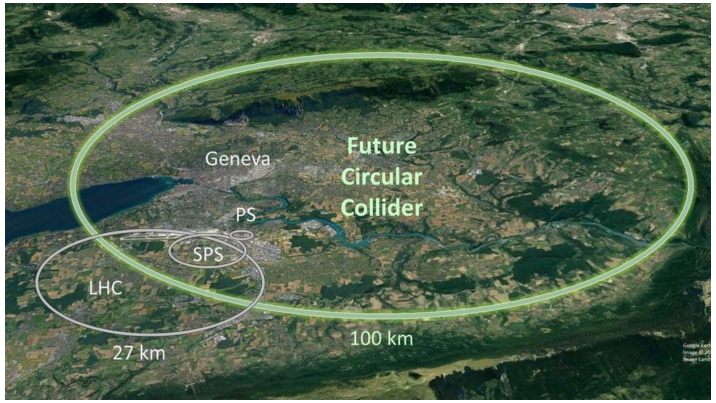


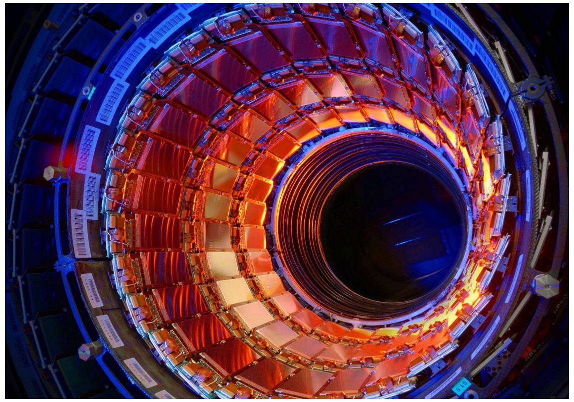












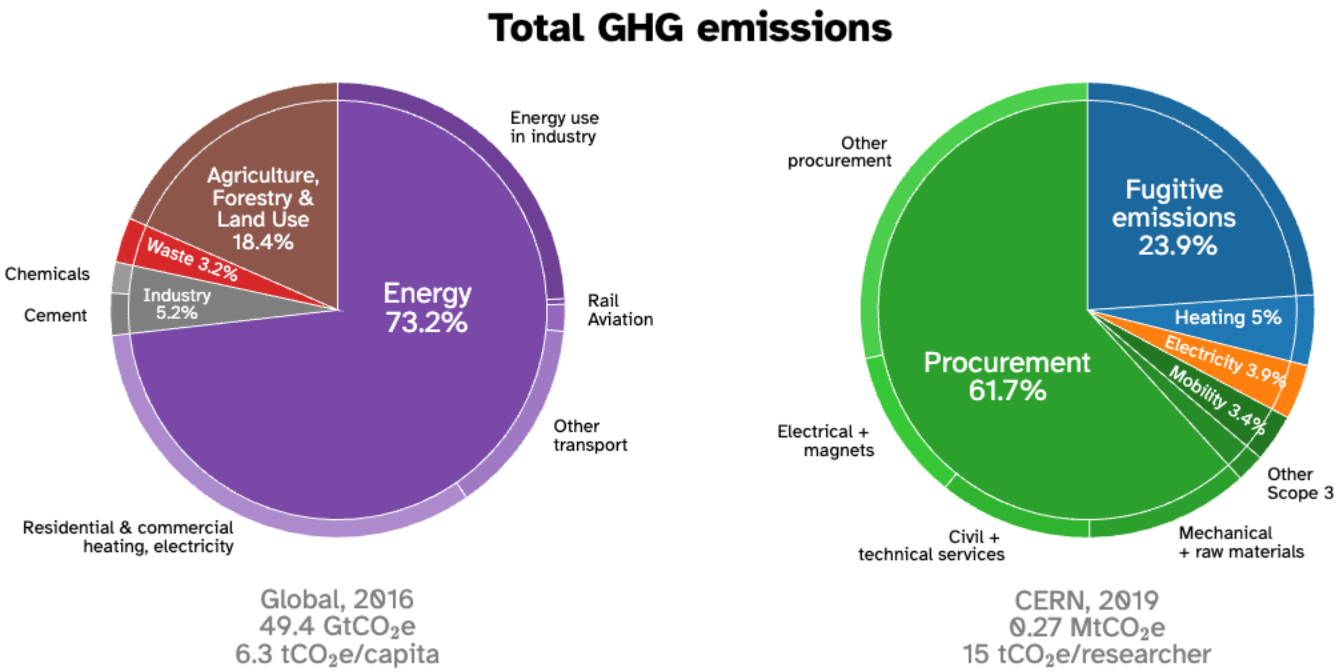


Figure 1.3: Distribution of 2016 global GHG emissions by sector, compared with CERN emissions for 2019, during LHC shutdown. Data are taken from Ref. [13] and CERN Environmental Reports [1, 14, 15].

[1] CERN, "Vol. 2 (2021): CERN Environment Report—Rapport sur l'environnement 2019–2020," https://doi.org/10.25325/CERN-Environment-2021-002, CERN, Geneva, Tech. Rep., 2021.

[12] J. Mariette *et al.*, "labos1point5," https://labos1point5.org," Accessed on: 2 June 2023.

[13] H. Ritchie *et al.*, "CO_2 and Greenhouse Gas Emissions," *Our World in Data*, 2020. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

[14] CERN, "Annual report 2019," https://doi.org/10.17181/AnnualReport2019, Geneva, 2020, Accessed on: 2 June 2023.

[15] C. Harley, "Environmental initiatives in procurement and Knowledge Transfer," 2022. https://indico.cern.ch/event/1166618/contributions/48996

the harsh reality for science

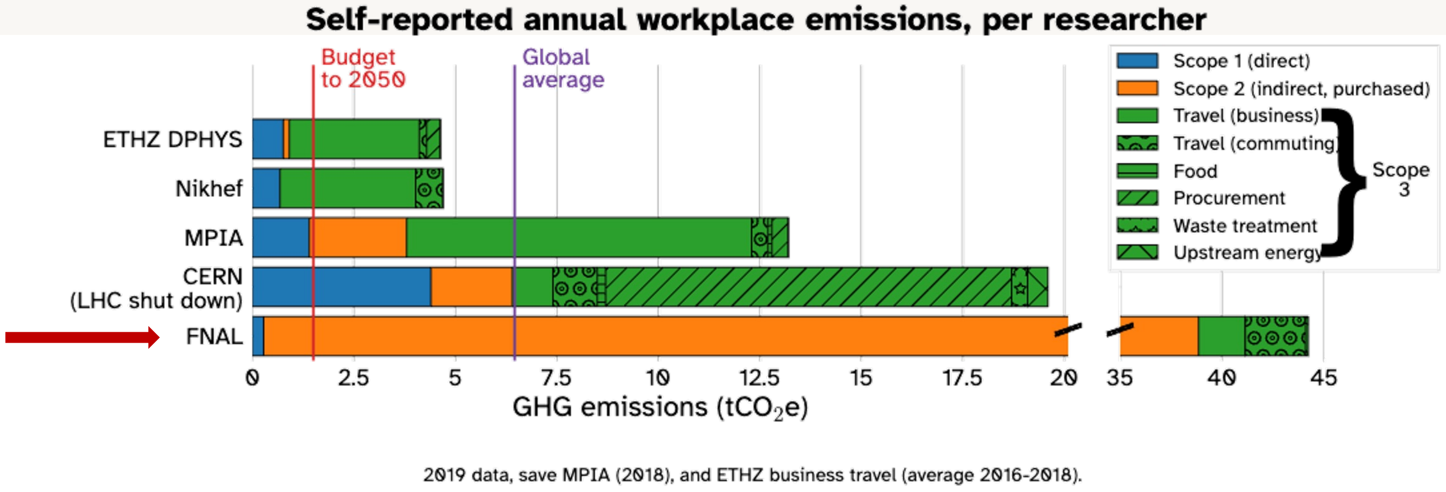


Figure 1.4: Reported workplace GHG emissions, distributed among researchers at five different HECAP+ institutions, with the global per-capita average, and remaining carbon "budget" to stay within the Paris Climate Accord limit of 1.5°C of warming shown for comparison. CERN data for 2019 is taken from Refs. [1, 14, 15, 18], MPIA data for 2019 from Ref. [19], ETHZ DPhys data from 2018 taken from Ref. [20], Nikhef data from 2019 from Ref. [21], and Fermilab (FNAL) data from Ref. [2]. Although FNAL's 2019 electricity consumption was half that of CERN, its Scope 2 emissions were an order of magnitude larger, reflecting local differences in carbon intensity of fuel sources for electricity generation [1, 22]. Two-thirds of FNAL's purchased electricity is used to run its high-energy accelerators [22]. Scope 3 estimates are incomplete for all but CERN. To estimate emissions per researcher, each individual emissions category was divided by the nominal number of users for that resource

[1] CERN, "Vol. 2 (2021): CERN Environment Report—Rapport sur l'environnement 2019–2020," https://doi.org/10.25325/CERN-Environment-2021-002, CERN, Geneva, Tech. Rep., 2021.

[2] Fermilab, "Report to the Director on the Fermilab Environment," https://eshq.fnal.gov/wp-content/uploads/2021/05/2019-Environmental-Report.pdf, FNAL, Tech. Rep., 2019.

[14] CERN, "Annual report 2019," https://doi.org/10.17181/AnnualReport2019, Geneva, 2020, Accessed on: 2 June 2023.

[15] C. Harley, "Environmental initiatives in procurement and Knowledge Transfer," 2022. https://indico.cern.ch/event/1166618/contributions/48996

[18] CERN, "CERN Annual Personnel Statistics 2019," http://cds.cern.ch/record/2719035, CERN, Tech. Rep., 2020.

[19] K. Jahnke *et al.*, "An astronomical institute's perspective on meeting the challenges of the climate crisis," *Nature Astronomy*, vol. 4, no. 9, pp. 812–815, 2020. https://doi.org/10.1038/s41550-020-1202-4

[20] N. Beisert *et al.*, "Towards sustainability in research at D-PHYS/ETH," https://ethz.ch/content/dam/ethz/special-interest/phys/department/department/CO2-DPHYS-201020v3.pdf, 2020, Accessed on: 23 June 2022.

[21] M. Scherrenburg, "Routekaart duurzaam Nikhef," https://www.nikhef.nl/wp-content/uploads/2022/08/Routekaart-Duurzaam-Nikhef-DEF.pdf, 2021, Accessed on: 2 June 2023.

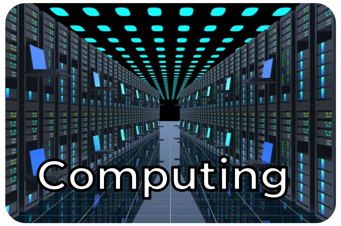
[22] Fermilab, "2021 Site Sustainability Plan," https://sustainability.fnal.gov/wp-content/uploads/2021/01/Fermilab-FY21-Site-Sustainability-Plan-posted.pdf, FNAL, Tech. Rep., 2021.

Other initiatives

- The All European Academies (ALLEA), Towards Climate Sustainability of the Academic System in Europe and Beyond
  - Published a report in May 2022 addressed to students, faculty and researchers
- Snowmass Contribution, Climate Impacts of Particle Physics
  - report "Climate impacts of particle physics", submitted to the proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)
- Recommendations by the young High Energy Physicists (yHEP) association in Germany
  - Report on a broad range of topics, including, but not limited to, travel, conferences, computing and infrastructure, resource management and financing, and green energy.

Our initiative

A broad-scope reflection on the environmental impacts of our research activities across:

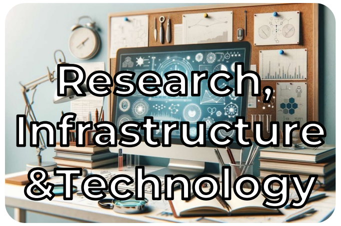


- Hardware
- Software
- Data Centers

- Sources
- Saving
- Recuperation

- Conferences
- Canteens

- Commuting
- Conferences
- Collaborations



- Life-Cycle
- F-Gases

- Consumables
- E-Waste

Summary discussions, best practices, case studies, and recommendations for

 **Individuals**

 **Groups**

 **Institutions**

from Peter Millington

UN Sustainable Development Goals (SDG)

The anchor that we aligned with as a guide to the areas that we must address is the UN Sustainable Development Goals.

All of these focus areas are affected by or affect scientific research.

More importantly, social justice cannot be disentangled from Sustainability and this is often overlooked within the broader scientific community.

SDG and Science

Computing

- 7 AFFORDABLE AND CLEAN ENERGY
- 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
- 12 RESPONSIBLE CONSUMPTION AND PRODUCTION
- 13 CLIMATE ACTION

Resources and Waste

- 3 GOOD HEALTH AND WELL-BEING
- 6 CLEAN WATER AND SANITATION
- 8 DECENT WORK AND ECONOMIC GROWTH
- 11 SUSTAINABLE CITIES AND COMMUNITIES
- 12 RESPONSIBLE CONSUMPTION AND PRODUCTION
- 13 CLIMATE ACTION
- 14 LIFE BELOW WATER
- 15 LIFE ON LAND

Energy

- 7 AFFORDABLE AND CLEAN ENERGY
- 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
- 11 SUSTAINABLE CITIES AND COMMUNITIES
- 12 RESPONSIBLE CONSUMPTION AND PRODUCTION
- 13 CLIMATE ACTION
- 16 PEACE, JUSTICE AND STRONG INSTITUTIONS
- 17 PARTNERSHIPS FOR THE GOALS

Mobility

- 3 GOOD HEALTH AND WELL-BEING
- 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
- 11 SUSTAINABLE CITIES AND COMMUNITIES
- 12 RESPONSIBLE CONSUMPTION AND PRODUCTION
- 13 CLIMATE ACTION

Food

- 2 ZERO HUNGER
- 3 GOOD HEALTH AND WELL-BEING
- 6 CLEAN WATER AND SANITATION
- 12 RESPONSIBLE CONSUMPTION AND PRODUCTION
- 13 CLIMATE ACTION
- 14 LIFE BELOW WATER
- 15 LIFE ON LAND

Research Infrastructure and Technology

- 6 CLEAN WATER AND SANITATION
- 7 AFFORDABLE AND CLEAN ENERGY
- 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
- 11 SUSTAINABLE CITIES AND COMMUNITIES
- 12 RESPONSIBLE CONSUMPTION AND PRODUCTION
- 13 CLIMATE ACTION
- 15 LIFE ON LAND

Best Practice 1.1: Nikhef renovation and sustainability plan

Nikhef is the Dutch National Institute for Subatomic Physics in the Netherlands. It is both a consortium of universities and an institution with a building in Amsterdam. The total tCO_2e footprint of Nikhef was 1,082 tCO_2e in 2019,[a] three quarters of which is due to flying to conferences and laboratories, and 15% is due to heating the building with natural gas [21]. The building is undergoing a major renovation in 2021–2023, which will remove the need for gas for heating. Instead, the heat from the nearby data centre will be used, in addition to better thermal insulation of the building.

The Nikhef sustainability roadmap [21] covers all sources of direct and indirect carbon emissions. For instance, by 2030, air travel should be reduced by 50% and daily commuting should be climate neutral. Intermediate targets for 2025 are also set and yearly emissions will be monitored and reported.

[a] We report the 2019 numbers, since the 2020 numbers may be unrepresentative due to the impact of the COVID-19 pandemic.

[21] M. Scherrenburg, “Routekaart duurzaam Nikhef,” https://www.nikhef.nl/wp-content/uploads/2022/08/Routekaart-Duurzaam-Nikhef-DEF.pdf, 2021, Accessed on: 2 June 2023.

Computing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computing costs

- **High Energy Consumption:** The High-Luminosity phase of the Large Hadron Collider (HL-LHC), expected to be operational from the end of this decade, will require 5 to 10 times the computing capacity needed for the Large Hadron Collider (LHC) , with data storage needs reaching about ten exabytes
- **Not even possible:** At the same time, some lattice quantum chromodynamics (QCD) calculations, applied, e.g., to studying heavy quark decays and anomalous magnetic moments, can be too expensive to pursue, even if approximately 10% of open-science super-computing in the United States is devoted to such studies
- **Individual impact:** Up to 88% of the electricity consumption of an astronomy researcher at MPIA, is due to (super)computing

recommendations

Recommendations — Computing

Individual actions:

- Make sustainable personal computing choices by considering the necessity of hardware upgrades, the repurposing of hardware, and the environmental credentials of suppliers and their products.
- Assess and improve the efficiency and portability of codes by considering, e.g., the required resolutions and accuracy.
- Assess and optimise data transmission and storage needs.
- Follow best practice in open-access data publishing, prioritising reproducibility and limiting repeat processing.

Recommendations — Computing

Further group actions:

- Right-size IT requirements and optimise hardware lifecycles.
- Schedule queueing systems with environmental sustainability in mind, so as to maximise the use of renewables, accounting for the geographical location of servers/data centres.

recommendations

Recommendations — Computing

Further institutional actions:

- Ensure that environmental sustainability is a core consideration when designing and choosing sites for large computing infrastructure, such as data centres, including, e.g., the availability of renewables, the efficiency of cooling systems and the reuse of waste heat.
- Proceduralise the repair, upgrade and repurposing of existing computing, the de-inventorising of personal equipment for leaving personnel or for donation, and the responsible recycling of retired hardware.
- Select cloud computing services for their carbon emission mitigation policies.

Energy

7 AFFORDABLE AND CLEAN ENERGY

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consumption

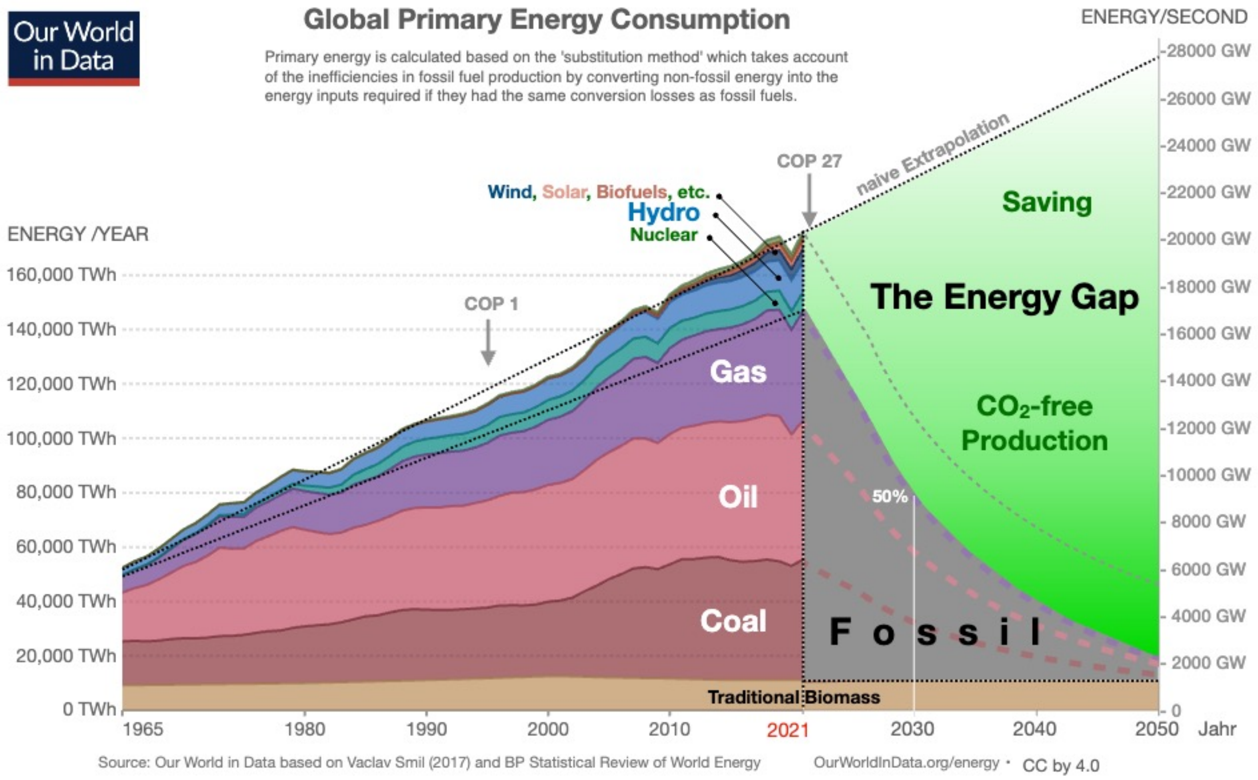

Figure 3.1: Global primary energy consumption is dominated by fossil fuels, the use of which has been increasing steadily despite repeated warnings from the climate change conferences of the United Nations (COP) dating as far back as 1995. Decreasing emissions by 50%, as recommended by the IPCC to avoid irreversible tipping points [64] (see blue line in Figure 1.1) creates a large energy gap that must be filled by additional climate-neutral power generation, or by energy savings and recuperation. Consumption was extrapolated linearly from 1965–2021 to account for additional demand from emerging countries. Left part of figure taken from Ref. [65], based on data from Refs. [60, 66], reused and adapted under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0) license.

CERN uses 1300 GWh of electricity annually,

This is the equivalent of what is used in a city of > 100,000 people in the USA

This is the equivalent of what is used in a city of > 600,000 people in Brazil

This is the equivalent of what is used in a city of > 2,00,000 people in India

[60] British Petroleum, "bp Statistical Review of World Energy," https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf, BP, Tech. Rep., 2022.

[64] OECD, *Climate Tipping Points: Insights for Effective Policy Action.* OECD Publishing, Paris, 2022. https://doi.org/10.1787/abc5a69e-en

[65] H. Ritchie *et al.*, "Energy," *Our World in Data*, 2020. https://ourworldindata.org/energy

[66] V. Smil, *Energy Transitions: Global and National Perspectives.* Praeger, 2016.

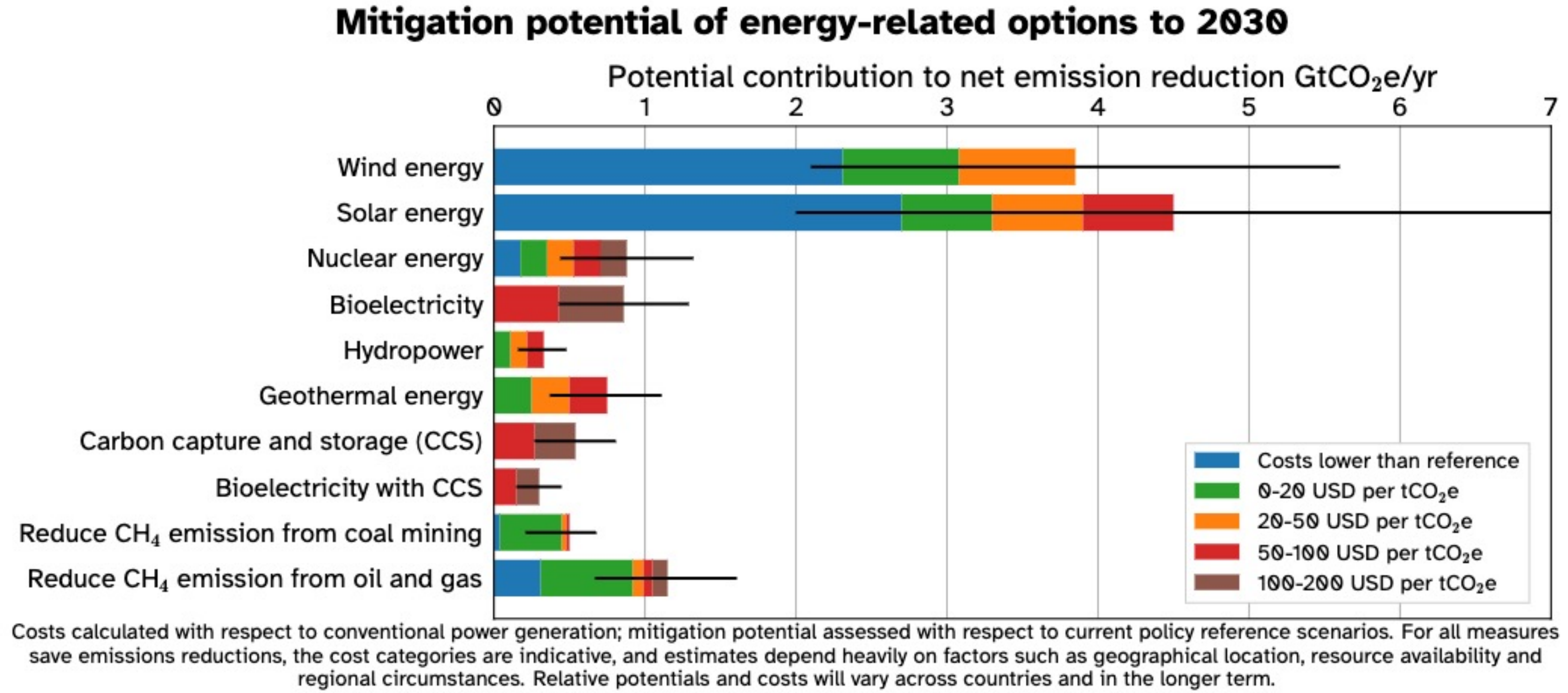

Figure 3.2: Overview of energy-related mitigation options and their estimated range of costs and potentials in 2030, as determined by the IPCC in their Sixth Assessment Report. All costs were calculated with respect to conventional power generation; potentials were assessed with respect to the reference scenario in the World Energy Outlook 2019 [69]. Data source: IPCC WGIII Summary for Policy Makers, Figure SPM.7, Ref. [70]. For further details on how the data was obtained, see Supplementary Material 12.SM.1.2 in Ref. [67].

[67] IPCC, 2022: *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.

[69] IEA, "World Energy Outlook 2019," https://www.iea.org/reports/world-energy-outlook-2019, IEA, Tech. Rep., 2019.

[70] M. Babiker *et al.*, "Data for Figure SPM.7 - Summary for Policymakers of the Working Group III Contribution to the IPCC Sixth Assessment Report," https://doi.org/10.48490/ayfg-tv12, 2022.

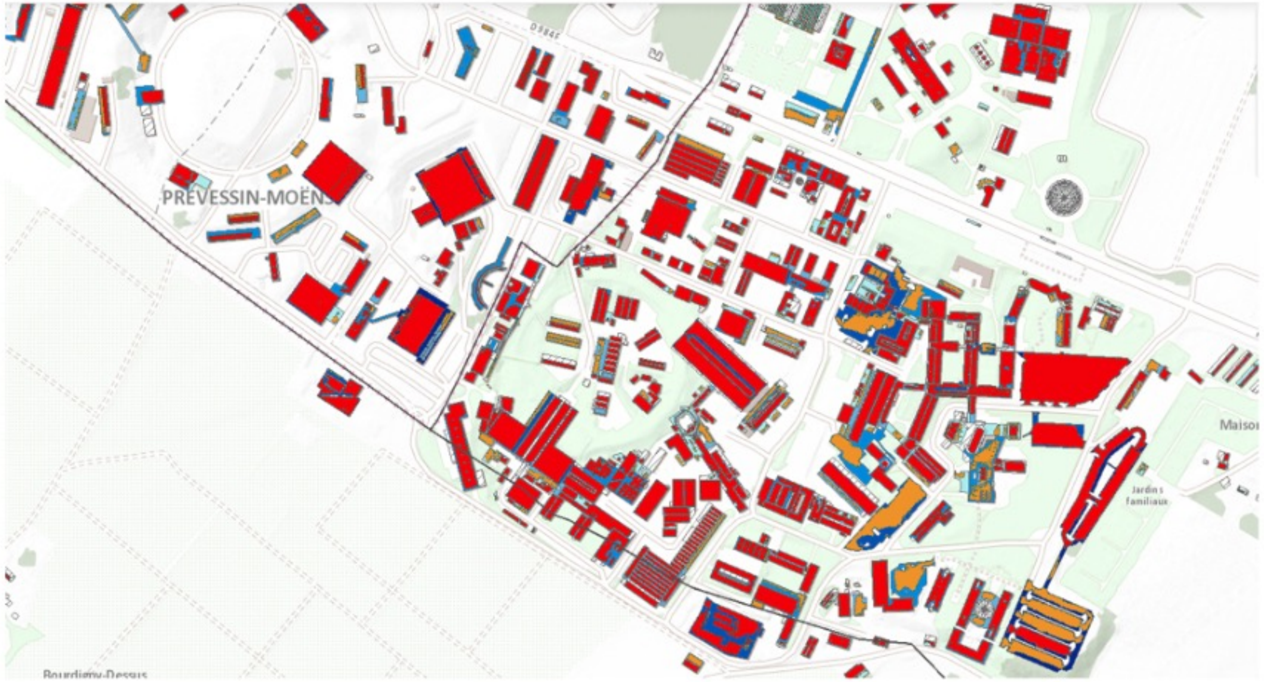

Figure 3.3: Map of CERN buildings. Rooftops that are suitable for PV installation in respect to their received solar irradiation are shown in red (very suitable) and yellow (suitable). In addition other areas like e.g., parking lots could also be covered by PV-panelled roofs. From Ref. [90].

CERN has 653 buildings with a total **roof area of 421,000 m²**, which amounts to approximately **80 GWh annual electricity generation** potential. A comparison with the electricity consumption in 2019 of **428 GWh, when the LHC was not in operation, shows that around 18% of CERN's basic (non-LHC) electricity demand could be produced locally with solar power.**

[90] SITG, "Cadastre solaire du Grand Genève," https://apps.sitg-lab.ch/solaire/," Accessed on: 2 June 2023.

Best Practice 3.1: Recycling energy at DESY

For existing experiments, where minimising energy usage was not a factor in the design process, it is still possible to save energy retroactively through recycling of energy/heat. Deutsches Elektronen-Synchrotron in Hamburg (DESY) is currently using the waste heat, which is generated by condensation of the helium that is used to cool the accelerator, to heat their buildings. This saves 7.5 GWh a year, which is approximately a third of the heat energy used on campus [110]. Together with the University for Applied Sciences in Hamburg, they are also investigating the potential for recycling waste heat from other sources, e.g., the many magnets used in the accelerator. First results suggest that it should be sufficient to heat all buildings on campus in this way [111].

[110] DESY, "DESYs 3-Punkte-Energieplan," https://pr.desy.de/newsletter/beitraege_extern/kompakt_01__2021/desys_3_punkte_energieplan/index_ger.html, 2021, Accessed on: 2 June 2023.

[111] DESY, "DESY Sustainability Report 2019–2021," https://nachhaltigkeit.desy.de/sites/sites_desygroups/sites_extern/site_nachhaltigkeit/content/e187633/e187643/DESY-SustainabilityReport2019-2021_eng.pdf, 2022, Accessed on: 2 June 2023.

Recommendations — Energy

Individual actions:

- Save energy in all ways practicable, e.g., by avoiding unnecessary heating or cooling of workspace, and by turning off electrical items when not in use.
- Read the sections about computing (Section 2) and mobility (Section 5).

Recommendations — Energy

Further group actions:

- Ensure that energy efficiency is a major focus in experimental design, and prioritise technologies that minimise consumption and maximise energy recovery.
- Monitor, report, and assess energy usage with the aim of reducing consumption and resulting emissions.

Recommendations — Energy

Further institutional actions:

- Ensure that energy efficiency is a major factor in the renovation of existing estates and the design and construction of new infrastructure.
- Prioritise moving to sustainable and renewable energy sources via both local generation, and energy import and export.
- Collate and publish energy usage and emissions statistics, stratifying by source, e.g., heating, experimental infrastructure, computing, transportation, and procurement.
- Lobby for environmentally sustainable energy policy.

Food

2 ZERO HUNGER

3 GOOD HEALTH AND WELL-BEING

6 CLEAN WATER AND SANITATION

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15 LIFE ON LAND

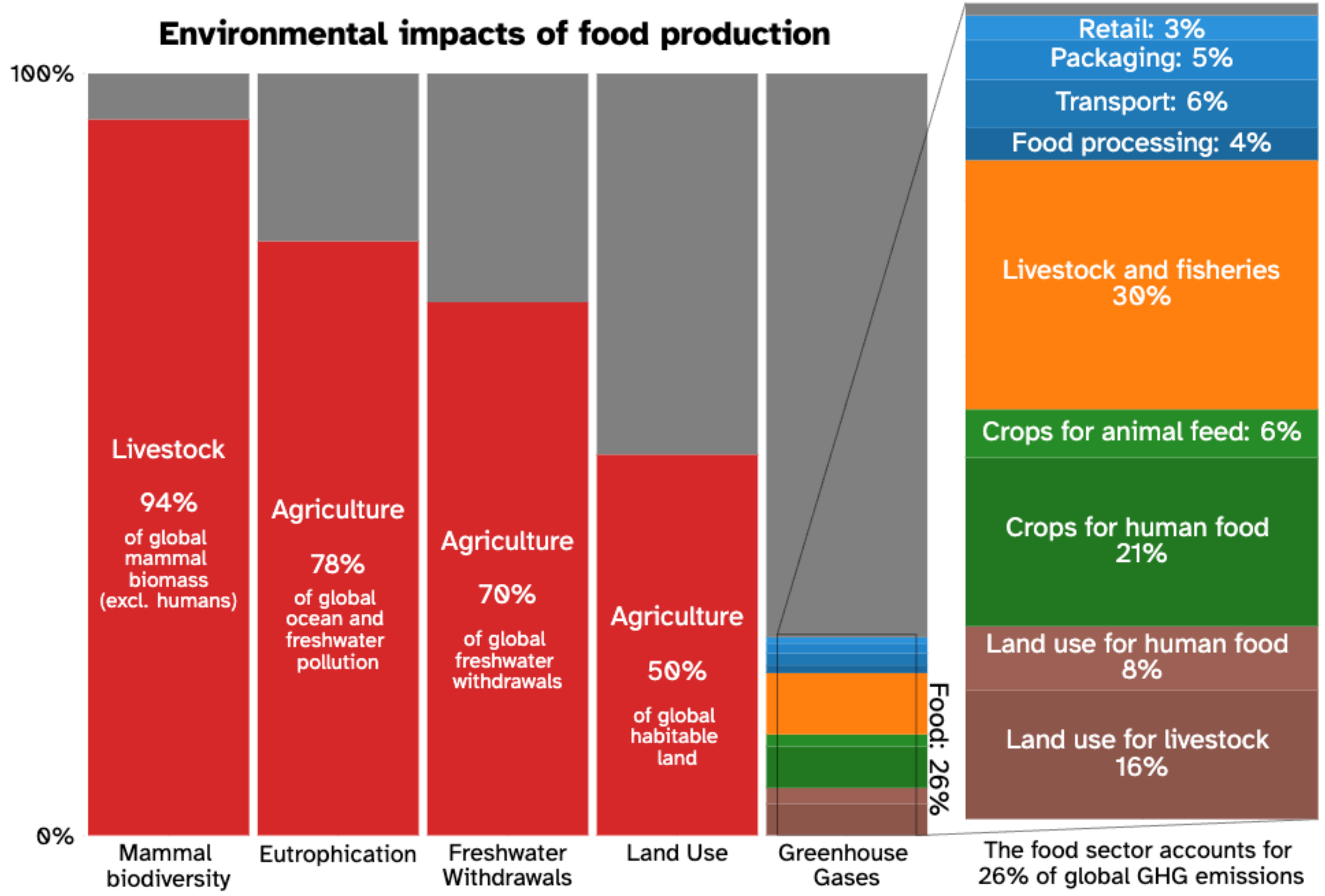


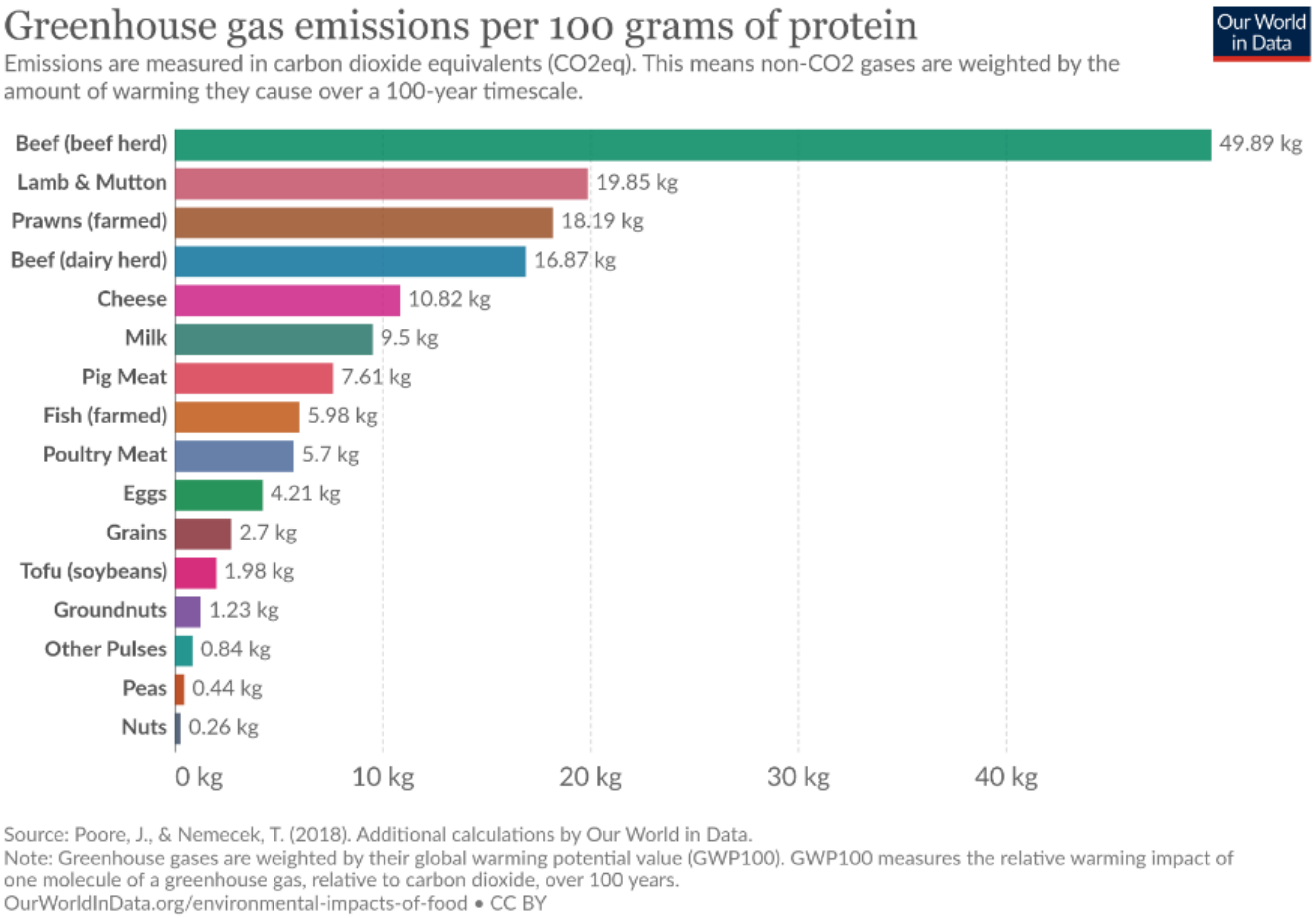
Figure 4.1: Environmental impact of food production, with fine-grained partitioning of GHG emissions by food sector. Figure modified from Ref. [122] under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0) license, based on data from Refs. [116] and [123].

[116] J. Poore and T. Nemecek, "Reducing food's environmental impacts through producers and consumers," *Science*, vol. 360, no. 6392, pp. 987–992, 2018. https://doi.org/10.1126/science.aaq0216

[122] H. Ritchie *et al.*, "Environmental Impacts of Food Production," 2022. https://ourworldindata.org/environmental-impacts-of-food. Accessed on: 2 June 2023

[123] Y. M. Bar-On *et al.*, "The biomass distribution on Earth," *Proceedings of the National Academy of Sciences*, vol. 115, no. 25, pp. 6506–6511, 2018. https://doi.org/10.1073/pnas.1711842115

cost of food



1.5em

Figure 4.3: GHG emissions in CO_2e per 100 g of protein. Figure reused from Ref. [122] under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0) license, based on data from Ref. [116].

[116] J. Poore and T. Nemecek, "Reducing food's environmental impacts through producers and consumers," *Science*, vol. 360, no. 6392, pp. 987–992, 2018. https://doi.org/10.1126/science.aaq0216

[122] H. Ritchie *et al.*, "Environmental Impacts of Food Production," 2022. https://ourworldindata.org/environmental-impacts-of-food. Accessed on: 2 June 2023

recommendations

Recommendations — Food

Individual actions:

- Reduce consumption of animal products, especially those that result in the highest emissions, e.g., ruminant meat, and dairy.
- Minimise food waste.

Further group actions:

- Prioritise plant-based options in conference catering, and optimise service method to reduce food waste.

Recommendations — Food

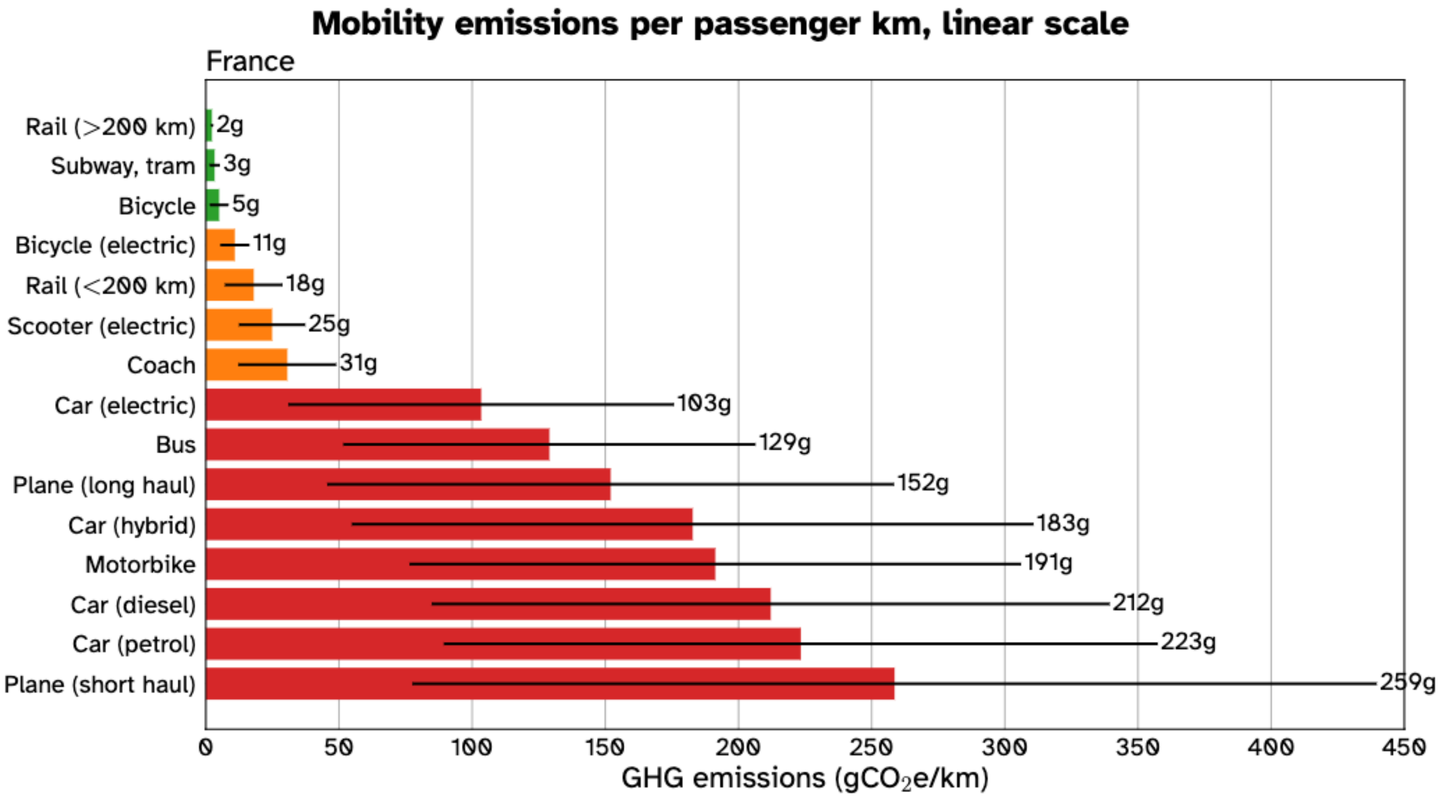
Further institutional actions:

- Incentivise the consumption of plant-based products at on-site restaurants by increasing their variety and quality, and subsidising their cost.
- Highlight the environmental impact of food choices through service layout and labelling.
- Minimise food waste by providing multiple portion sizes and donating unused food.
- Read section on waste (Section 7) and limit food-service waste e.g., through industrial composting of biodegradable food containers.

Mobility


3 GOOD HEALTH AND WELL-BEING
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
11 SUSTAINABLE CITIES AND COMMUNITIES
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
13 CLIMATE ACTION

emissions



Source: Labos1.5 database. Estimates include production emissions, and may vary slightly based on occupancy of public transport, and between countries.

Figure 5.1: GHG emissions for different means of transport (in gCO_2e per km). Emissions from electricity and vehicle production as well as fuel combustion are included. All data is for 2019–2020, and comes from the database of Ref. [157] — see, in particular, Ref. [158] — and assumes the electricity comes from the French grid, which is a factor of 10 less carbon-intensive than other countries [159]. For a comparison with the UK, see Ref. [146]. Note that emissions from personal transport do not scale linearly with number of passengers.

[146] H. Ritchie, "Which form of transport has the smallest carbon footprint," 2020. https://ourworldindata.org/travel-carbon-footprint. Accessed on: 2 June 2023

[157] J. Mariette *et al.*, "An open-source tool to assess the carbon footprint of research," *Environ. Res.: Infrastruct. Sustain.*, vol. 2, no. 3, p. 035008, 2022. https://www.doi.org/10.1088/2634-4505/ac84a4

[158] O. Aumont *et al.*, "Récapitulatif des choix effectués concernant les facteurs

[159] Our World in Data, "Carbon intensity of electricity, 2021," https://ourworldindata.org/grapher/carbon-intensity-electricity?region=Europe," Accessed on: 2 June 2023.

Institute	Initiative	Comments
DESY	Reduced-price ticket for public transport for all employees	The non-transferable ticket, with a 30% subsidy for employees, is also usable outside working hours, and allows free network-wide travel for an additional adult and up to 3 children (age 14 and under) on weekends and holidays. This requires a subscription of more than 6 months. Once suspended, a cooling-off period of 9 months is required to be eligible for re-subscription. This is problematic if the employee is posted abroad for a few months. With the implementation of the "Deutschlandticket" in Germany, the terms have slightly changed [111, 150, 151].
FNAL	Shuttle service to and from Chicago Metra trains for all employees	There are two scheduled connections in the morning and three in the afternoon, on demand at other times, from 06:30 to 18:50. A ticket costs $2.25 (cash only), payable to the bus driver [152]. The regular shuttle does not connect to the Metra station serving the fast train to Chicago (Route 59); FNAL do not offer pre-tax public transport ticket purchase.
France	Public transit subsidy [153] or 300 €/year for all employees who cycle or carpool [154]	Honours system for the 300 €/year. The adoption of the roughly 50 % reimbursement on public transport subscription depends on how well connected each institute is.
Germany	General tax reimbursement for commuting depending on distance	For each km travelled to work, 0.30 € is deducted from the taxable income (0.38 € per km above 21 km per one way starting from 2022) [155]. While this was originally thought to cover the expenses of private cars, it now applies to all means of transport, so that also cyclists or pedestrians obtain the same financial advantage even if they have no direct costs.
University of Sheffield	Bike to work scheme for all employees	There is the possibility to borrow an e-bike (or a bike) for free for 2 months in order to test commuting by bike, to rent bikes throughout the semester and to buy reconditioned bikes. Over 1,400 cycle parking spaces are available throughout campus and at the residences. Services are provided for free bike checks and at-cost servicing and repairs for staff and students funded by the university. (All UK universities.) Financial help is available to buy an e-bike. (However, this is based on reducing the university's financial contribution to the pension scheme over a set amount of time.) [156]

Table 5.1: Institutional/country-wide measures to encourage sustainable commuting amongst employees. This is a non-exhaustive list; similar initiatives are also offered by other employers.

[111] DESY, "DESY Sustainability Report 2019–2021," https://nachhaltigkeit.desy.de/sites/sites_desygroups/sites_extern/site_nachhaltigkeit/content/e187633/e187643/DESY-SustainabilityReport2019-2021_eng.pdf, 2022, Accessed on: 2 June 2023.

[150] S-Bahn Hamburg GmbH, "hvv ProfiTicket: minibroschüre," https://www.hvv.de/resource/blob/23570/b796854bba28b2cbb0b607a4594d6c4a/profiticket-mini-brochure-data.pdf, 2021, Accessed on: 18 August 2023.

[151] hvv Hamburger Verkehrsverbund Gesellschaft mbH, "ProfiTicket," https://www.hvv.de/de/profiticket, 2023, Accessed on: 2 June 2023.

[152] Pace Suburban Bus, "Batavia on demand," https://www.pacebus.com/sites/default/files/2020-08/BataviaOnDemand_08-2020.pdf, 2020, Accessed on: 2 June 2023.

[153] Service Public France, "Fonction publique : le forfait mobilités durables est étendu," https://www.service-public.fr/particuliers/actualites/A16223, 2022, Accessed on: 2 June 2023.

[154] Service Public France, "Quelles aides pour les trajets domicile-travail en 2023 ?" https://www.service-public.fr/particuliers/actualites/A16211, 2022, Accessed on: 2 June 2023.

[155] Bundesministerium der Justiz, "Income Tax Act," https://www.gesetze-im-internet.de/estg/, 2022.

[156] University of Sheffield, "Cycling," https://www.sheffield.ac.uk/efm/cycling," Accessed on: 2 June 2023.

cost & emissions

Distance	Origin	Mode of Transport	Travel time (one way)	Itinerary	Price (EUR)	Emissions (kg CO_2e)
< 600 km	Paris	Train	3h15	**Out:** Mon 24th 08:18–11:29 **In:** Fri 28th 14:29–17:42	178	25
		Flight ORY–GVA	∼1 hr	**Out:** Mon 24th 08:20–09:25 **In:** Fri 28th 19:05–20:15	98	235
		Car	5h42			116
> 600 km	Hamburg	Train (2 changes)	∼13.5 hrs	**Out:** Sun 23rd 20:50–10:18 (+1 day) **In:** Fri 28th 18:15–07:54 (+1 day)	258	46
		Flight HAM–GVA (1 change)	∼3 hrs	**Out:** Mon 24th 07:00–10:10 **In:** Fri 28th 19:10–22:35	261	497
		Car	9h50			225
	London	Train (2 changes out; 1 change in)	∼8 hrs	**Out:** Sun 23rd 15:31–23:29 **In:** Fri 28th 15:30–22:30	288	25
		Flight LTN–GVA	1h40	**Out:** Mon 24th 08:00–10:45 **In:** Fri 28th 21:40–22:20	80	402
		Car	8h32			196
	Rome	Train (1 change)	∼8.5 hrs	**Out:** Sun 23rd 15:25–23:54 **In:** Friday 28th 13:39–21:40	238	70
		Flight FCO–GVA	1h30	**Out:** Mon 24th 09:00–10:30 **In:** Friday 28th 18:45–20:20	77	392
		Car	∼8 hrs			183
	Barcelona	Train	7-8 hrs	**Out:** Sun 23rd 08:15–16:35 **In:** Fri 28th 12:35–19:32	147	18
		Flight BCN–GVA	∼1.5 hrs	**Out:** Mon 24th 08:40–10:20 **In:** Fri 28th 17:00–18:25	83	370
		Car	7 hrs			164
> 1, 200 km	Warsaw	Train (2 changes)	22.5–24.5 hrs	**Out:** Sat 22nd 19:49–18:18 (+1 day) **In:** Fri 28th 18:42–19:15 (+1 day)	319	176
		Flight WAW–GVA	2h20	**Out:** Mon 24th 07:20–09:40 **In:** Fri 28th 19:45–21:55	185	531
		Car	12.5 hrs			398

Traveling to CERN (Geneva) from other parts of Europe

	AGU Fall Meeting 2019	ICHEP Melbourne 2012	ICHEP Valencia 2014	ICHEP Chicago 2016	ICHEP Seoul 2018	ICHEP Prague 2020 (virtual)
Number of participants	24,009	764	966	1,120	1,178	2,877
GHG emissions per participant [kg CO_2e]	2,883	8,432	1,902	2,699	2,648	0

Table 5.3: Total number of participants of recent ICHEP conferences and the GHG emissions per participant. The corresponding numbers for the American Geophysical Union (AGU) Fall Meeting [149] are shown for reference.

[149] M. Klöwer *et al.*, “An analysis of ways to decarbonize conference travel after COVID-19,” *Nature*, vol. 583, pp. 356–359, 2020. https://doi.org/10.1038/d41586-020-02057-2

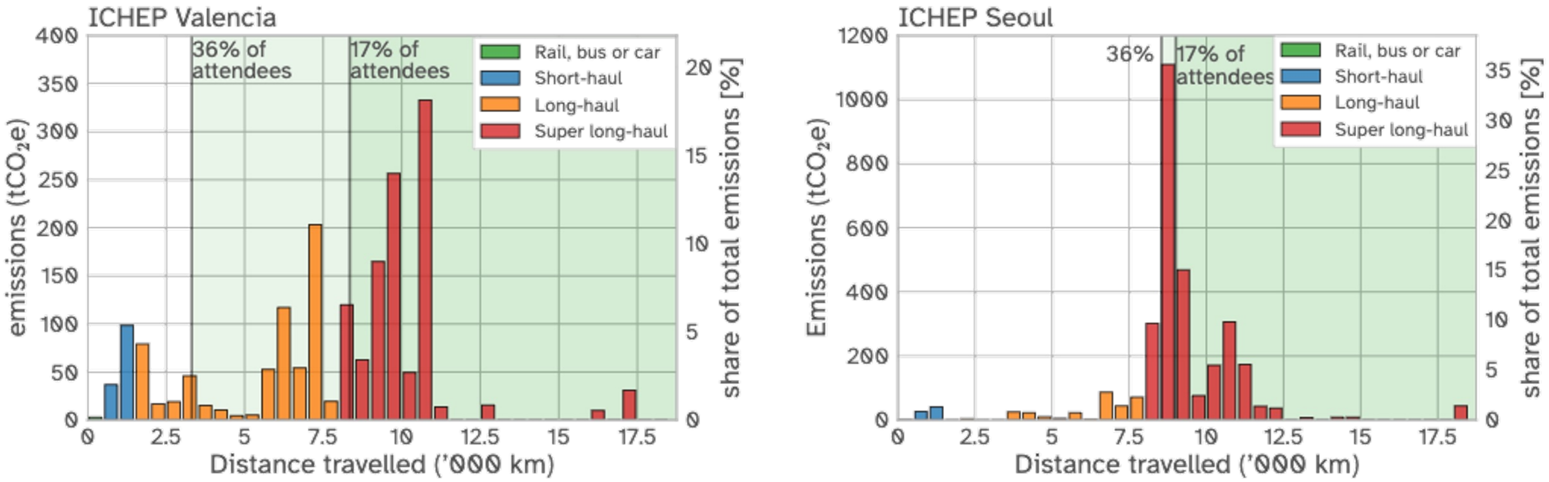


Figure 5.2: Emissions per distance for ICHEP Valencia and ICHEP Seoul shown in tCO_2e (left axis) and as share of the total emissions. Additionally, the emissions caused by the 17% and 36% of participants travelling furthest are shaded in green.

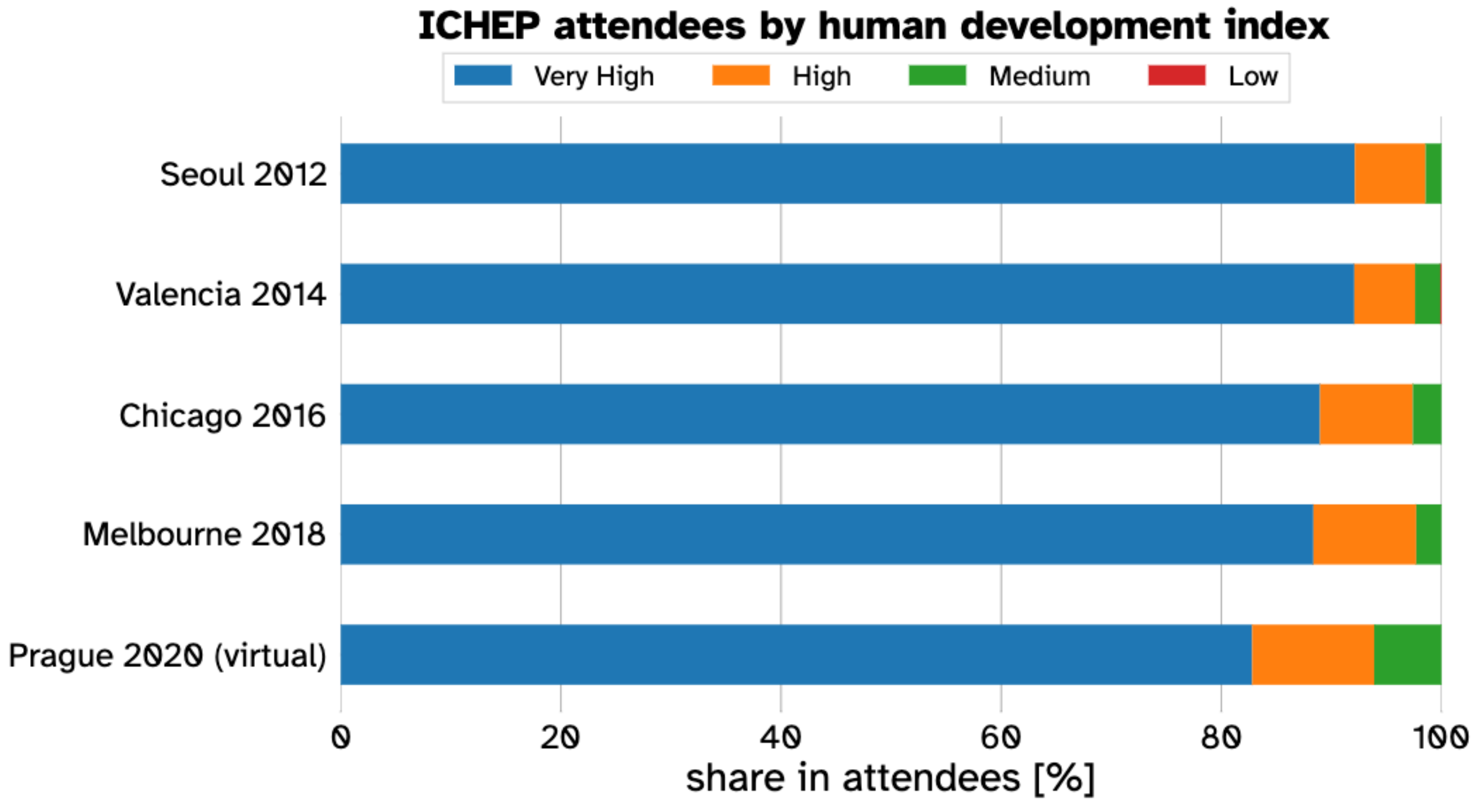


Figure 5.3: The fraction of participants, categorised by human development index (HDI) [172] attending the last 5 instances of ICHEP.

Examples of countries with very high HDI are Norway, Malaysia, Kuwait and Serbia, high HDI are, e.g., Trinidad and Tobago, Albania, Egypt and Vietnam. Medium HDI countries include Morocco and Pakistan, while low HDI countries are e.g., Nigeria, Chad and Niger. A brief overview of the categories can be found in Ref. [172].

[172] UNDP (United Nations Development Programme), *Human Development Report 2019: Beyond income, beyond averages, beyond today: Inequalities in human development in the 21st century*. New York, 2019. http://hdr.undp.org/en/content/human-development-report-2019

Recommendations — Mobility

Individual actions:

- Re-assess business travel needs, using remote technologies wherever practicable.
- Choose environmentally sustainable means of transport for daily commutes as well as unavoidable business travel, amalgamating long-distance trips where possible.

Recommendations — Mobility

Further group actions:

- Define mobility requirements and travel policies that minimise emissions, while accounting for the differing needs of particular groups, such as early-career researchers or those who are geographically isolated.
- Re-assess needs for in-person meetings, and prioritise formats that minimise travel emissions and diversify participation by making use of hybrid, virtual or local hub participation, and optimising the meeting location(s).

Recommendations — Mobility

recommendations

Further institutional actions:

- Support environmentally sustainable commuting by improving on-site bicycle infrastructure, subsidising public transport and providing shuttle services.
- Disincentivise car travel where viable alternatives exist, facilitate car pooling, and provide on-site charging stations.
- Incentivise the reduction of business travel, e.g., by implementing carbon budgets with appropriate concessions.
- Ensure unavoidable travel is made via environmentally sustainable means through flexible travel policies and budgets, and the use of travel agents that offer multi-modal itineraries. Employ carbon offsetting only as a last resort.
- Remove any requirement on past mobility as an indication of quality in hiring decisions.
- Lobby for improved and environmentally sustainable local and regional transport infrastructure.

Research Infrastructure and Technology

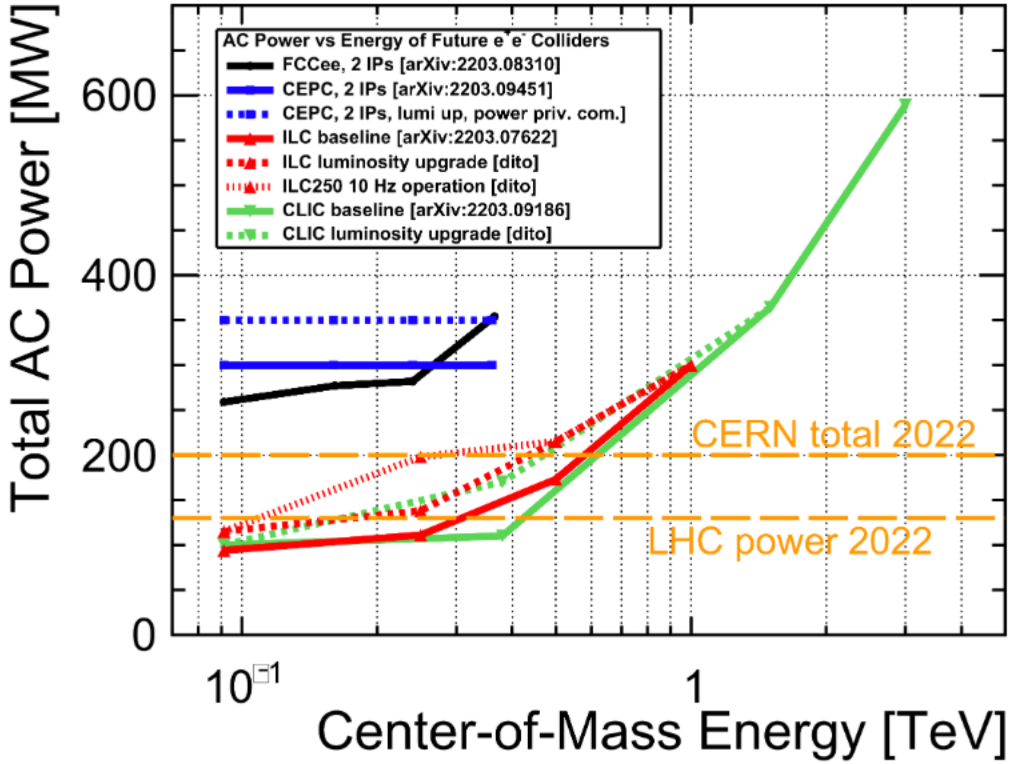
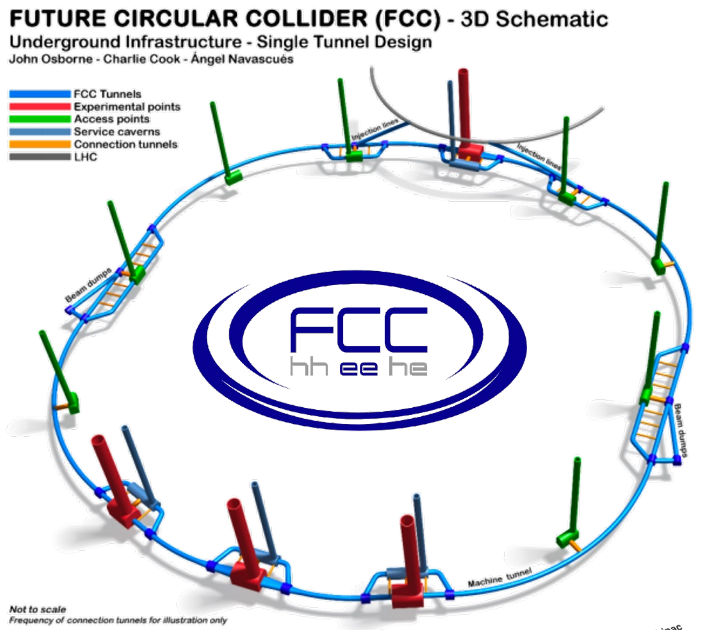
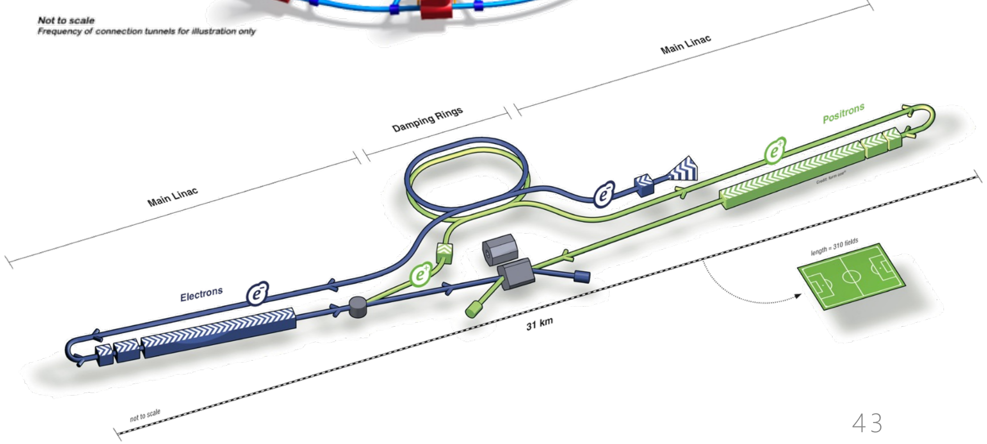


Figure 6.1: Site power required for proposed electron-positron (e^+e^-) collider projects at different center-of-mass energies, compared to the power consumption of CERN and the LHC in 2022 [197].





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
Perfluorocarbons (PFCs)			
PFC-14	CF_4	50,000	7,390
PFC-116	C_2F_6	10,000	12,200
PFC-218	C_3F_8	2,600	8,830
PFC-3-1-10	C_4F_{10}	2,600	8,860
PFC-5-1-14	C_6F_{14}	3,200	9,300

Table 6.2: Environmental impact associated with GHGs, from Ref. [219], which also forms the source for the calculations in the CERN environmental report and the EU regulations described in Ref. [220].

[219] Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood and D. Wratt, 2007: Technical Summary. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-ts-1.pdf

[220] European Parliament, Council of the European Union, "Regulation (EU) No 517/2014 of The European Parliament and of the council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006," http://data.europa.eu/eli/reg/2014/517/oj, 2014.

carbon footprint

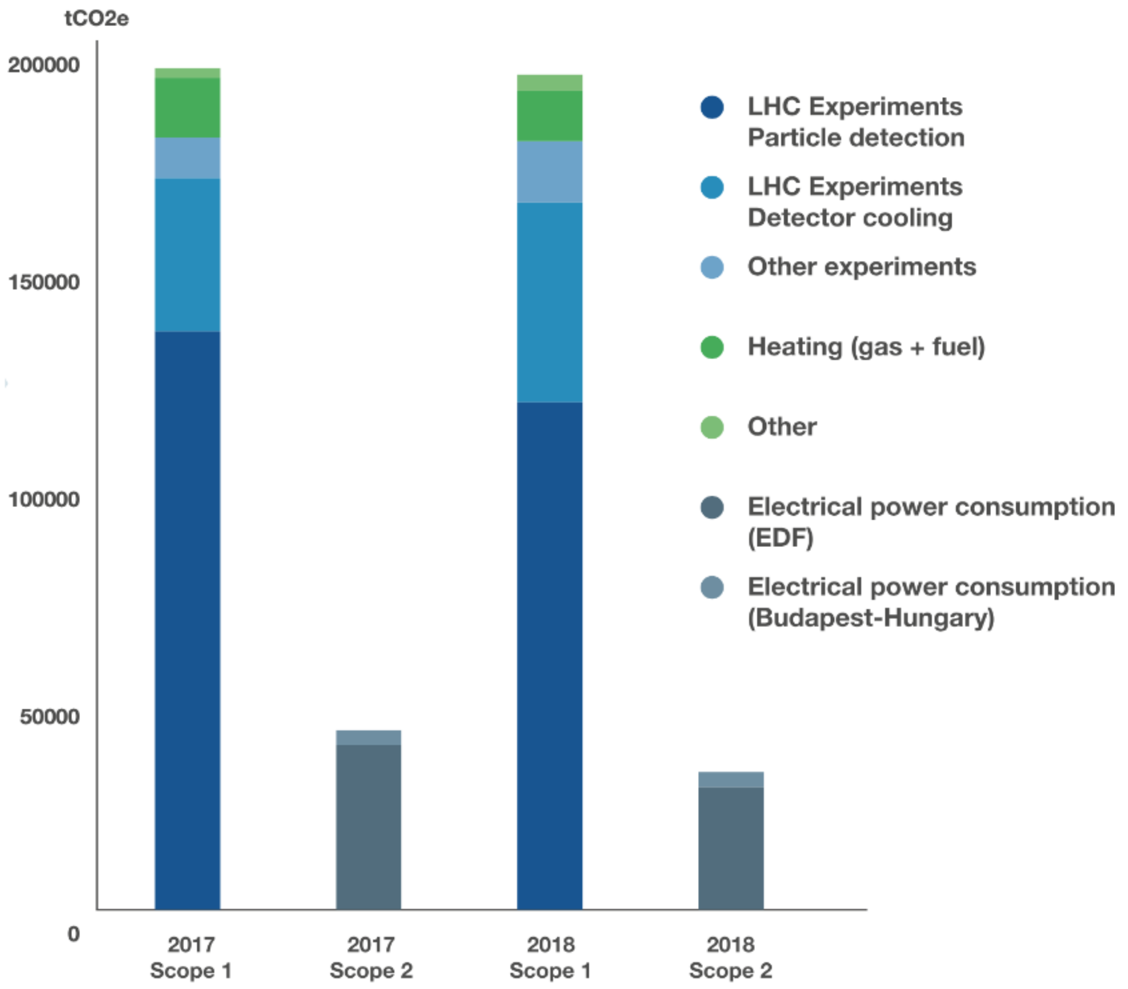


Figure 6.2: CERN Scope 1 (direct) and Scope 2 (indirect, by electricity consumption) emissions for 2017 and 2018, in CO_2 equivalent tonnes, by category; “other” includes air conditioning, emergency generators and CERN vehicle fleet fuel consumption (reproduced from Ref. [214]). ‘Budapest’ refers to electricity use at the (now inactive) Wigner data centre in Hungary.

Environmental report for all major experimental facilities, universities and national labs?

[214] CERN, “Vol. 1 (2020): CERN Environment Report—Rapport sur l’environnement 2017–2018,” https://doi.org/10.25325/CERN-Environment-2020-001, CERN, Geneva, Tech. Rep., 2020.

recommendations

Recommendations — Research Infrastructure and Technology

Individual actions:

- Seek out new innovations and best practice.
- Rethink how the impact of frequently-used equipment can be reduced, and reduce "over-design" by reassessing safety factors and other margins to reduce resource consumption.

Recommendations — Research Infrastructure and Technology

Further group actions:

- Ensure that environmental sustainability is an essential consideration at all stages of projects, from initial proposal, design, review and approval, to assembly, commissioning, operation, maintenance, decommissioning and removal, using life cycle assessment and related tools.
- Engage with industrial partners who exemplify best practice and sustainable approaches.
- Appoint a dedicated sustainability officer to oversee project development, and institute regular meetings with a focus on environmental sustainability.

Recommendations — Research Infrastructure and Technology

Further institutional actions:

- Critically assess the environmental impact of materials, construction and the operational life cycle as an integral part of the design phase for all new infrastructure.
- Provide training opportunities, required tools and technical support to assess and improve the environmental sustainability of project life cycles.
- Recognise and reward innovations that minimise negative environmental impacts, regardless of revenue.
- Promote knowledge exchange on sustainability initiatives between groups and institutions, including decision-makers, designers and operators of projects, setups and infrastructure.

Resources and Waste

3 GOOD HEALTH AND WELL-BEING

6 CLEAN WATER AND SANITATION

8 DECENT WORK AND ECONOMIC GROWTH

11 SUSTAINABLE CITIES AND COMMUNITIES

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

13 CLIMATE ACTION

14 LIFE BELOW WATER

15 LIFE ON LAND

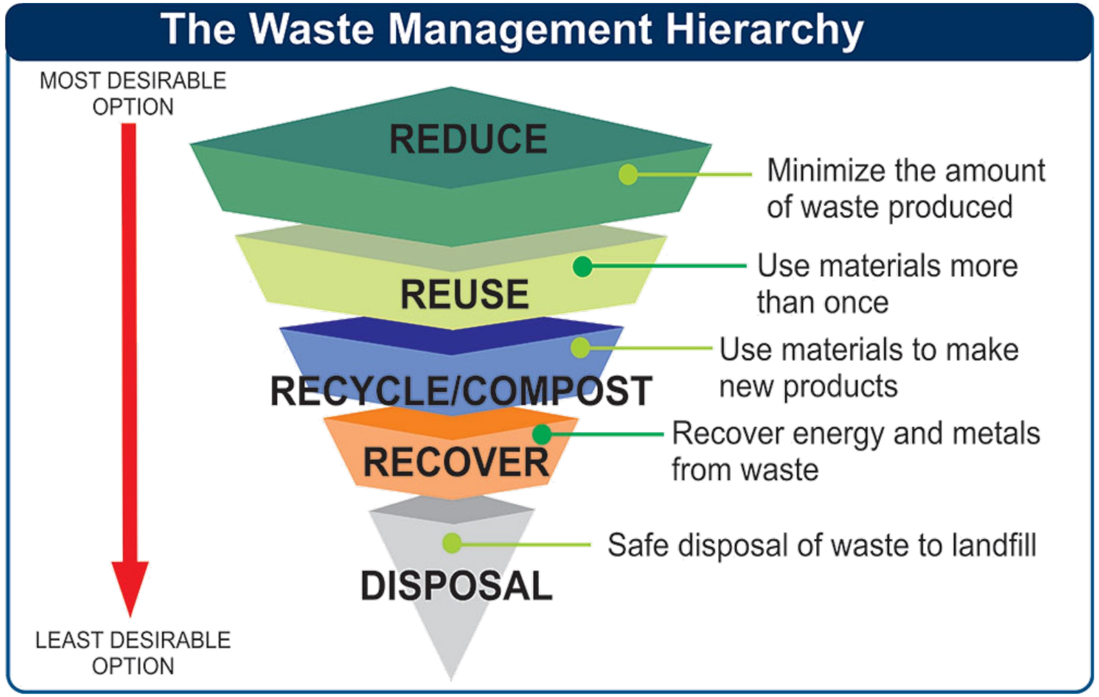
circular economy and waste

a Circular Economy does not necessarily eradicate waste, it is a means for reducing waste.

The entire process has one common waste: Energy

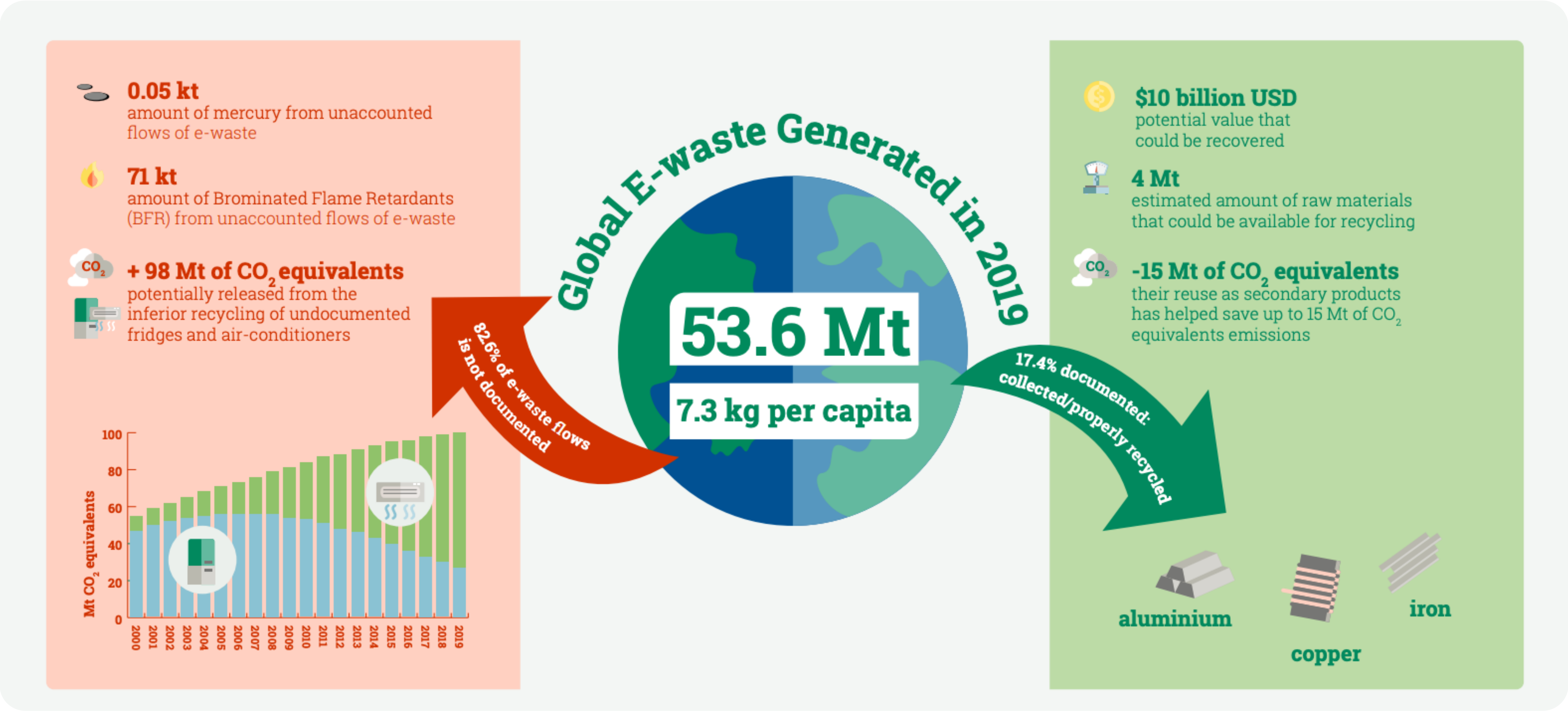
the inverted waste pyramid

a circular economy is not the final solution

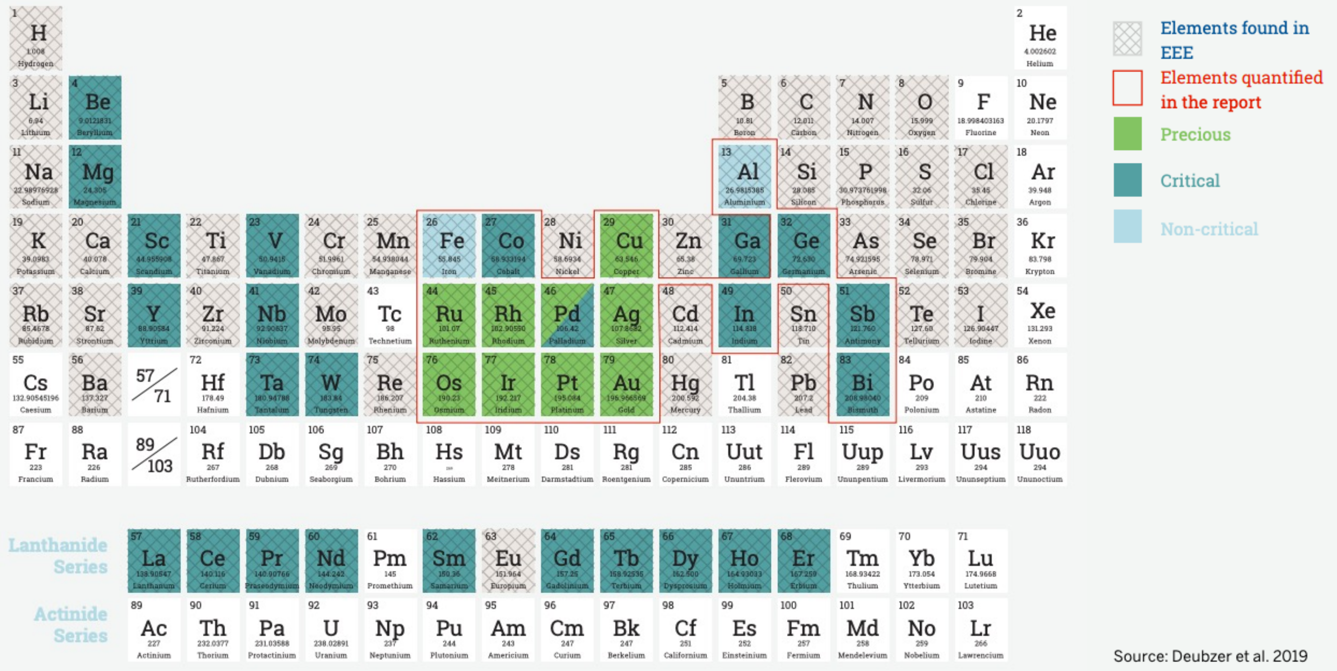


a paradigm shift in the way we approach consumption is necessary

e-waste accountability



e-waste accountability



Source: Deubzer et al. 2019

Elements found in e-waste

Environmental impact of elements

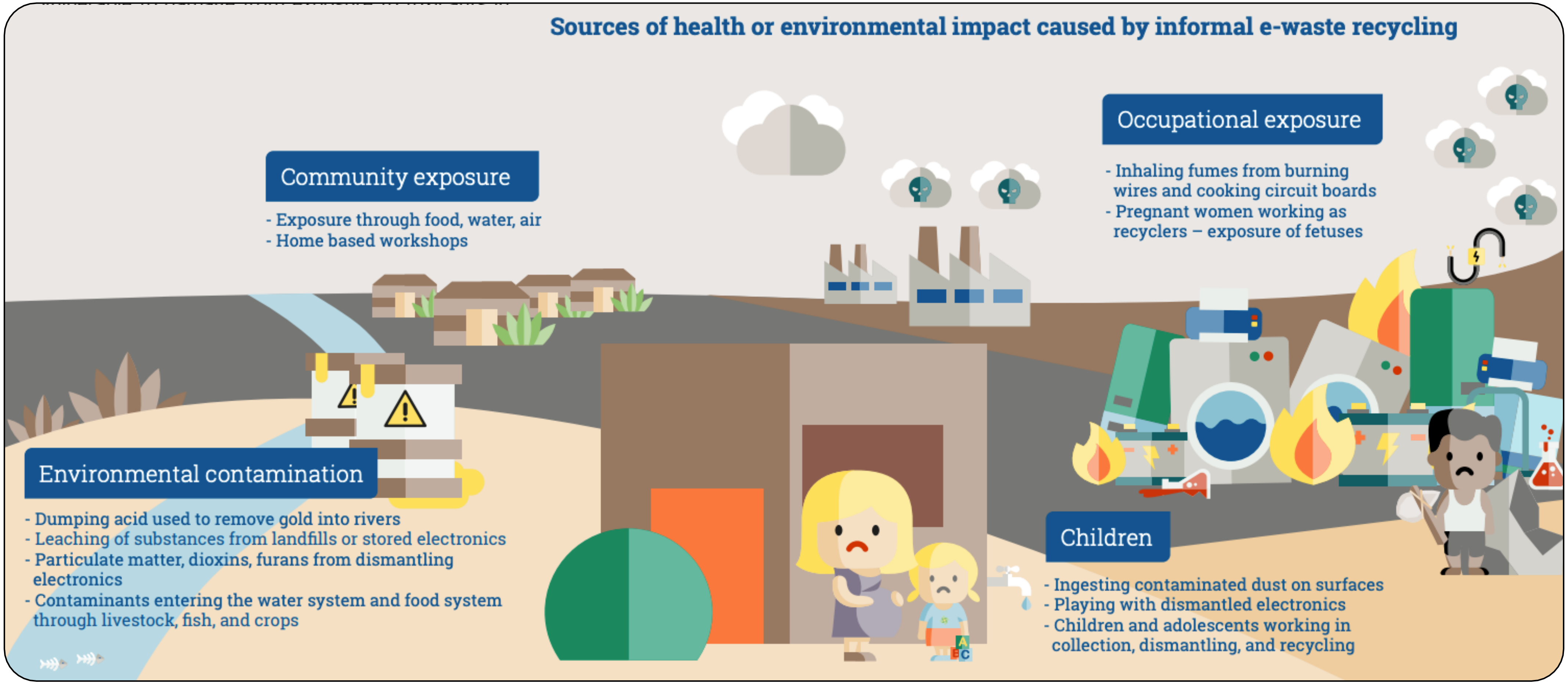
Ranking	Impact per kg	Impact global production
1	Palladium	Iron
2	Rhodium	Chromium
3	Platinum	Aluminium
4	Gold	Nickel
5	Mercury	Copper
6	Uranium	Palladium
7	Silver	Gold
8	Indium	Zinc
9	Gallium	Uranium
10	Nickel	Silicon

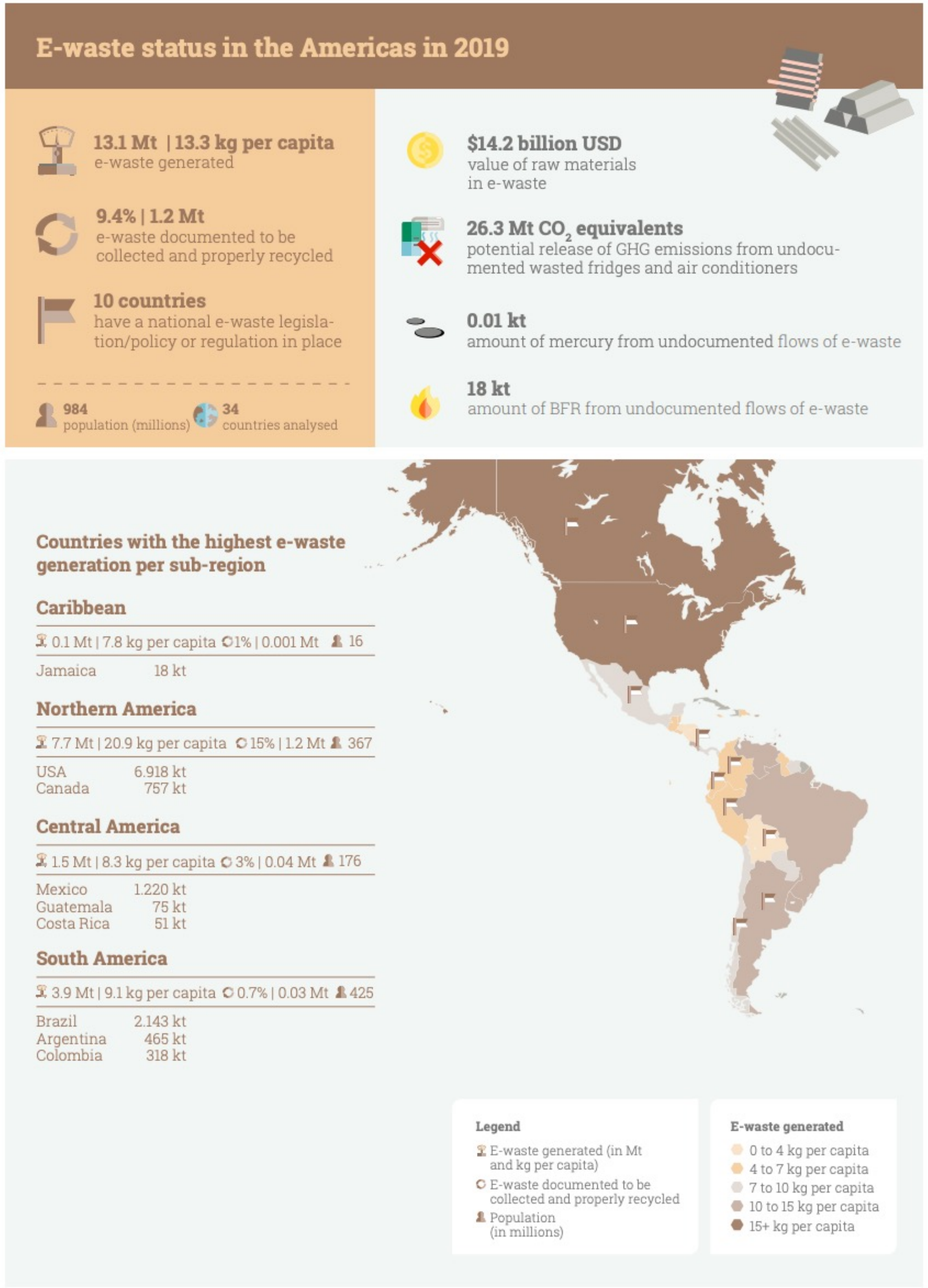
Table 7.1: Environmental impact associated with primary metals, ranked by impact per kg, and total impact due to global production. Taken from Ref. [255], with material from Ref. [256].

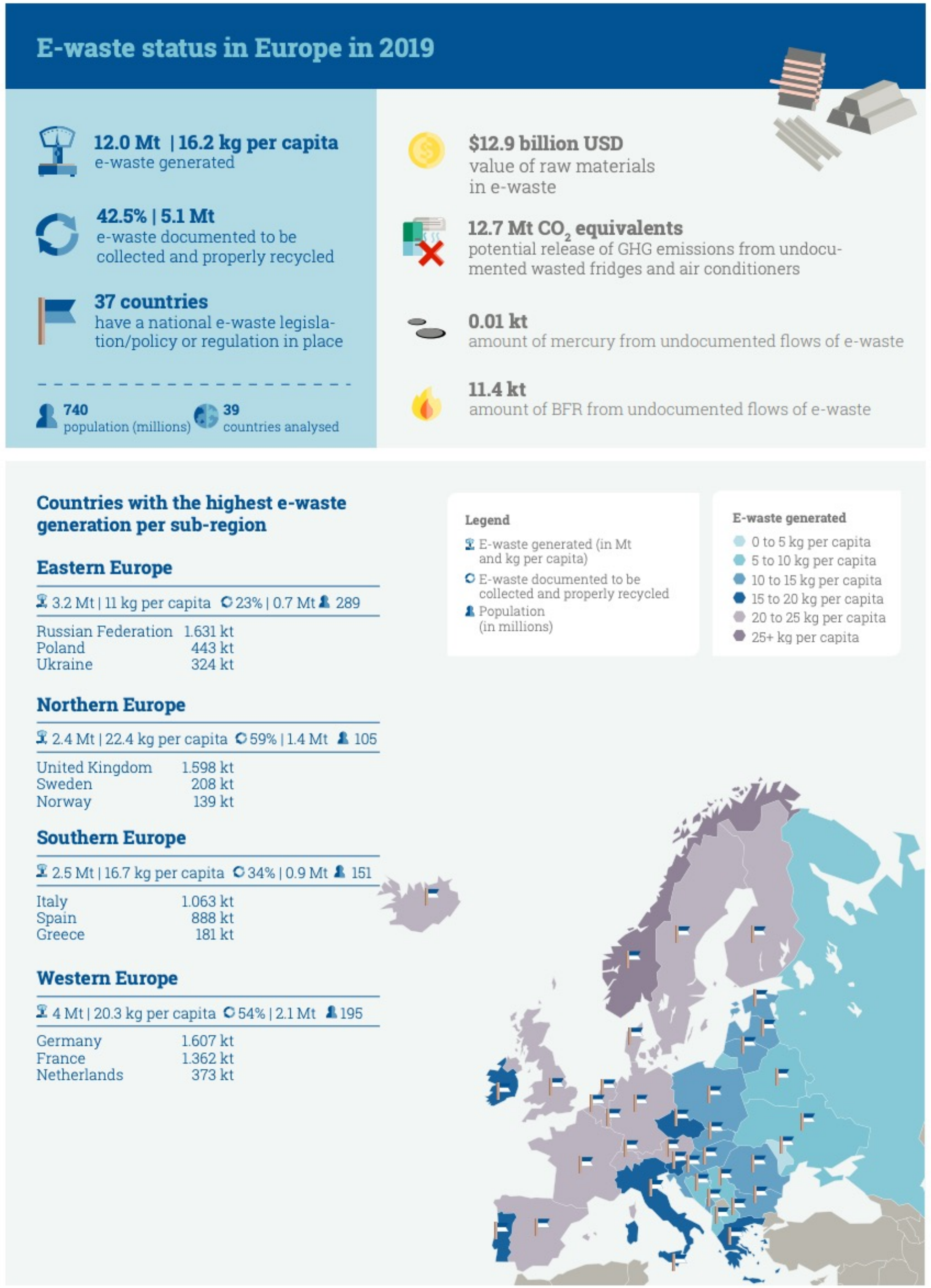
[255] European Commission, "Raw Materials Information System," https://rmis.jrc.ec.europa.eu/?page=environmental-impacts-along-the-supply-chain-3dfccf," Accessed on: 2 June 2023.

[256] E. Hertwich *et al.*, "Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials," https://www.resourcepanel.org/reports/assessing-environmental-impacts-consumption-and-production, United Nations Environment Programme, Tech. Rep., 2010.

e-waste hazard





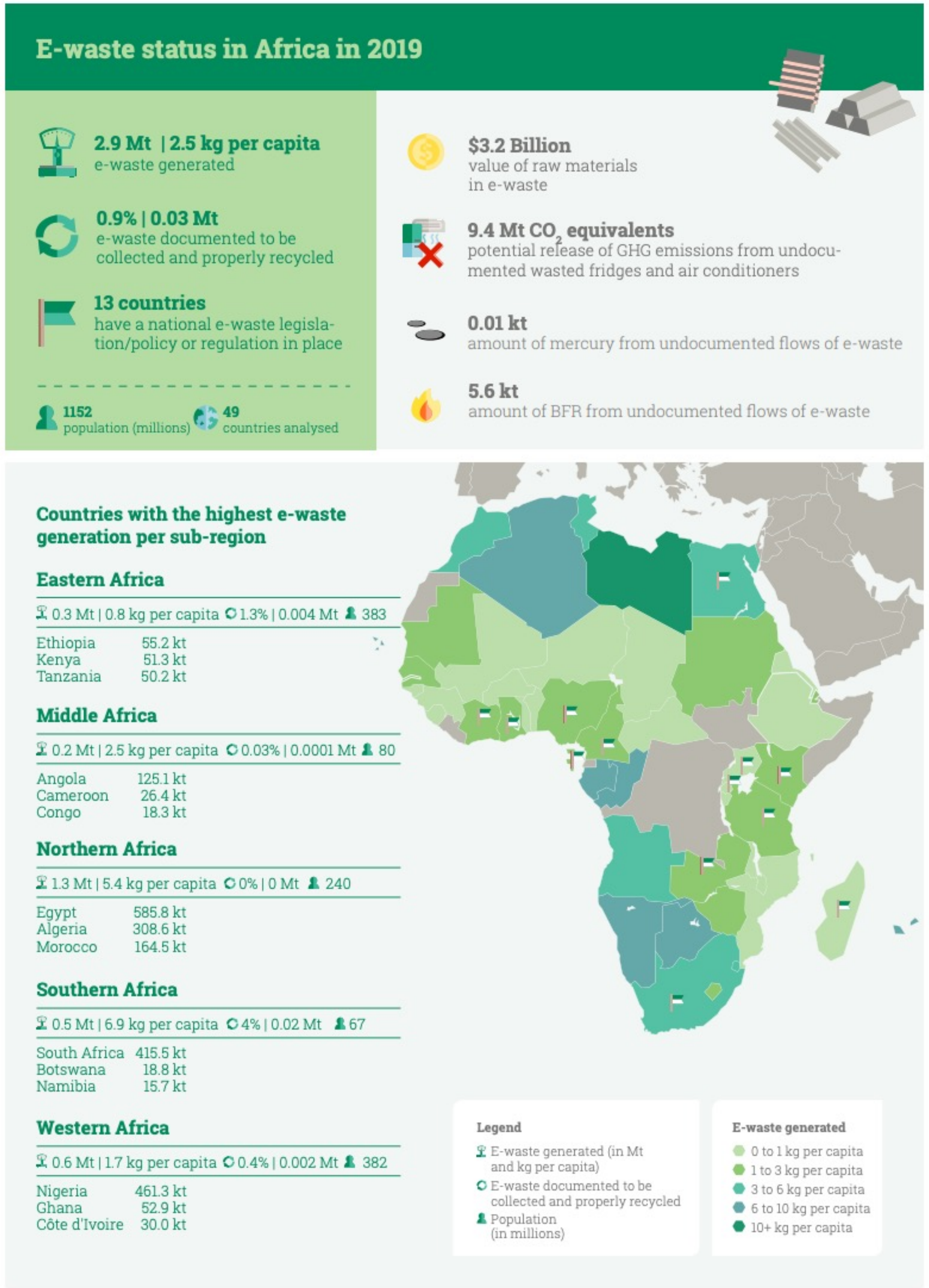


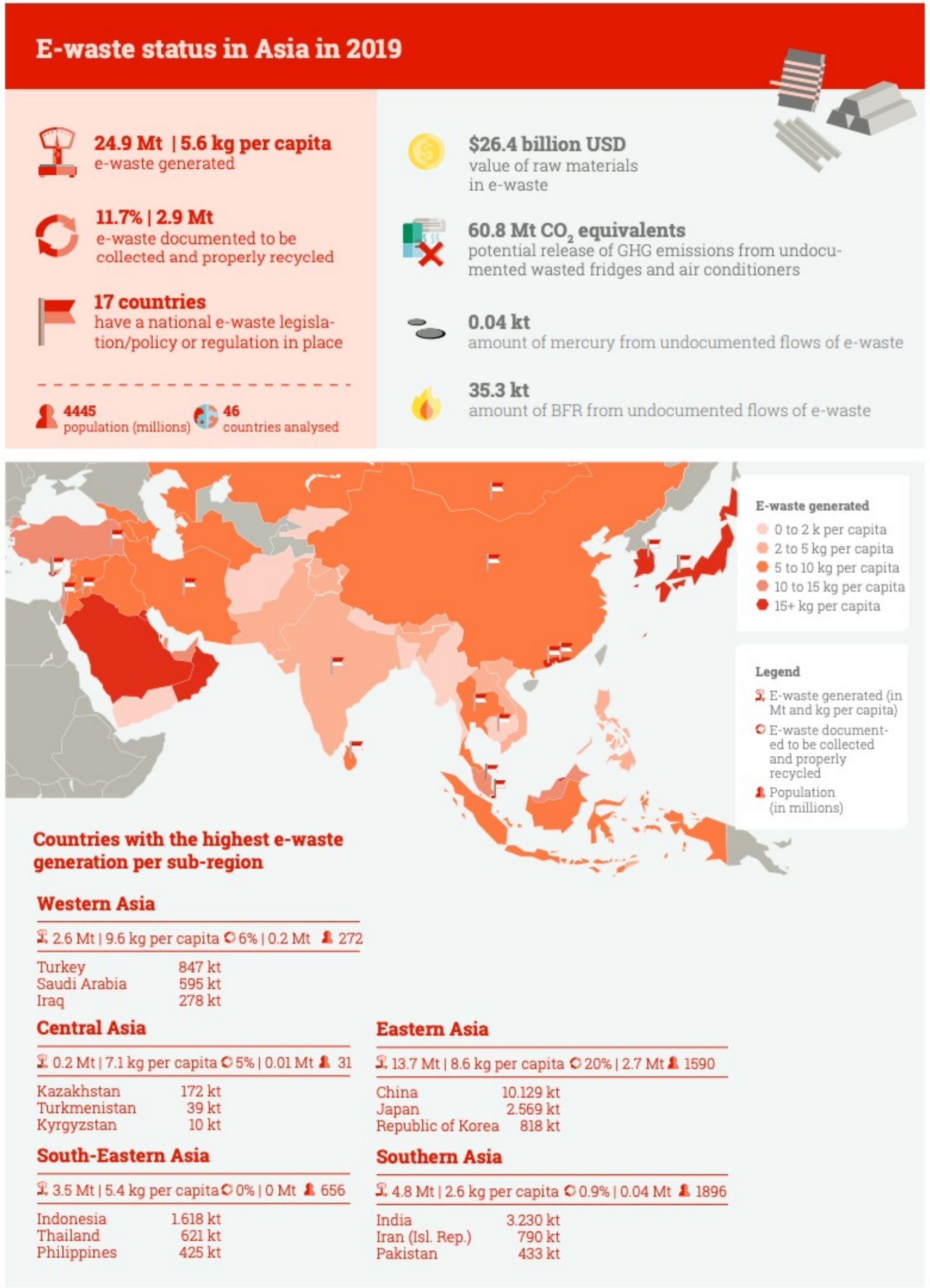
e-waste

per Capita e-Waste

1. Northern Europe: 22.4 kg
2. Northern America: 20.9 kg
3. Western Europe: 20.3 kg
4. Southern Europe: 16.7 kg
5. Eastern Europe: 11 kg
6. South America: 9.1 kg
7. Central America: 8.3 kg
8. Caribbean: 7.8kg

Global e-waste monitor 2020 report: https://ewastemonitor.info/gem-2020





e-waste

per Capita e-Waste

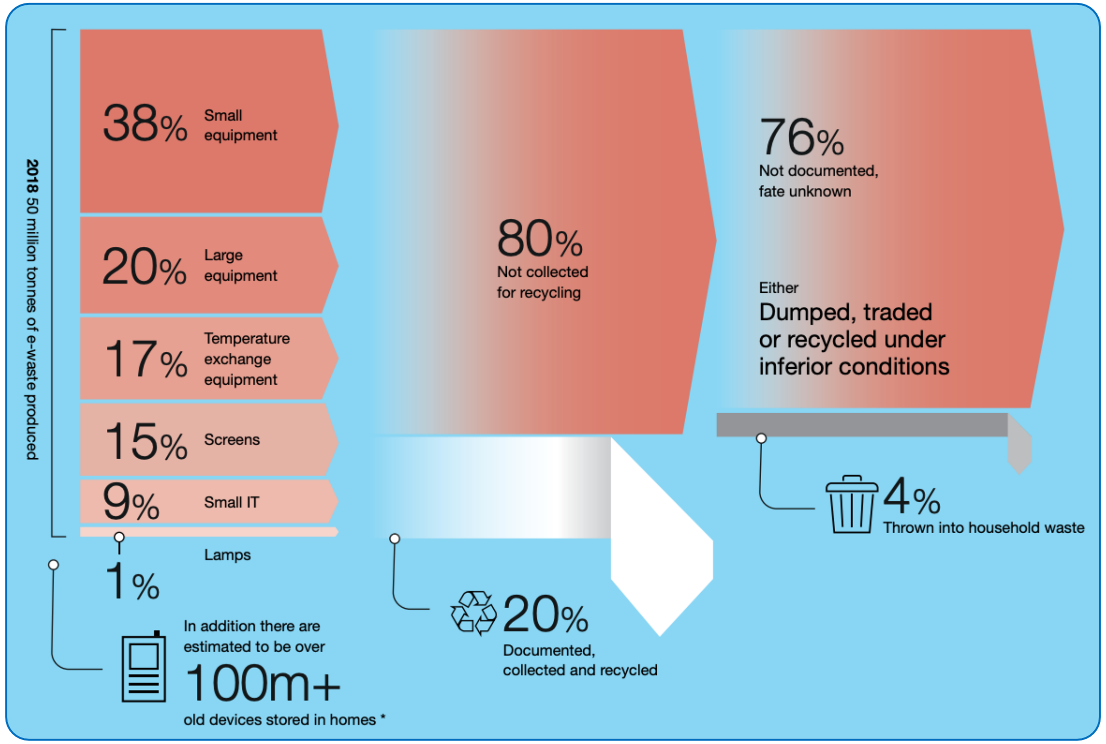
1. Western Asia: 9.6 kg
2. Eastern Asia: 8.6 kg
3. Central Asia: 7.1 kg
4. Southern Africa: 6.9 kg
5. South-Eastern Asia: 5.4 kg
6. Northern Africa: 5.4 kg
7. Southern Asia: 4.8 kg
8. Middle Africa: 2.5 kg
9. Western Africa: 1.7 kg
10. Eastern Africa: 0.8 kg

Global e-waste monitor 2020 report: https://ewastemonitor.info/gem-2020

Our contribution to e-waste

In 2019, e-waste weighed substantially more than all the adults in Europe, or as much as 350 cruise ships the size of the Queen Mary 2, enough to form a line 125 km long.

Only 17.4% of 2019's e-waste was collected and recycled. This means that gold, silver, copper, platinum and other high-value, recoverable materials conservatively valued at US $57 billion – a sum greater than the GDP of most countries – were mostly dumped or burned rather than being collected for treatment and reuse.



Primary sources of waste in academia

Short-term and regular

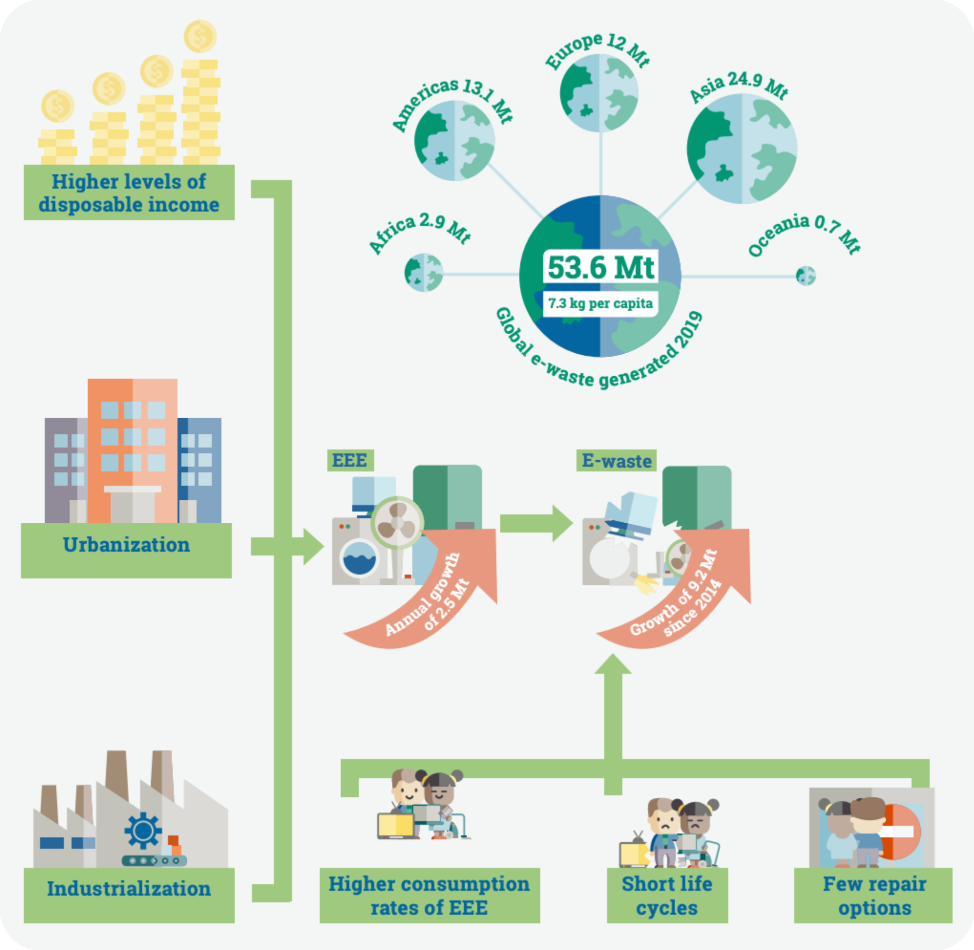
- Paper: journal articles, official documents, circulars and newsletters, books
- Plastics: stationary, organizational aids (clips, binders, folders)
- Essential consumables: Food, chemicals
- Energy: electricity, heating and cooling, fuel for transportation, computation

Short-term and irregular

- Conference gifts
- Conference supplies
- Allied footprints of conferences, workshops and meetings

Long-term

- Electronic waste: computers, tablets etc.
- Electrical appliances: coffee machines (a much smaller concern)
- Furniture
- Constructions with a shorter lifecycle, civil engineering for experiments, etc.



Recommendations — Resources and Waste

Individual actions:

- Limit purchases and consider environmental credentials such as repairability and recyclability of products in purchasing decisions.
- Service appliances regularly; share, repair, reuse and refurbish to minimise waste; sort and recycle.
- Read the sections on computing (Section 2), energy (Section 3), food (Section 4), and research infrastructure and technology (Section 6).

Recommendations — Resources and Waste

Further group actions:

- Adopt life cycle assessments and associated tools to assess environmental impact of all activities.
- Institute sustainable purchasing, usage and end-of-life policies in the management of group consumables, office supplies and single-use plastics e.g., in conference events (see also Section 7.2.3 and Best Practice 7.4).

Recommendations — Resources and Waste

Further institutional actions:

- Prioritise suppliers instituting sustainable sourcing and operating policies, with a particular focus on the raw materials processing stage (see Best Practice 7.1) and with the aim of creating demand for recycled (secondary) raw materials.
- Provide an institutional pool of infrequently-used equipment to avoid redundancy in purchasing.
- Proceduralise and prioritise repair of equipment, and enable through provision of tools and know-how.
- Assess waste generation and management for the design, operation and decommissioning of IT and infrastructure projects by right-sizing needs, establishing specific treatment channels for all waste categories, and setting recycling targets that include the recycling of all construction waste, see, e.g., Best Practice 7.3.

Thank you!

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EPISTORM

The Institute for Experiential AI
Northeastern University

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