Striving towards Environmental Sustainability in High Energy Physics, Cosmology and Astroparticle Physics (HECAP)

Important: Statement of intent

The climate crisis and the degradation of the world's ecosystems require humanity to take immediate action. Given this, the High Energy Physics, Cosmology and Astroparticle Physics (HECAP) communities have a responsibility to limit the negative environmental impacts of their research.

This **incomplete document** is being developed as part of a grassroots initiative *Striving towards Environmental Sustainability in High Energy Physics, Cosmology and Astroparticle Physics*. It is intended to be a synthesis of current data and best practices from research in climate science and sustainability, as applied to our field to the best of our ability as physicists, and a reflection on the roles that our community can play in limiting negative environmental impacts due to our research work and scientific culture. Its scope is inspired by the holistic approach of annual environmental reports of major institutes, which include emissions directly related to research and collateral emissions, such as from personal commutes and institutional catering. Addressing this broad scope requires input from across the community, in particular to identify the technical challenges of limiting the environmental impacts of our current and future research infrastructure. **We need your help to complete it.**

We need new contributors, new contributions, and constructive feedback on this document to help us to achieve this goal, particularly in relation to: **energy consumption and recovery** (e.g., of research infrastructure, inc. computing), **material resource consumption**, **waste production and management**, **direct emissions** (i.e., from gases in detectors and cooling systems), and ways that our expertise can be applied directly to **sustainability projects**.

Please get in touch with us via the online platform at:
https://sustainable-hecap.github.io/.

Thank you.

Version: Draft, September 2022

Please read this document in electronic format where possible and refrain from printing it unless absolutely necessary. Thank you.

Contents

Forewords

In the past century the ever increasing resource demands of humans have a devastating impact on the climate of our planet. The resulting heat waves, droughts, strong rain falls, violent storms, melting ice and rising sea levels are posing an existential threat to many people world-wide already today, and even more in the future. This situation demands action from all of us individually, and as groups and institutions, to do whatever we can to reduce (or ideally eliminate) the emission of CO_2(equivalent) gases, and more generally to preserve the resources of the planet. This report illustrates well, that scientists working in the fields of high energy physics, cosmology and astroparticle physics are using on average more resources than what will be acceptable, and action is needed immediately. Many recommendations are proposed for individuals, groups and/or institutions. Some are rather easy while others are challenging and require core habits to change. Given the very international nature of the research performed in these fields, there is a large potential to propagate the actions to 100s of institutions in countries of all continents and thereby increasing the impact further. I very much hope this document will help us embark on the right path.

Prof. Dr. Beate Heinemann
Director for Particle Physics at DESY,
Professor of Physics at Albert-Ludwigs-Universitaet Freiburg, and
former Deputy Spokesperson for the ATLAS Collaboration at CERN

To do

Additional forewords to be solicited.

Executive Summary

Humanity's impact upon the world's climate and ecosystems is now as unequivocal as it is extreme [1]. Averting this climate catastrophe must be a critical concern for all global citizens at this pivotal time in world history.

High energy physics, cosmology and astroparticle physics (HECAP) research has direct impacts on the environment. Our accelerators, detectors and telescopes require enormous power generation, our computing infrastructure is global and power-hungry, and we generate a large amount of waste that is unsafe for the environment.

As scientists working in HECAP, our responsibilities to limit and mitigate our impact on the world's climate and ecosystems are manifold. Our opportunities and training have given us the science capital to appreciate the evidence that has been collated over many years by climate and environmental science. We must use our unique and privileged platform to impel positive changes in, as well as educate and advocate on, environmental sustainability and the connected issues of social justice. Moreover, as a community, we should be no less accountable for our impacts on the world's climate and ecosystems than any other industry, and we should anticipate that our activities will come under increasing scrutiny from the public, governments and funders. We have moral and pragmatic obligations to act.

This document follows the holistic approach taken by several HECAP institutions in their annual environmental reports in assessing the environmental impacts of HECAP research across six areas: computing, energy, food, technology, travel and waste and resources, also within the larger context of global emissions. Specific recommendations are made for each of these areas, but the overarching message is simple:

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

This requires action at an individual level, at a group level (including research groups, collaborations and organising committees) and at an institutional level (including universities, research institutes, funding agencies and professional societies). Moreover, it requires systematic positive changes in everything from our day-to-day activities and the ways we interact as a global community through to the design and running of the 'big science' infrastructure on which HECAP research depends.

We urge all members of the HECAP community to take individual actions and push for group-level and institutional changes that:

- Consider the environmental cost of computational infrastructure and algorithms in decision making and prioritise the development of common and reusable software solutions across HECAP.
- Prioritise the use of sustainable and renewable energy to power our workspaces and research infrastructure; increase its energy efficiency and recovery, and energy storage capacity.
- Move towards plant-based catering at conferences and in cafeterias, immediately reducing the provision of carbon-intensive foods, such as beef.

- Prioritise responsible business travel that balances in-person and online meetings, acknowledges the benefits of virtual and hybrid meetings for inclusivity, and considers the disproportionate impact of changes to travel culture on different groups, e.g., early career researchers.
- Prioritise environmentally sustainable modes of transport for commuting where possible.
- Propagate and expand the culture of "reduce, reuse, recycle", including the implementation of lifecycle awareness and end-of-life planning for hardware.
- Prioritise environmentally- and socially-sustainable sourcing of raw materials for experiments and infrastructure.
- Educate and advocate on issues of environmental sustainability and social justice, and engage more broadly with policy makers to push for wider change, e.g., the improvement and decarbonization of local transport infrastructure.

Outline

This document is divided into sections, each of which focuses on one particular topic: Computing, Energy, Food, Technology, Travel and Waste. For each topic, the relevant Sustainable Development Goals (SDGs) are identified, and a summary and simple list of recommendations are provided. The sections are largely self-contained to allow them to be read independently. Each recommendation includes an itemised list of concrete and impactful measures, to serve as a library of ideas which could be implemented. Their target audiences — individuals, groups (i.e., research groups, collaborations, organizing committees) and institutions (universities, research facilities, professional societies, funders) — are identified as follows:

Recommendations

Individual actions. Groups and institutions should encourage, support and incentivise positive individual actions.

Group actions. Institutions should encourage, support and incentivise group actions. Individuals should press for group action.

Institutional actions. Individuals and groups should push for institutional action.

Each set of recommendations is followed by a longer discussion, containing case studies and best practice examples, which can be read independently of the surrounding material. Collated lists of the case studies, best practices, figures, tables, and acronyms and abbreviations are included at the end of this document.

The section that follows (Section 1) begins by acknowledging the climate crisis and the environmental impacts of high energy physics, cosmology and astroparticle physics (HECAP). It provides a summary of the UN (United Nations) SDGs and how these relate to HECAP research, and briefly reviews similar and complementary documents.

1 Preliminaries

1.1 Introduction

The 2021 report of the Intergovernmental Panel on Climate Change (IPCC) [2] is emphatic in its statements about the current status of the climate and the damaging impact that humanity continues to have upon it [1]:

> "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]."

It is also clear on the consequences of further inaction [1]:

> "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 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."

Net global CO_2 emissions must be brought to zero by 2040 to fulfill the Paris Climate Agreement. Without this, we are unlikely to meet the target of limiting global warming to 1.5°C in order to avoid fatal tipping points in the global biosphere (see Figure 1.1) [3]. Carbon offsetting via verified providers of Removal Units (RMUs), Emission Reduction Units (ERUs) or Certified Emission Reduction (CERs) units (see Ref. [4]) should be seen as a last resort, used only once all other options for reducing the CO_2e emissions have been exhausted and to offset any residual CO_2e output.

According to Oxfam's recent publication "Confronting carbon inequality" [6], greenhouse gas (GHG) emissions are strongly correlated with income level, with the richest 10% of the world's population, having an average annual income of around €34,000, accounting for over half of cumulative global emissions. See Figure 1.2 for a visual breakdown.

Many HECAP physicists lie within this income bracket and have large work-related emissions that far surpass their personal household emissions. See Figure 1.3 for a visual comparison of estimated average annual GHG emissions for researchers employed by European Organization for Nuclear Research (CERN), as well as those at the Max Planck Institute for Astronomy (MPIA) in Heidelberg, Germany, the Department of Physics (D-Phys) at ETH Zürich and Nikhef in the Netherlands. An estimated per capita GHG "budget" to 2050, as is needed to stay within the 1.5°C

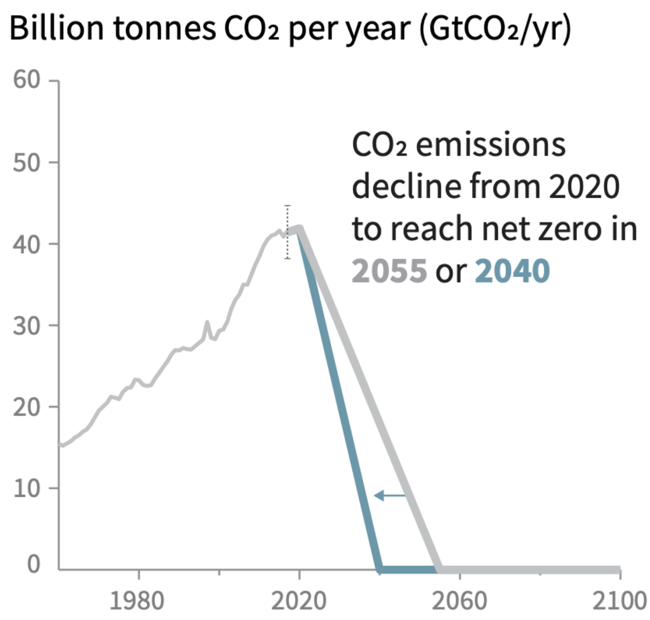

Figure 1.1: According to IPCC, the global net CO_2 emissions have to come down to zero to limit global warming and to avoid irreversible tipping points. A reduction until 2055 will have a probability of only 66 % to limit the temperature rise to 1.5°C (grey stylised pathway). Therefore, IPCC proposes to reach net-zero already in 2040 as shown in the blue stylised pathway to have a higher chance of limiting warming to 1.5°C. Figure from Ref. [5].

limit recommended by the Paris Climate Accord with a 66% probability [1], is also shown for reference.[1] Whilst some part of our work-related emissions are a direct outcome of HECAP research which perhaps more correctly could be attributed to society as a whole, a significant portion relates to peripheral choices made by us, as individuals or as a community, and the institutions that we work for. These choices include, for instance, how we commute between our home and workplace; what food we consume at work; what tools we use in our work; how we collaborate or communicate the results of our research; how our offices are powered, heated and ventilated. The rapid and systematic societal change needed to keep to our climate change goals requires system-wide engagement at all levels of academia. We can impel positive change throughout the academic system by re-assessing these choices and how central they are to our primary function as scientists.

[1] The per capita budget is computed using the population growth estimates by the United Nations (UN) [7] (assuming constant percentage population growth in each 5-year interval) and two estimates of the remaining GHG budget by the IPCC corresponding to different measures of warming.

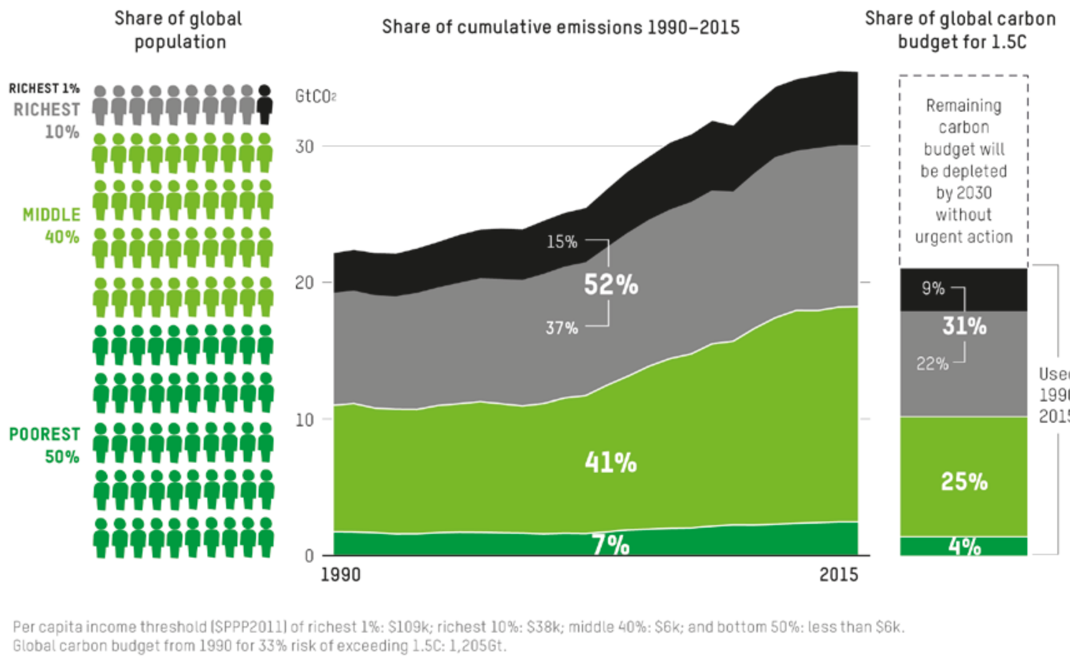

Figure 1.2: Share of cumulative emissions from 1990 to 2015 and use of the global carbon budget for 1.5°C linked to consumption by different global income groups. Taken from Ref. [6].[a]

[a]This figure, is reproduced with the permission of Oxfam, 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.

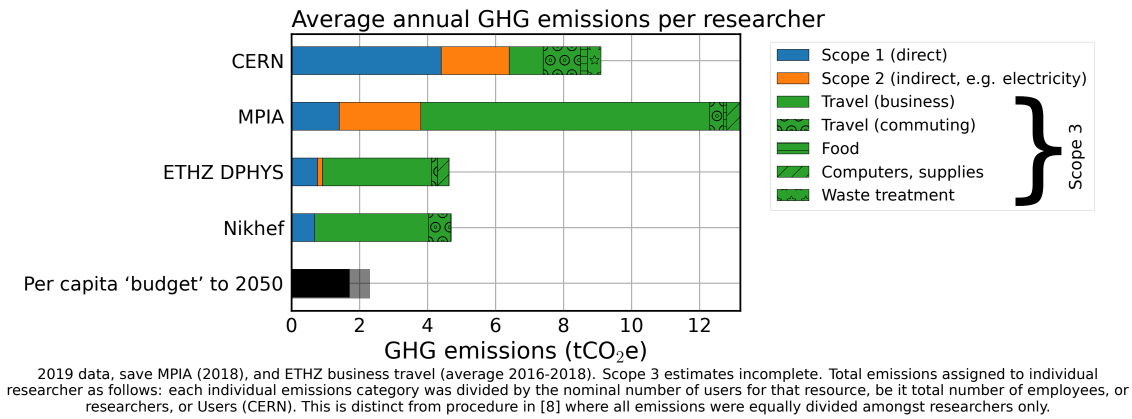

Figure 1.3: Comparison of average annual GHG emissions for researchers at three different HECAP institutions, compared to the remaining carbon "budget" to remain within the Paris Climate Accord limit of 1.5°C of warming. Researcher footprints include only work-related emissions. CERN Scope 3 data does not include emissions due to procurement, including computers, which is likely significant; Scope 3 data for other institutions incomplete. CERN data for 2019 taken from Ref. [8–10], MPIA data for 2019 from Ref. [11], ETH data from 2018 taken from Ref. [12], Nikhef data from 2019 from Ref. [13].

Our work-related emissions can be compared with the most significant sources of personal emissions. Figure 1.4 shows the conclusions of a recent meta-study from Lund University [14] in which individual climate actions were ordered by impact. Note that the estimates assume "average conditions in developed countries", and neglect the effects of climate policy.[a] This figure highlights the disconnect between the moderate-impact measures (rightmost 5 bars) that consumers are commonly encouraged to take, and the high-impact measures (leftmost 7 bars) that pertain to more complex and nuanced issues. In particular, Ref. [14]'s estimate for the climate cost of having an additional child is based on a single article from 2009 [16], and relies on the assumption that the global emissions per capita remain constant over time at their 2005 values. The original study quotes results for two additional emissions scenarios considered in the 2007 IPCC report: an 'optimistic' scenario, in which emissions per capita decrease linearly to 0.5 tCO_2e by 2100, and a 'pessimistic' one, in which a linear increase in global per capita emissions to 150% of its value in 2000. The systematic uncertainty in the result due to this choice is huge, with the outcome ranging from 4.6 tCO_2e in the optimistic scenario, to 81 tCO_2e in the pessimistic one.[b] This still raises the question of how responsibility for the emissions of future generations should be allocated, given that children are essential to the functioning of our society and institutions. A full discussion of these issues are beyond the scope of this document.

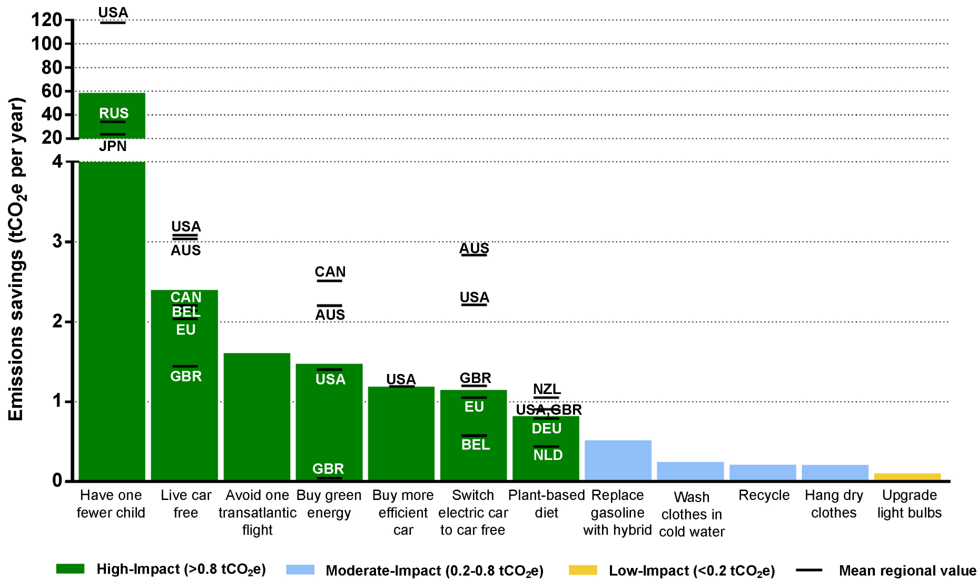

Figure 1.4: Emissions reduction from individual actions. Black lines correspond to individual developed nations studied, the mean over which is shown as a coloured bar. Note that these numbers are based on average current emissions in developed countries, and neglecting the effects of climate policy. The break in the left-most bar distinguishes between the emissions due to direct offspring and integrated emissions over all generations of descendents. Moreover the integrated estimate assumes emissions per capita that are constant in time. See the accompanying text for a more detailed exposition of the underlying assumptions and leading systematic uncertainties. Figure taken from Ref. [14]

[a] For one estimate of how national climate policies might modify the ordering, see Ref. [15].

[b] The lower and upper limits of this range were obtained by dividing the lifetime emissions per child by the average human lifespan, as reported in Ref. [7], in the developed country in question.

The purpose of this document is to improve awareness of the impact that HECAP has on the environment, to provide suggestions and encourage immediate action on ways that we, as a community, can play our part in limiting further degradation of the world's climate and ecosystems, as well as to provide impetus for ongoing and collective discussions of how we can make positive changes to our community's work practices, in terms of environmental sustainability and for the issues of social justice from which climate change and environmental degradation cannot be disentangled.

1.2 Previous and Parallel Initiatives

This document is focused on environmental and social justice issues of particular relevance to the activities of HECAP. This section provides a brief review of other documents with similar and complementary focuses on environmental sustainability and social justice.

1.2.1 ALLEA, Towards Climate Sustainability of the Academic System in Europe and Beyond

The All European Academics (ALLEA) Working Group on Climate Sustainability in the Academic System published a report in May 2022 [17], the aim of which is "to assess current practices and to critically examine current and proposed measures." The document urges stakeholders — either individual (researchers and students) or structural (universities, funding bodies, conference organisers, ranking agencies and policy makers) — to know their roles and responsibilities toward a climate-sustainable academic system. After summarizing available data on GHG emissions from various stakeholders and reviewing the current practices aimed at reducing those emissions, the report outlines recommendations for individual and group stakeholders. Dimensions of social justice and equity are among the principles underlying all recommendations, as well as the opportunity for the academic system to be a role model in the matter. While all group stakeholders are advised to embed sustainability in their strategies, individual ones differ: students and academic members are encouraged to hold university management accountable, to demand divestment and to generate awareness. The importance of the development of an evidence base is emphasised, along with mix-and-match approaches to meeting formats. Finally, stakeholders are pushed to allocate funding to the decarbonization of the academic system.

1.2.2 Snowmass Contribution, Climate Impacts of Particle Physics

The report "Climate impacts of particle physics" [18], submitted to the proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021) focuses on facility construction, detector gases, computing, and GHG emissions from particle physics laboratories. The report highlights two key motivations for addressing the ecological and climate impacts of particle physics: (i) that the particle physics community has a moral obligation to do so and (ii) that its professional activities will be under increasing scrutiny from a number of stakeholders. The latter means that the community will be under increasing pressure to justify its carbon emissions against its relative size, compared to other industries, and its societal benefits.

As a concrete example, the report focuses on the Future Circular Collider (FCC) — the proposed 100 TeV electron-positron (and later hadron) collider. The authors estimate that the construction of the $\sim$ 100 km circumference tunnel alone would lead to CO_2 emissions at the level of a few hundred kilotons, several times more than other large US building projects. This corresponds to "per physicist" emissions 80 times larger than the 1.1 tCO_2 per capita per year limit needed to keep global warming to less that 1.5°C. The authors emphasise the significant impact of the GHGs used in particle physics detectors and for cooling, which can have warming potential that exceeds CO_2 by as much as four orders of magnitude (in the case of SF_6). The report then highlights a number of avenues for reducing the GHG emissions due to the electricity consumption of computing, which is pivotal to running and exploiting such facilities. The report also discusses the additional GHG emissions from scholarly activities, with a particular emphasis on taking careful steps to reduce air travel that minimise unintended negative consequences for members of the community while capitalizing on potential benefits for social justice.

The report's recommendations stress the needs: for reporting of planned emissions and energy usage for new facilities, for standardised reporting of emissions across the sector, and for community-wide engagement to tackle the negative climate impacts of particle physics research through dedicated research time.

To do

Include a discussion of the other Snowmass reports that have appeared recently on environmental impacts and sustainability in the context of high energy physics.

1.3 Impelling Positive Change

The aim of this document is to provide a comprehensive discussion of the various impacts of HECAP research, from our day-to-day activities through to the large infrastructure projects on which our science depends. The discussions presented here have much in common with those of the documents described in Section 1.2. This document is, however, intended to have broad scope, and to illustrate through case studies and best practice potential actions that can be implemented at individual, group and institutional levels to limit the impacts of HECAP research on the world's climate and ecosystems.

However, if the HECAP community is to succeed in improving the sustainability of its working practices, then the environment and related issues of social justice must be recognised as integral parts of the planning and management of our research activities. With this in mind, we collect below a list of recommendations for structural changes to the organisation of our community, our training and our professional development.

These recommendations complement those listed in the discussions of specific sources of environmental impacts of HECAP research on which the bulk of this document focuses. Together, these provide concrete suggestions of ways in which the HECAP community can act to reduce its negative climate and ecological impacts, and address issues of social justice in line with the United Nations Sustainability Goals, discussed in the next subsection.

Recommendations — Impelling Positive Change

Individual actions. Take advantage of opportunities to learn about the environmental impact of their work practices and be proactive in seeking best practice and making positive changes across all aspects of your work.

Group actions. Include critical assessments of the environmental impact of all activities during planning stages.

Support members to undertake training and dedicate time to environmental sustainability and social justice, in relation to their research activities, and acknowledge and reward their positive actions.

Institutional actions. Ensure that undergraduate and postgraduate programmes in physics include a focus on global citizenship, encompassing, but not limited to, social responsibility, environmental sustainability, social justice, and equity, equality, diversity and inclusion. This should be incorporated directly by means of designated programme elements and concurrently within existing programme elements. This focus should be required and formally acknowledged in the accreditation of degrees by governments and professional bodies.

Require discussion of environmental sustainability and social justice in assessment criteria for funding, including a clear emphasis upon strategies to report and minimise adverse environmental impacts of proposed research and to ensure that research is undertaken in line with strong principles of equity, equality, diversity and inclusion.

Encourage, incentivise, and acknowledge positive actions towards environmental sustainability and social justice in professional development and appraisal processes.

1.4 United Nations Sustainable Development Goals

Figure 1.5: The seventeen United Nations Sustainable Development Goals [19].

As a global research community of people in HECAP, we have an impact on society all over the world. We contribute to society's knowledge with facts that shape the way the Universe is understood. Furthermore, we drive innovation and have reliable funding through institutions, which is being used to employ many individuals and invest in infrastructure. This makes the institutes of the HECAP community a significant factor in their local economic systems. They provide jobs and are often purchasers of goods and services. This economic activity gives us leverage to demand that improvements to social and environmental standards be put in effect.

We also have a responsibility towards society to advance the sustainable development of the world. This is why we, the HECAP community, support the United Nations SDGs (see Figure 1.5). The topics discussed in this document are meant to support a multiplicity of these goals, and we aim to identify the influence of our work in all aspects. We have a higher impact on some goals than on others, and further work to quantify these impacts and the steps that the HECAP community can take to limit and ideally remove them require dedicated, on-going research beyond the scope of this document.

The Sustainable Development Goals are defined in UN resolution A/RES/70/1 in detail [20]. The goals are listed below, followed by ways our work impacts on each respective goal. This list is not complete but is intended to inspire action to reach the goals in the many aspects of our daily scientific and personal lives.

Goal 1: No poverty — End poverty in all its forms everywhere

- The contractual and payment standards in employment contracts of institutes and collaborations influence their employees' lives.
- The terms of contract with external companies influence the working and living conditions of their employees.

2 Zero hunger: End hunger, achieve food security and improved nutrition and promote sustainable agriculture

- The food consumed at institutes and events has an effect on the behaviour of the food market/ industry from which it is purchased.

3 Good health and well-being: Ensure healthy lives and promote well-being for all at all ages

- Physics research helps to develop medical treatments, e.g., for cancer.
- The working culture practised everyday has an impact on the mental health of ourselves and co-workers.
- The design of experimental setups has an effect on (work) safety issues.
- Food served and consumed at institutes and events has an impact on the health and well-being of the consumers.

4 Quality education: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all

- Research develops and uses scientific methods to establish a general body of knowledge that can be passed on in educational settings.
- Researchers are often teachers for their respective field and have an effect on the teaching culture.
- Researchers and institutes, through their conduct and integrity, have an impact on the credibility of science in society.

5 Gender equality: Achieve gender equality and empower all women and girls

- As an historically male-dominated field, HECAP should strive to act for the visibility and acceptance of all genders.

6 Clean water and sanitation: Ensure availability and sustainable management of water and sanitation for all

- Our research requires the use of water for various purposes (heating, cooling, cleaning, sanitation, food production and preparation, etc.). Its sources are affected by our needs and behaviour.
- HECAP research creates waste water. The treatment of this has an impact on the water quality in the linked aquatic ecosystems.
- The behaviour and lifestyle choices of our community in professional and private lives have an impact on the water needs in the surrounding and indirectly linked area.

7 Affordable and clean energy: Ensure access to affordable, reliable, sustainable and modern energy for all

- The sources of energy planned and used for institutes, accelerators and experiments have an environmental impact on a global level.
- The high consumption and the resulting financial impact of research facilities have an impact on the energy market.

8 Decent work and economic growth: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

- The terms of employment contracts and working culture in HECAP research influence employees' living conditions.

9 Industry, innovation and infrastructure: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

- Innovation is at the core of HECAP research.
- Institutes influence the local infrastructures on which they rely and construct infrastructure for research.
- Industry and HECAP research are linked as knowledge and products are transferred. This transfer can be shaped actively.

10 Reduced inequalities: Reduce inequality within and among countries

- Research facilities that span multiple nations have the ability to impact the inequalities between the involved countries. They can also set examples for countries which are not (yet) involved.

11 Sustainable cities and communities: Make cities and human settlements inclusive, safe, resilient, and sustainable

- The campuses of research facilities have an impact on the cities and neighbourhoods that they are built in.
- The behaviour and lifestyle choices of our community in professional and private lives have an impact on our local communities.

12 Responsible consumption and production: Ensure sustainable consumption and production patterns

- The facilities, accelerators, machines, and experiments we build use up resources and energy in their design, construction, overall lifetime (e.g., maintenance) and disposal.
- The disposal of obsolete equipment and other waste generated by the work we do has an impact on our environment.
- Our daily choices on consumption have a wider effect on the systems which produce them, e.g., food and travel.

13 Climate action: Take urgent action to combat climate change and its impacts*[2]

- The emission of various gases by HECAP research has an impact on the earth's climate.
- The sources of the electrical and thermal energy used by HECAP facilities impact the global climate.
- The behaviour and lifestyle choices (eating, travel, product consumption) of our community in professional and private lives have an impact on the global climate.

[2] Footnote by the UN: *Acknowledging that the United Nations Framework Convention on Climate Change is the primary international, intergovernmental forum for negotiating the global response to climate change.

14 Life below water: Conserve and sustainably use the oceans, seas and marine resources for sustainable development

- Some of the HECAP experiments and facilities are built close to aquatic ecosystems, e.g., Antarctica, and therefore affect these indirectly.
- Many goods, products and experiments used in research are travelling the oceans prior to use.
- The industries that produce the goods that we consume use water and produce waste products, some of which ends up in the ocean.
- The behaviour and lifestyle choices of our community in professional and private lives have an impact on the oceans, through the demand for clean water and the production of waste water and residues.

15 Life on land: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

- Campuses are ecosystems.
- Expanding the campuses of research institutes can have an impact on surrounding ecosystems.
- Our consumption has direct (e.g., deforestation for agriculture and construction) and indirect (e.g., our emissions give rise to more frequent extreme weather events) effects on land use, damaging ecosystems.
- The behaviour and lifestyle choices of our community in professional (and private) life have an impact on the land and its ecosystems, because of the extraction of resources and the production of waste or residues.

16 Peace, justice and strong institutions: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels

- HECAP is part of society, and it is composed of institutions that can help shape the societies and politics within which they are embedded.
- Large-scale HECAP projects can have a positive impact on industrial and political partnerships.

17 Partnership for the Goals: Strengthen the means of implementation and revitalize the global partnership for sustainable development

- As an international community based on research and a driver for innovation, we can influence our partners and work together to strengthen a sustainable society around the globe.

The impact of the HECAP community on sustainable development is manifold, as is clear from this non-exhaustive list. It is impossible to cover all aspects in this document. The goals are meant to inspire and provide guidance in order to raise awareness and initiate a change towards more sustainable behaviors.

2 Computing

Computing, used for theoretical modelling, data analysis and (detector) simulations, represents an integral part of HECAP research. With increasing data sets and demands for accuracy, HECAP computing resource consumption is expected to rise. This poses concerns in the context of climate sustainability. For example, the High-Luminosity phase of the Large Hadron Collider (HL-LHC), predicted to be operable from 2026, is expected to rely on 50 to 100 times the computing capacity needed for the Large Hadron Collider (LHC), with data storage requirements reaching exabytes [21]. At the same time, some lattice 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 [22]. Up to 88 % of the electricity consumption per MPIA astronomy researcher reported in Figure 1.3 is due to (super)computing and makes up to a third of the researchers footprint. The emissions due to electricity use of a CERN researcher is about half of the emissions of an MPIA researcher, according to the environmental report for the years 2019–2020. CERN, however, uses the French grid with its low-carbon energy, naturally reducing its computing carbon footprint. Note that the LHC was not running in that period.

HECAP research infrastructure ranges from local and portable computing to the high performance computing (HPC) and high-throughput computing (HTC)[3] in centralised computing centres that — depending on the applications — deal with high volumes of experimental data. As an international community, we rely on communication technologies and the ability to move large volumes of data around the globe. This infrastructure contributes to our community's energy consumption and the waste that our research generates. This aspect of computing, further discussed as "hardware", needs to be made more sustainable by extending the lifecycle of personal equipment, optimizing the lifecycle of communal (i.e., data centre) equipment, by generally improving the energy efficiency of components used in computing, as well as sourcing it sustainably, and by carefully planning (large) data centres so as to recycle the energy dissipated as heat.

The most energy efficient hardware has its limitations, especially if not used appropriately. The "software" aspect of computing — defined as the programs used for research — is equally as important as hardware in the goal of sustainability as the software architecture employed can contribute significantly to the carbon footprint of HECAP researchers.

[3] Generally, synchronization requirements of large parallel HPC applications place more constraints on runtime scheduling choices and use of power saving functionalities, whereas HTC applications can be naturally run parallel. However, constraints are placed through memory consumption, and data access and transfer.

Recommendations — Computing

Individual actions. Assess the efficiency and portability of codes, considering, e.g., profiling, the efficient use of parallel I/O, and the required resolutions and accuracy [23].

Assess and optimize data transmission and storage needs [23].

Share files via secure share links rather than emailing them as attachments to multiple recipients.

Group actions. "Work collectively and reproducibly" [23], following the FAIR principles and best practice in open-access data publishing, and ensuring that data is Findable, Acccessible, Interoperable and Reusable [24].

Develop queueing systems with environmental sustainability in mind, with scheduling focused on maximising the use of renewables, taking advantage of under or overclocking subject to the availability of greener energy and the geographical location of servers/data centres [23].

Institutional actions. Regularly assess hardware lifecycles in order to balance the environmental cost of replacing functional hardware against the financial and productivity costs of increased maintenance and/or hardware failures. This should include support for repairing and upgrading existing central and personal computing, and programs to re-purpose, donate or ensure responsible recycling of retired hardware.

Encourage and incentivise procurement of modular/fair-trade laptops.

Select cloud computing services for their carbon emission mitigation policies.

Regularly and critically assess the efficiency of cooling systems and ways to utilize waste heat from computing.

2.1 Hardware

When considering the future of sustainability in HECAP the hardware aspect of computing is of great concern. Hardware is both an energy and resource consumptive facet of computing. The manufacturing and transport, and the energy consumption of each piece of hardware contributes substantially to the footprint of HPC that HECAP relies on to continue analysis of large swathes of data.

Firstly, the manufacture and transport of hardware is the largest contributing factor of computer hardware carbon emission. For example, it contributes upwards of 70–80 % of carbon emissions in the lifetime of a personal device [25] (about 75-85 % for laptops according to some more pessimistic calculations from a company selling refurbished laptops 2021 [26], some older calculations from 2011 by Fujitsu put the figure at about 50 % for a specific model [27]).

For HPC, rare metals must be mined, amongst them tantalum, tin, tungsten and gold, which are, in particular, known as conflict minerals, fueling wars and human rights abuses. Other substances found in computing equipment are linked to environmental hazards and a variety of other risks. An analysis of components used inside a smartphone and their impacts can be found in Ref. [28]. Obvious ways to reduce the amount of material usage is to enable circularity and proper e-waste recycling. At the same time, longevity is important. In fact, the extension of the life of hardware is increasingly being shown to have major benefits over upgrading to more efficient technology [29].

A study held by the University of Edinburgh Department for Social Responsibility and Sustainability [29] found that simply keeping 174 computer monitors for 6 years instead of 4 saved 33,000 kg CO_2e, which when incorporated into standard practise would not only save on costs but would have the equivalent effect of keeping 150 cars off the road (380,000 kg CO_2e per annum). The ability and the (institutional) willingness to support repairs is crucial. This applies in particular to personal equipment, e.g., laptops, which come with additional peripherals, in the form of display, keyboard and housing compared to the HPC units used in HPC data centres.

When buying new equipment, using suppliers that prioritise sourcing fair materials is an option that should be pursued. Smartphone manufacturer Fairphone has achieved sourcing 56 % of 8 materials used in its phones fairly in 2020 and has increased their target to achieve 70 % fair sourcing for 14 materials by 2023 [30]. TCO Certified [31] is the world-leading sustainability certification for IT products, some of which come from standard suppliers such as Lenovo, Dell or Acer and should therefore meet standard expectations for equipment. According to its own account, TCO Certified compliance is independently verified, both pre- and post-certification. The certification also includes data centre products, which could be given preference above non-certified ones for local computing clusters.

Secondly, the usage of the hardware is energy consumptive in itself. The main contributors of energy consumption in computer hardware are the processors, memory and runtime of jobs. Processor upgrades and the optimization of memory type can greatly reduce energy consumption. However, this reduction of energy usage is fruitless in the face of the aforementioned carbon and resource costs of manufacturing, thus these upgrades must be timed well. In 2007, a change in the paradigm for constructing the computing architecture for data centres was suggested to ensure that the hardware used in computing centres is "energy proportional" [32], that is that the energy consumption is proportional to the computing performance over the full range of applications — often the hardware was designed to be most efficient during highest performance loads, but realistically spend most of its time (and energy) being idle or performing less intensive computations. These considerations triggered changes in architecture towards more transistors and multicores, which profited from the parallelism possible in most HECAP applications and finally contributed to the rise of graphics processing units (GPUs) and custom chip design by Amazon and Google for the specific needs [33].

Generally, to reduce runtime, parallelization can be implemented within processors. This can also reduce the number of processors needed. In addition, by replacing central processing units (CPUs) with graphics processing units (GPUs), the energy usage can be reduced. However, before implementing these parallelization and GPU techniques, it is important to test whether the overall energy usage of a task is reduced, as even though the runtime would be reduced, the energy consumption per second could be increased. Some issues with just continuing to parallelise are the increase in total amount of memory needed and problems with the scalability of job management and data access systems. Reference [34] discusses these issues specifically for the case of the WLCG and gives suggestions for power-aware software applications and scheduling that could reduce power consumption. Some of the needed changes (e.g., the move to multi-threading) are software specific and are further detailed in Section 2.2. As already pointed out in Ref. [18], a Green500 list exists [35] that regularly publishes reports of the most energy efficient high-performance computing systems (measured in GFlops/Watts). The carbon footprint of these computing facilities, however, depends critically on how their infrastructure (that is electricity, cooling and scheduling) is implemented. This aspect is further discussed in Section 2.3.

2.2 Software

Software is integral to the work of HECAP. It underpins how the global HECAP community communicates, shares data, produces papers and graphics, and acquires, manages, processes and analyses huge amounts of data from experiments, observatories and simulations.

It is therefore pivotal that the software developed and used by the HECAP community is efficient in order to minimise CPU hours, and to facilitate data sharing and long-term reproducibility. This requires a balance to be struck between optimization for particular architectures and portability. While not directly linked to environmental sustainability, initiatives focused on software sustainability in HECAP, such as the IRIS-HEP [36] and the HEP Software Foundation [37], may provide an important platform for accelerating the inclusion of environmental considerations in software development. Doing so is compatible with the FAIR principles [24] for scientific data management, that software (and data) should be Findable, Accessible, Interoperable and Reusable.

Much of the code used in HECAP computing relies on libraries and public codes. Experiments use general frameworks and software infrastructure provided by experts in the experiments. They can have a tremendous impact on the energy efficiency of the employed code and, in some cases, work to meet strict requirements posed by the computing environment. Decisions on the computing language employed can be crucial, with Fortran and C++ specifically suited for numerical calculations, whilst others prioritise convenience or readability over performance. Changes in processor architecture have been utilised through dedicated and collaborative efforts (see Case Study 2.1), leading to a factor of 2 improvement in the performance (and energy efficiency) of the reconstruction code of the ATLAS experiment [38]. Other examples of software improvement are recent improvements in a MC generator core code, having led to an improvement in speed of a factor of 20. In the case of cosmological analyses, it has been suggested that the Likelihood Inference Neural Network Accelerator (LINNA) can lead to efficiency increases that would save USD 300,000 in energy costs and around 2,200 tCO_2 in first-year Rubin Observatory's Legacy Survey of Space and Time (LSST) analyses [39].

Sustainable use of software can also be encouraged at an individual level. The energy used in a job directly correlates with the memory assigned/available for a job, so mitigation by individuals can be easily implemented through assigning the correct memory used and by optimising code [40]. Further examples of conscientious use of software include limiting resolution or precision to that which is necessary, effective testing to avoid wasted CPU hours, good practice in data retention to avoid data loss and the need to rerun analysis or simulations, and scheduling CPU hours when a higher percentage of the local energy mix is from renewables.

Best Practice 2.1: Optimization of Software

A targeted effort enabled by the UK-based SWIFT-HEP project recently brought together experimentalists and MC developers to greatly improve the computational efficiency of multi-leg NLO calculations by focussing on two major components of general purpose Monte Carlo event generators: The evaluation of parton-distribution functions (PDFs) along with the generation of perturbative matrix elements. A dedicated CPU profiling illustrated that for the cost-driving event samples employed by the ATLAS experiment to model irreducible Standard Model backgrounds, such as V+jets as well as ttbar+jets production, these components dominate the overall run time by up to 80%. Improved interpolation and caching strategies in LHAPDF, the main evaluation tool for PDFs used by the experiments, along with the introduction of a simplified pilot run in Sherpa for the unweighting achieves a reduction of the computing footprint by factors of around 50 for multi-leg NLO event generation, while maintaining the formal accuracy of the event sample. The speed-up translates into a direct CPU (and hence energy) saving, paving the way towards affordable and sustainable state-of-the-art event simulation in the HL-LHC era.

2.3 Infrastructure

To do

Infrastructure section, to include cloud computing.

The energy efficiency of IT equipment is important, but an equally big driver of CO2e are the large infrastructures within which this IT equipment is used, namely data centres and cloud computing. For data centre infrastructure, a commonly used measure of the energy efficiency is power usage effectiveness (PUE). It is defined as the ratio of the total power used by the facility over the energy used by the IT equipment and is essentially a measure of the overhead energy costs predominantly due to cooling. Commonly PUE values range from 1.2 to 1.5 with an average around 1.4, that is 40% of the energy used by the IT equipment is additionally used to provide cooling and other services.

The IT equipment energy is provided by electricity and can therefore relatively easily be made green, provided energy from renewable sources are available – indeed even the most energy efficient data centre are not sustainable if they are powered by carbon fuels [18]. Often, the PUE is therefore multiplied by a carbon dioxide emission factor (CEF) to obtain a clearer measure of CO_2e emissions. Here, the CEF is the amount of CO_2 in kg emitted for each kilowatt-hour of electricity.

However, electricity is only one aspect. The overhead energy costs for cooling depend crucially on the design on the cooling system. This is more difficult to design sustainable and rely either on reusing the heat from the data centre or on innovative low-power cooling methods or a combination of both. This aspect can be helped by selecting the location of the centres carefully (e.g., prefer colder climates). Two examples for best practices in recent data centre designs are given in Best Practice 2.2 and Best Practice 2.3.

Best Practice 2.2: Prevessin Computing Centre, CERN (in construction)
Contribution by Wayne Salter, IT Project Manager for the PCC

CERN has for some time been wishing to build a second Data Centre (DC) on its Prévessin site (named the PCC) to augment the capacity being provided by its Meyrin Data Centre, in particular in light of the increased demands from the LHC experiments in the HL-LHC era. In 2019, a project was approved to build a turn-key Data Centre with an initial capacity for computing of 4 MW, but with the possibility to upgrade the IT capacity in two steps to 8 MW and finally to 12 MW. A Call for Tender was initiated at the end of 2019 for the design, construction and 10 year operation and maintenance of a new Data Centre and the result of the tender was adjudicated at the CERN Finance Committee in December 2020 in favour of a consortium led by EQUANS [41]. A contract was signed with the winning consortium in July 2021 and construction began at the beginning of 2022. The DC is expected to be operational in the final quarter of 2023. An important aspect included in the thinking for the new DC was sustainability and, in particular, energy efficiency. As such, the specification required a target Power Usage Effectiveness of 1.1, but contractually allows for a PUE of no worse than 1.15, for energy recuperation of at least 25 % of the heat generated by the IT equipment and for a roof with vegetation.

When considering the increased energy efficiency compared with CERN's existing Meyrin Data Centre, which now has a PUE of around 1.5 after many years of efforts to bring this down, this equates to significant energy savings. The first phase for the PCC will have a capacity of 4 MW for IT load with the possibility to go to 8

MW and then 12 MW in two further steps. Assuming the PCC running at full first phase capacity of 4 MW with a PUE of 1.1, cf. 1.5 for the current CERN Data Centre, then the annual saving in terms of electricity would be 14 GWh. Obviously, should the PCC be eventually upgraded and used at its full final capacity then the savings could be tripled, cf. with running a similar capacity with the PUE of the current Meyrin Data Centre. It should be noted that the PUE of the current Data Centre is the result of many years of efforts to improve the energy efficiency, which have substantially reduced its PUE, but that further improvements would now be complex and costly.

In addition to aiming for high energy efficiency, the design of the PCC also allows for the heat produced by the IT equipment to be recuperated and used to help power a new building heating plant that will soon be built close to the PCC to replace an existing ageing and inefficient heating plant. The specification for the PCC required the possibility to recover a minimum of 25 % of the generated heat per phase, implying 1.3 MW per phase leading to a total of 3 MW once the full 12 MW configuration would be operational. However, during the design phase it has been decided to request 3 MW already during the first phase. In the second phase, the heat recuperation will be increased to 4 MW.

During hot weather, water is sprayed on the heat exchanger elements of the dry coolers to improve their efficiency. In the original design, this water was lost, resulting in a non-insignificant water consumption over the year. However, with sustainability and environmental protection considerations in mind, it was decided to make efforts to reduce the water consumption as far as possible without impacting the efficiency of the cooling solution. As such, it was agreed with the constructor to change the design to include water re-circulation at the level of the dry coolers and hence substantially to reduce the water consumption. In the first phase, the annual water consumption is estimated to be reduced by 61 % from 21,455 m^3 to 8,645 m^3, based on the average meteorological data for the area.

To further improve sustainability and to make the building more ecologically friendly, it was also decided to request that vegetation be planted on the roof of the building, which is effectively in two halves. The first half contains the IT rooms (two per floor for three floors) and the second half is for all the technical rooms. The roof is similarly split in two. The first half is used for the dry coolers and associated technical infrastructure and hence cannot be used for vegetation, but the second half will be planted with grass covering an area of approximately 1,250 m^2.

Best Practice 2.3: Cooling in Swiss National Supercomputing Centre (CSCS)
The information for this case study was taken from CSCS fact sheets [42, 43] and vetted by the organization.

The Swiss National Supercomputing Centre is a three-floor concrete building in Lugano that houses the "Piz Daint" supercomputer and the system used by MeteoSwiss for weather predictions, among other things. It currently operates at a PUE (power usage effectiveness) rating of 1.20 at 25 % of full load, with a design PUE of 1.25. Approximately one third of the electricity used in a conventional data centre is dedicated to cooling. At CSCS, this is achieved with a state-of-the art cooling system using the water from Lake Lugano, extracted at a depth of 45 m and a temperature of 6°C. 420 litres of this water per second are pumped to the facility over a distance of 2.8 km into large heat exchangers, where it meets and cools the water in the internal cooling circuit for the supercomputers. The resulting warmer water is then sent to a heat exchanger in a second cooling circuit, which cools the components with a lower thermal sensitivity, as well as the building itself in the summer, before being returned to the lake. The return flow of water falling back into the lake is used to produce electricity via a microturbine in the pumping station further reducing the power consumption of the pumps by 30 %. Due to modular cooling and room concepts, the different parts of the facility are equipped only as necessary. Not only does this reduce the initial budgetary outlay, but it also results in increased flexibility to react to future hardware needs, while keeping the PUE close to its final design value from the outset.

3 Energy

Large-scale research facilities have a significant energy footprint from the operation of experimental equipment and computing facilities. In addition, energy is required for the construction and disassembly of facilities and infrastructure, for heating and cooling buildings, for commuting and business travel of employees, and transport of goods. To comply with the Paris Agreement, future facilities must be effectively climate neutral, and this presents a significant challenge for HECAP.

The European particle research laboratory CERN is a prominent example of a power-hungry facility. With its particle accelerators, detectors and extensive infrastructure, CERN consumes up to 1,300 GWh of electricity annually, of which 55 % is due to LHC operations [8, 44]. To push forward the energy and intensity frontiers, CERN plans to significantly increase the scale of its installations. Doing so responsibly will require a concerted effort to reduce power consumption and increase the energy efficiency of the infrastructure, and a careful analysis of how to source the remaining energy needs in a sustainable way.

CERN receives most of its electricity from the French grid, which is currently characterised by a high share of low-carbon nuclear power, suppressing its electricity-related CO_2 emissions in comparison with other facilities (see Figure 1.3).[4] However, taking into consideration the decreasing share of nuclear power in the French grid over the last 15 years, as well as the wider common European electricity market, where fossil fuels account for 35 % of electricity production on average, the outlook is more worrying.[5]

It is important to place the energy needs of HECAP research infrastructure within the context of the world's necessary and rapid transition to zero-carbon energy sources. Global primary energy consumption in 2019 was approximately 160,000 TWh (equivalent to an average power consumption of 18,000 GW), around 80 % of which comes from CO_2-emitting fossil fuels [46]. Moreover demand is rising, primarily due to the growth and industrialization of emerging countries. A reduction to net zero emissions by 2040, as stipulated in the Paris Agreement, will create a huge global energy gap, as shown in Figure 3.1. Many experimental technologies such as CO_2 sequestration will not be viable for large-scale implementation within this short time frame, and the transition is therefore likely to result in energy becoming scarce and expensive in the coming decades, with the potential to directly limit our capabilities to conduct energy-intensive experiments and data analysis in basic research.

This chapter focuses on potential sources of sustainable energy for HECAP research infrastructure. A discussion of energy saving and recuperation can be found in Section 3.2. Energy saving by efficiency increase through structural and organiza-

[4] CERN's annual electricity emissions range from 9,000 tCO_2 (LHC shut down) to 15,000 tCO_2e (LHC in operation) [8].

[5] For a live visualisation of the carbon emissions of electricity by country, see Ref. [45].

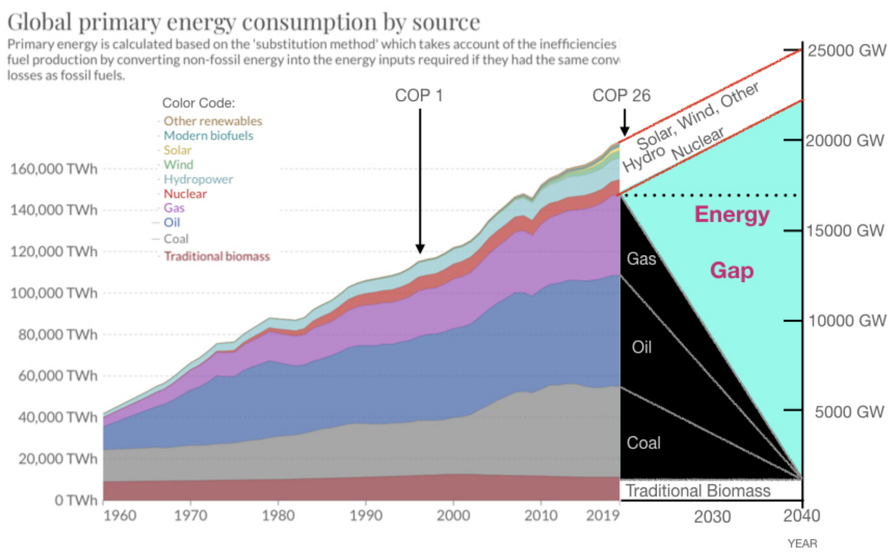

Figure 3.1: Global primary energy consumption is dominated by fossil fuel, whose use has been increasing steadily despite warnings from the 26 climate change conferences of the United Nations (COP) since 1995. Phasing these out by 2040, as shown by the sketched black triangle, creates a large energy gap that must be filled by additional climate-neutral power generation, or by energy saving and recuperation. Consumption was extrapolated linearly after 2019 to account for additional demand from emerging countries. Figure taken from Ref. [47], based on data from Refs. [48, 49].

tional changes are described elsewhere, see Section 2 for computing and Section 7 for travel.

Recommendations — Energy

Individual actions. Read the sections about travel (Section 7) and computing (Section 2) and save energy in all ways practicable, e.g., by avoiding unnecessary heating or cooling of workspace and turning off electrical items when not in use.

Group actions. Consider energy consumption in the choice and design of experiments, monitor energy usage, and choose technologies that maximise efficiency and minimise consumption.

Institutional actions. Monitor and report energy usage; incentivise saving and recovering energy where possible, and prioritise moving to renewable sources of energy.

- Change defaults when heating and cooling systems are active.
- Decrease default temperatures in offices.
- Shut down office buildings during quiet periods.
- Publish monthly performance tables/real-time displays of energy consumption.
- 'Game-ify' decreasing energy use with e.g., monthly cross-departmental competitions.

Many of the above suggestions were inspired by the energy-consumption reduction measures introduced by the UK Government in 2010 [50].

3.1 Low-Carbon Energy

Transitioning the energy demands of HECAP research to CO_2-neutral sources will likely require a mix of sources: solar, wind, hydro, geothermal and nuclear power, many of which will be strongly location-dependent. Despite their decreasing costs (see Figure 3.4), the geographical and geological limitations of renewable sources of energy, combined with the challenge that significantly increasing the share of nuclear power presents (see Case Study 3.3 for details), a rapid transition to carbon-neutral energy will not be possible without some large-scale transmission or importation of sustainable energy or efforts to site future facilities near to abundant renewable energy sources. World-leading research centres like CERN are uniquely placed to implement such schemes, with their history of cooperation across political and ideological boundaries.

To do

Include the IPCC figure on the relative reduction in emissions for transitions to different energy sources.

Solar Solar energy is abundant, and near-universally available. Its intensity depends only on latitude, with the highest efficiencies in the deserts near the equator. According to a 2021 report by the Carbon Tracker Initiative [51], populating an area of only 450,000 km^2 with solar panels would be sufficient to satisfy global energy demands. This corresponds to an area the size of Morocco. For Europe, 4 % of its landmass would be necessary. Surprisingly the report also states that there is at most a factor of 2 difference between the hours of full sunlight available in the most and least sunny countries (Namibia and Ireland, respectively).

Solar panels are also easily retrofitted onto existing infrastructure. Unfortunately solar power is usually unavailable when it is needed most: at night and during winter (in countries at higher latitudes), leading to a need to increase its efficiency and storage capacity (see "Energy storage" below). See Case Study 3.1 for a study on the implementation of in-house solar power at CERN.

Wind By comparison with solar energy, wind energy is more sensitive to localised conditions. In Europe, competitive locations for wind energy, with costs below 0.06 € per kWh, are concentrated along the coasts of the North and the Baltic seas, including Galicia (Spain), the British Isles, the North of France, Germany, Benelux, Denmark as well as North Poland and the Baltic states, South Sweden and Finland [52]. As winds are stronger and more consistent around the coasts, landlocked countries, such as Switzerland or Austria, are generally less suited for production of energy through wind turbines. In Switzerland, e.g., close to 100 % of all agricultural farmland would be needed in order to produce 25 % of its energy demand through wind (although of course this doesn't preclude growing crops beneath windmills). For Denmark or Estonia, this number is less than 4 % [52].

Hydro Water power is even more reliant on local conditions, such as high flows or water volumes and large altitude difference, which naturally limits its applicability. However, the energy output of hydroelectric plants is consistent, and can be adjusted to demand very quickly, making it a good complement to other renewable sources that provide a (fluctuating) base load. The largest hydroelectric capacity is in China, which produces almost 30 % of the global hydroelectric power [53], thanks to its large projects in the Yangtze River valleys.

Mega-dams, however, constitute a large intervention on the natural environment, and consequently come with associated risks such as landslides and earthquakes and destruction of habitats, and can themselves be a source of the potent climate gas methane when flooded flora rots. The Three Gorges dam in particular has been controversial both domestically and abroad [54].

While the potential for marine power generation from ocean currents, tides, waves and gradients in salt and temperature is huge, there is no technology currently mature enough to produce marine power at large scale.

Geothermal

> **To do**
>
> Discussion of geothermal power.

Nuclear By definition, an energy source is only sustainable if it does not carry any significant long-term risk for future generations. This understanding of sustainability based on the Brundlandt Report [55] has also been adopted by the International Atomic Energy Agency (IAEA) [56].

Nuclear power production has been stagnating on all continents except Asia for the last two decades, and has a share of just 4 % of the global energy production, more than 60 years after initial deployment [57]. Safety and security of the reactors and availability of fuel, as well as storage of spent fuel, are important concerns. The exact form these concerns take is crucially dependent on future technological developments. Today, several new reactor types are being developed, which promise to have additional safety features, an efficient use of more abundant isotopes and less long-lasting nuclear waste. Nevertheless wars, terrorism and proliferation will always remain a concern.

Energy storage

> **To do**
>
> Discussion of various forms of energy storage: batteries versus hydroelectric or mechanical storage, as well as the ways energy grids can be managed to deal with the changes in relative production from different renewables.

Recent drops in cost for lithium-ion batteries, which have decreased by a factor of 40 in the last 30 years [58], and solar panels (see Figure 3.4), have unlocked the potential for decentralised, economically viable, sustainable power production. This would help reduce foreign energy import dependencies, particularly of coal, oil and uranium.

Energy import The uneven geographical distribution of sources of renewable energy naturally begs the question of whether large-scale importing of renewable energy could be a cost-effective way of closing the energy gap. According to Ref. [59], which reviews options for the energy transition with a specific focus on the United Kingdom, "Any plan that doesn't make heavy use of nuclear power or 'clean coal' has to make up the energy balance using renewable power bought in from other countries".

Technical options to transport electricity over long distances have improved significantly in the last decades. In South America and China, projects to transport electricity over more than 2,000 km by Ultra High Voltage Direct Current (UHVDC) lines are already operational [60].

To do

SLAC example on moving hydro power.

This technological progress opens up an alternative to the traditional import of chemical energy: direct import of renewable electricity, e.g., from Northern Africa to Europe [61, 62]. Indeed, the Xlinks Morocco-UK Power Project [63] aims to connect a solar and wind energy facility in Morocco's Guelmim Oued Noun region to the UK energy grid by 3,800 km HVDC sub-sea cables by 2030.

An excellent potential for electricity generation by solar and wind power, large unused tracts of land, and existing energy trade partnerships for fossil fuels make North African countries ideal export partners for procuring electricity from sustainable sources. HECAP has a record of successful collaboration between nations and could thus be an important player in making this happen. Hence, importing renewable energy should be considered as part of a catalogue of solutions to cover our future energy needs. One possible scenario for the import of solar energy is detailed in the Case Study 3.2 below.

While the import of energy is a promising solution on the technical and economic level, constructing wind or solar farms, e.g., in the sun belts of Africa to then export the power to Europe involves geopolitical and social considerations. Resource and person-power extraction from Africa to the benefit of Europe and America has a long and damnable colonial history. Therefore, it is of utmost importance to make fair power trade agreements between the continents that ensure strong integration into local communities and include the local population in the planning and implementation of such projects and related infrastructure. In this way, a win-win situation for all stakeholders should be ensured. Moreover, well planned cooperation has the potential to act in a geopolitically stabilizing way in line with the 16th and 17th UN SDGs.

Case Study 3.1: Local solar power at CERN

In-house solar power production is not sufficient to cover the full needs of a huge laboratory such as CERN. Nevertheless, it can make up an important contribution to foster a fast transition to renewables.[a] Research centres are often characterised by the many flat rooftops. These roofs make excellent locations for installing photovoltaic (PV) panels.

Using publicly available tools provided by the Canton of Geneva [65] and the Swiss Federal Department of Energy (BFE) [66], it is possible to estimate the solar potential of these rooftops. Similar public tools are now available for most countries, provided by local governments or non-governmental organizations (NGOs). Figure 3.2 shows part of the main CERN site as taken from the Geneva solar cadastre [65]. Buildings in red are classified as "optimal" for their orientation towards the sun. The large rectangular building in the middle is assembly hall 157. The cadastre lists an estimate of 392 MWh per annum of electricity generation for the south-west half of this 2,055 m^2 roof, with the other part capable of producing an additional 335 MWh per annum. CERN has 653 buildings with a total roof area of 421,000 m^2,[b] which amounts to approximately 80 GWh annual electricity generation potential. A comparison with the electricity consumption in 2019 of 428 GWh [8], 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.

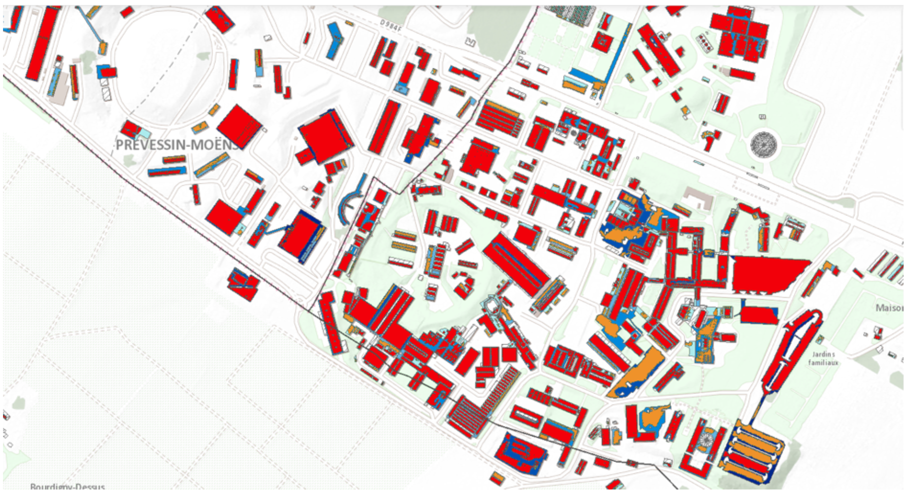

Figure 3.2: Map of CERN buildings. Roofs that are suitable for PV installation in respect to their received solar irradiation are shown in red (very suitable) and yellow (suitable). In addition other areas like e.g., parking lots could also be covered by PV-panelled roofs. From Ref. [65].

Using the cadastre, the cost for electricity from rooftop PV for CERN can be estimated to be fixed around at 50 €/MWh for the next 30 years. This cost is well below current wholesale market spot prices in France (>120 EUR/MWh), but also below the average price over summer 2021 (> 70 EUR/MWh) [67].

[a] For a discussion on potential future energy system configurations for Switzerland, see Ref. [64].

[b]This number does not include areas that are otherwise assigned, e.g., parking spaces for personal vehicles, which can also be roofed with PV panels.

Case Study 3.2: CERN-LINK — Clean power from the desert

The HECAP community, CERN in particular, has a long history of effective cooperation across geographical and socio-political boundaries, in the pursuit of science. CERN brought scientists from East and West together during the Cold War, and Arabic and Israeli people together for the Synchrotron-Light for Experimental Science and Applications in the Middle East (SESAME) project, the first accelerator laboratory powered by solar energy from the desert [68]. This makes CERN ideally placed to spearhead a project to import solar energy from the deserts of North Africa. This type of spin-off could help cover CERN's energy needs, while also reinforcing the idea that fundamental research has the potential to solve problems outside its immediate purview in new and innovative ways.

Figure 3.3: Potential CERN-LINK cable (in blue) connecting North African solar power plants with the European electricity grid. Also shown are existing power lines (purple, red, dashed blue), gas and oil pipelines (green/yellow) and PV plants (yellow/red dots). Base map taken from Ref. [69] and annotated.

A scenario for connecting, e.g., Morocco, Algeria or Tunisia to Southern France, Spain or Italy by sub-sea cable is plausible from a technological point of view (for a detailed feasibility study see [70]), and could be employed for HECAP applications (see Figure 3.3. Costs are estimated to be around 0.06–0.07 € kWh for a year-round power supply of 3.6 GW in the daytime and 2.2 GW at night [61, 62]. This estimate includes infrastructure costs for generating the electricity, buffer storage and transmission line costs. Feasibility and cost estimates agree well with those for previously proposed commercial projects [71].

Electricity imports on this scale would exceed the power needs of CERN, and surplus power could be returned to the European electricity grid to power other research institutions and universities that join the initiative. Southern France is well-suited to the role of import terminal for electricity due to its pre-existing grid infrastructure, as well as its proximity to CERN and other major research institutions.

It is important to acknowledge that additional environmental considerations are required when planning and implementing a project such as CERN-Link, in terms of minimising the impacts on local ecosystems, as well as the marine environments across which the underwater cables would be installed.

Case Study 3.3: Filling the energy gap with nuclear reactors

A typical nuclear reactor produces on the order of 1 $\mathrm{GW_{el}}$. This corresponds according to the "substitution method" used in Figure 3.1 to 2.5 GW primary energy.[a] According to the IAEA, nuclear reactors have a median construction time of 93 months [76], not including planning and permissions. Filling the entire global energy gap using nuclear power would require $\sim 8,800$ additional nuclear power plants within 18 years, which corresponds to building and commissioning an average of 9 new nuclear power plants every week in that period. A community like HECAP, with experience in planning and implementing large projects, knows that such a huge technological conversion in such a short time represents a significant challenge, especially in the absence of a global road map for such a transition.

[a] The substitution method accounts in a simplified way for the inefficiencies in energy usage and conversions of different primary energy sources, and assumes that electricity is 2.5 times as useful as fossil fuels of the same energy content. The factor 2.5 comes from the 40 % efficiency in fossil power plants [74] and is consistent with comparing the numbers in Ref. [75].

3.2 Energy Saving and Recuperation

A first step in reducing energy usage is energy monitoring, which will allow us to assess where we need to implement improvements. The best energy saving measures will be individual to each location and facility, making it hard to recommend specific actions here. While insulating buildings, and ensuring that the heating/ cooling systems are maximally efficient are universally applicable measures, these are often the direct purview of the institution, and difficult to influence directly.

The lion's share of energy budget for an high-energy experimental group is almost certainly due to the accelerators and detectors themselves. Initiatives to reduce their energy use are many and varied, relevant references for detectors are collected in Section 6. A particularly impressive example of energy-efficient accelerator design is CBETA [77], based in Cornell. This accelerator saves energy, both by recovering the energy of the bunched particles to accelerate the next batch, and by using permanent magnets to guide the particle beam.

To do

More details on energy saving and recuperation for HECAP community. See Best Practices 3.1 and 3.2.

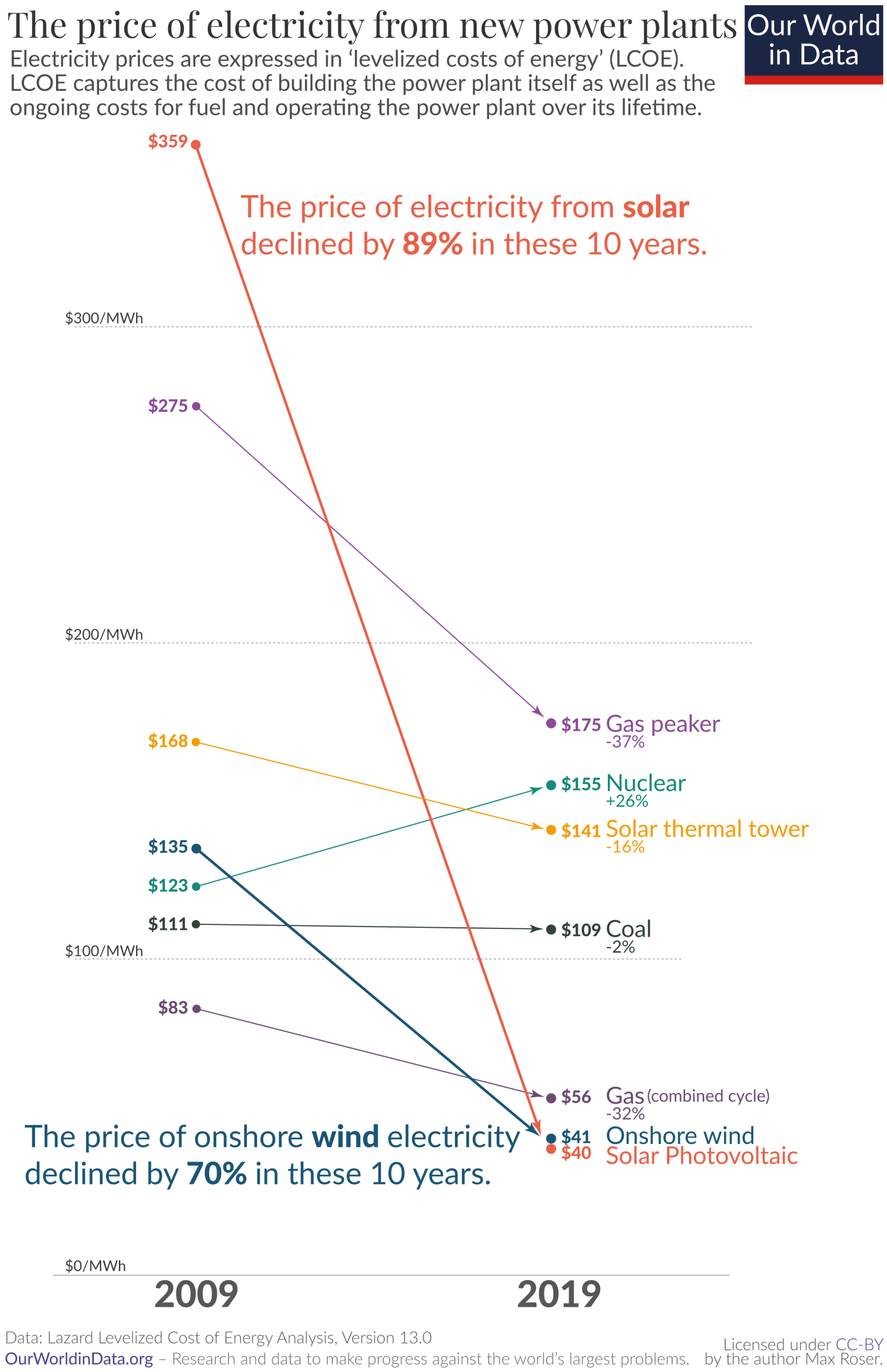

Figure 3.4: The levelised costs of energy for nuclear power has been rising in the last 10 years. The costs for renewable energy dropped drastically due to steeply falling learning curves. While prices for wind power declined by 70 %, prices of photovoltaics dropped by a factor of 10. Figure taken from Ref. [72], using data from Ref. [73].

Best Practice 3.1: Recycling Energy at DESY

For existing experiments, where minimizing energy usage was not a factor in the design process, it is still possible to save energy retroactively through recycling of energy/heat. DESY is currently using the waste heat that 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 [78]. 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 it should be sufficient to heat all buildings on campus in this way.

Best Practice 3.2: Nikhef renovation and sustainability plan

Nikhef is the national institute for high-energy physics in the Netherlands. It is both a consortium of universities and an institution with a building in Amsterdam. The total CO_2 footprint of Nikhef was 1,082 tCO_2e in 2019,[a] three quarters of which is due to flying to conferences and labs, and 15 % is due to heating the building with natural gas [13]. The building is undergoing a major renovation in 2021–2023, which will remove the need of gas for heating. Instead, the heat from the nearby data centre will be used, in addition to better thermal insulation of the building. More generally, however, renovations of buildings dating from last century quickly pay off in energy bills and have a positive impact on the climate.

The Nikhef sustainability roadmap [13] 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.

4 Food

Food choice is a significant contributor to an individual's carbon footprint (see Figure 1.4) [14]. Moreover, food production contributes over a quarter of global carbon emissions [79] (see Figure 4.1) and has further negative impacts on the environment through land use, freshwater use, terrestrial acidification and eutrophication[6] (see Figure 4.2). Food waste accounts for 6 % of total global GHG emissions [80], three times the emissions due to aviation [81].

Shifting consumption away from animal products [82, 83], particularly factory-farmed beef and towards a more plant-based diet significantly reduces GHG output. Beef, for example, gives rise to twice the emissions per gram of protein compared to its nearest contender (see Figure 4.3). Eating less meat, and beef in particular, is among the most significant changes anyone can immediately make in their personal lives on their GHG emissions [84]. The difference in emissions between animal and plant-based sources is significantly larger than emissions variability between different farms, providers [82], or the contribution due to transportation of food products, which accounts for 6% of food-related emissions.

A global shift to plant-based diets would bring us significantly closer to our goal of limiting warming to 1.5°C. More precisely, "... shifts in global food production to plant-based diets by 2050 could lead to sequestration ... equivalent to 99–163 % of the CO_2 emissions budget consistent with a 66% chance of limiting warming to 1.5°C." [85]. Furthermore, it has been argued that this target cannot be met even if fossil fuel emissions were immediately halted without "ambitious changes to food systems" [86].

However, the food we eat is a deeply personal choice, which is loaded with much cultural and social significance. As such, it is important to acknowledge that changing our food culture will be a gradual process and will not have a 'one size fits all' solution. Even so, the HECAP community must move to reduce the consumption of animal-derived food products and minimise food waste.

[6] The concentration of plant nutrients in natural water systems, sometimes due to fertiliser run-off, giving rise to a decreased capacity to support larger underwater animals.

Recommendations — Food

Individual actions. Urgently reduce consumption of animal products, especially beef, and move towards a more plant-based diet.

Group actions. Prioritise plant-based options in conference catering, minimise food-related waste, and communicate the reasoning behind these choices with participants.

- Orient conference catering towards including more, and more varied, plant-based options, particularly in buffets.
- Clearly label available food items with environmental impact to enable participants to make informed choices.
- Decrease plate size to minimise food waste in buffet settings.
- Provide reusable cutlery and crockery where possible.

Institutional actions. Food service establishments should encourage and incentivise the consumption of more plant-based products, inform their clientele of the environmental impact of their food choices, and minimise food-related waste.

- Increase variety and quality of plant-based food options.
- Clearly label available food items with environmental impact to empower consumers to make informed choices.
- Optimise food service layout to highlight food options with lower environmental impact (plant products front and centre, animal products options further from the entrance).
- Price food items in a way that reflects their true (unsubsidised), or environmental cost.
- Provide multiple portion sizes to minimise food waste.
- Provide reusable take-away containers for food and coffee and incentivise their use (e.g., via significant discounts).
- Prioritise industrial composting of compostable waste and take-away containers.

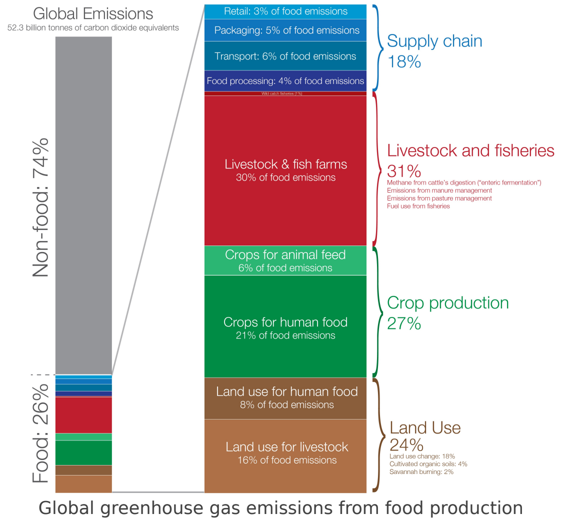

Figure 4.1: The graph shows the GHG emissions from the food sector and categorises it into emissions from livestock and fisheries, crop production (used directly for human consumption and used as livestock feed), land use, and the supply chain. Figure reproduced from Ref. [81], based on data from Ref. [82].

4.1 Agriculture

Anthropogenic climate change can be broadly divided into greenhouse gas (GHG) emissions (carbon dioxide, methane, nitrous oxide, water vapour, and ozone), land use, freshwater depletion, eutrophication of water bodies with excess nutrients, and acidification.

In the agriculture sector, 53% of emissions come from animal agriculture (from land use, livestock and fish farms, and crops for animal feed), 29% come from crops raised directly for human consumption, and 18% emissions come from a combination of retail, packaging, transport and food processing. Hence, just at the level of direct emissions, animal agriculture contributes around twice the emissions of plant cultivation for direct human consumption [81–83]. Moreover, out of the total habitable land on our planet, around 38.5% is used for animal agriculture, causing intensive and extensive deforestation (leading to more erratic weather conditions), and habitat destruction. On the other hand, only 11.5% of the total habitable land is used for human-edible crop production. Despite this breakdown in the use of habitable land, animal-derived foods contribute to only 18% of global calorie supply and only 37% of global protein supply [81–83]. Organic and local, animal-derived foods often have higher yields of GHG emissions [87]. This is partly because the livestock take longer to grow to an equivalent size.

Agriculture is responsible for 70% of global freshwater withdrawals. By 2025, two-thirds of our world's population may face water shortages [88]. Eutrophication is another important marker for climate change, which has played the part in previous mass extinctions [89]. 78% of the global contribution to eutrophication comes from agriculture [81–83]. The impact of agriculture on our biodiversity is also staggering. Of the total land animal biomass distribution on earth, wildlife contributes to only 4–6%, humans to 36% and livestock animals to 60%, causing a massive imbalance [90] in biodiversity.

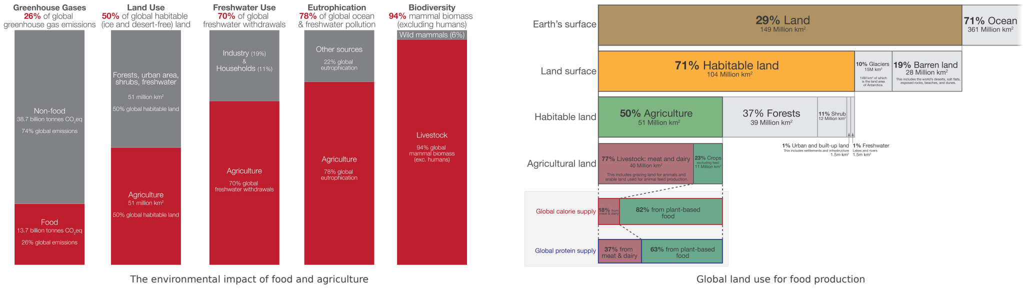

Figure 4.2: The graph on the left shows the effect of agriculture on GHG emissions, land use, freshwater use, eutrophication, and biodiversity. The graph on the right explains how much of the habitable land is used for agriculture and how much of it is used for livestock versus plant (directly for humans) agriculture. It further shows the contribution to protein and calorie intake contributed by both kinds of farming. Figures reproduced from Ref. [81], based on data from [82].

4.2 Food, Health and Inclusivity

Environmental impacts aside, the meat industry also influences the medical outcome of disease outbreaks in humans, through over-use of antibiotics in animal agriculture. Antibiotics are used to prevent common diseases and enhance growth in livestock. These are then consumed indirectly by humans as part of their daily diet [91]. Antimicrobial resistance [92] and resulting 'superbug' infections claimed 1.2 million human lives in 2019, and will be responsible for taking up to an estimated 10 million human lives by 2050, if unchecked [93].

Animal agriculture is potentially a major risk factor for the emergence of new zoonotic diseases [94–96]. Moreover, as shown in a recent systematic review and meta-analysis of several studies including over 1.4 million adults in total, food choices have a significant impact on the development and progress of coronary diseases [97]. According to the analysis an intake of 50 grams/day or more of processed meat (bacon, ham, sausages) can increase the risk of coronary diseases by 18%. Unprocessed meat can raise this risk by 9% [97].

In addition, a move toward plant-based diets is beneficial from the perspective of inclusivity towards people with religious and other dietary restrictions. In fact, many religions have fasting traditions in which practitioners are expected to abstain from meat/animal products for a time. Moreover, plant-based alternatives offer a viable option for people with certain dietary restrictions, such as lactose intolerance.

Case Study 4.1: CERN Restaurant 1

CERN Restaurant 1 (R1) serves an average of 2,000 meals per day [98]. It offers five hot meal options daily, and has recently overhauled its menu options to include a larger variety of vegetarian and plant-based options, including at least one plant-based main course. We assume each of the five mains are chosen with equal likelihood, neglecting the cold food options, such as the salad bar and sandwiches.

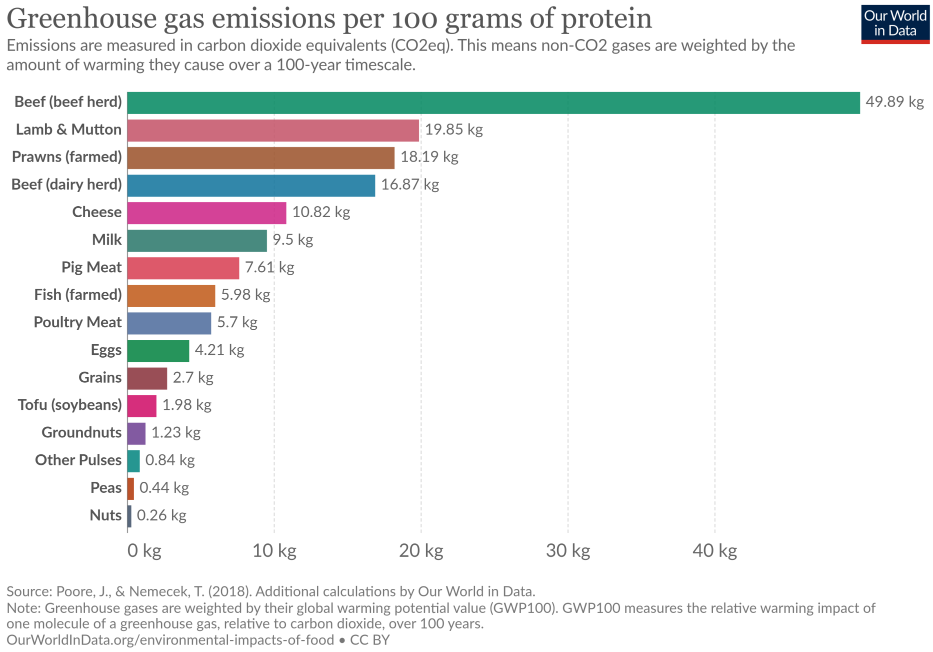

Figure 4.3: Greenhouse gas emissions in CO_2e per 100 g of protein. Figure reproduced from Ref. [81], based on data from [82].

On the week beginning June 27, 2022, e.g., beef, fish and seafood were each served thrice as the primary component of the meal, veal once, poultry five times and fish twice. We assume that these distributions are representative of a typical weekly menu at R1 and that the beef originated from beef-herd cows. The GHG emissions of the various forms of protein are shown in Figure 4.3, reproduced from Our World in Data, with data sourced from Ref. [82].

Substituting each gram of protein from beef with a gram of protein from chicken or fish reduces emissions by 440 g CO_2e. Assuming a serving contains 20 g of protein,[a] substituting all beef meals at R1 with farmed fish or chicken would result in a reduction of its annual carbon footprint by 528 tCO_2e.[b] This corresponds to approximately 260 return flights between London and New York. This number overshoots CERN's 2019 beef-related emissions quoted by the CERN Environmental Group [99] by a factor of 2.[c] The emissions savings would be even larger if plant-based substitutions were made.

Instituting one weekly meat-free day (taking as a benchmark a day where one beef, one fish and one poultry meal was served, and replacing them with one tofu-based meal and two pulse-based meals) would result in a reduction of 735 tCO_2e annually (where the bulk of the savings comes from the beef replacement).

[a] The Mayo Clinic recommends 15–30 g of protein per meal.

[b] Substituting 1,200 beef meals weekly over 50 weeks, each meal consisting of 20 g protein with chicken or fish $= 1,200 \times 50 \times 20 \times 0.440$ kg CO_2eemissions.

[c] The reason for this discrepancy is unclear, since details of their calculation were not shared.

Best Practice 4.1: Plant-Based (Vegan) Catering at Conferences and Workshops

The conference 'Women in Physics 2019' [100] at McGill University in Montréal was designed as a 'sustainable' conference. Ecologically friendly choices were made by offering purely plant-based catering, sustainable goodie bags, and use of reusable tableware. Most of the feedback regarding these measures was positive. An important point for the organisers was to advertise the catering as sustainable, and not only as vegan, since according to their experience this 'helped the way the catering was received' by the participants. The organisers mentioned that it can be difficult to find a vegan caterer if the only choices are partners of the university hosting the conference, but it was nevertheless possible in their case.

The school and workshop 'YRISW (Young Researchers Integrability School and Workshop) 2019: A modern primer for 2D CFT' [101] in Vienna offered only plant-based catering. The organisers of the school selected this option as the "most inclusive approach", where people are not separated according to their eating habits". They wanted to advertise vegan food to the participants, and "reduce the environmental impact of the event". The choice of food options also reduced the total cost of the catering. The organisers obtained positive feedback, not only for the food itself but also for the "effort to reduce the ecological impact of the school". The organisers emphasised the importance of finding a specialist vegan caterer to ensure the quality and flavour of the food.[a]

[a]We thank Hannah Wakeling (for WIP 2019) and Stefan Fredenhagen (for YRISW 2019) for sharing their experience as part of the respective organizational teams.

4.3 Canteens and Conference Catering

Several universities and other institutes for higher education [102–105] have already implemented measures to limit, or even eliminate, animal-derived foods, and to price food products according to their environmental impact wherever possible (with plant-based meals cheaper to purchase than animal-derived ones). Cambridge University [104] and Goldsmiths University [105] have banned red meat from their cafeterias. See Case Study 4.1 for a study of the estimated emissions savings that would result if CERN R1 were to replace beef with poultry, fish or plant-based protein.

It has also been shown that conference catering could be made entirely vegan, with no decrease in participant satisfaction. Successful examples are YRISW 2019 in Vienna [101] and WIPC/FEPC 2019 in Montreal [100] (see Case Study 4.1). Conference catering organisers can also present a rough estimate of the carbon dioxide equivalent of every meal, to make consumers aware of their choices [87]. Moreover, traffic light labelling systems, showing red (i.e., the topmost of three lights to make the label readable for colourblind people) for high GHG emissions, yellow for numbers in the middle, and green for the lowest emissions (see, e.g., Ref. [106]). Allowing registrants to choose their diet/meals in advance also makes it possible to reduce waste.

Fair-trade and organic coffees are those with the smallest climate impact, having about one third of the carbon footprint of conventional coffee [107], which should motivate to offer more or only products with these certificates. For some of the drinks containing coffee, the highest climate impact comes from the dairy products used. Using non-dairy substitutes reduces the emissions again by a factor of three. (There may be a preference for different plant-based milks: Ref. [108].)

The use of single-serving plastic containers at conferences and in canteens has a significant impact on waste. Sometimes there are ways to change to reusable containers for take away meals and coffee, like "recup" in Germany [109], which has recently been introduced into the DESY canteen, or offering fully compostable cups in the US in areas where curbside composting is available. If these are not available, offering fewer single-serving containers automatically motivates people to bring their own, most often reusable containers, which reduces waste immediately.

In some countries (e.g., France), disposing of food that is still good for consumption just because the expiration date is reached has already been banned. Instead, the leftover food is mandated to be given to food banks or other charities. Canteens could volunteer to do that for leftover food that is still fit for human consumption.

4.4 Catering Tableware

A life-cycle analysis by the UN Environment Programme concludes that “reusable tableware consistently outperforms single-use tableware in all the studies and across all environmental impact categories (with water use being the exception, because of washing). This type of analysis takes into account all the variables that affect the environmental impact of a product, from manufacturing to end-of-life treatment. The case for reusable tableware is strengthened in countries where renewable energy makes up a high proportion of the grid mix and where end-of-life treatment options are not well developed” [110].

In outdoor or remote environments or ‘pop-up’ events with no fixed catering facilities, where reusable tableware is impractical, single-use biodegradable tableware is preferable to other single-use tableware if it is industrially composted mixed in with food waste [110].[7]

Unlike emissions due to reusables, which are dominated by their use phase due to repeated washing, the main impact of biodegradable tableware is due to its production. For conventional plastic, a significant role is also played by end-of-life management. Quantitative analysis of their relative emissions are thus strongly dependent on assumptions about manufacture and disposal, including the material demand. On the practical side, to minimise this impact when planning conference catering one should always choose the lightest-weight disposable tableware fit for purpose, preferably manufactured in a country with a significant proportion of renewables in its energy and electricity mix.

Case Study 4.2: Conference catering tableware

[7] Industrial composting of household food waste is currently not the norm in most geographical locations within the USA [111], and many existing industrial composters do not accept biodegradable plastic waste [112].

Quantifying the environmental impact of single-use tableware is not simply a matter of providing a single number for its carbon footprint, as it has a significant impact across all environmental factors, including acidification, eutrophication, human health, land use and water depletion. For the purposes of this case study, however, we will focus on its climate sustainability, as the most urgent issue facing us today, and the one with the most reliable and robust indicators for decision making.

We will consider for benchmarking purposes a large-scale conference with 1,000 attendees and informal lunchtime catering (i.e., with no dishwashing capability), and compare the life-cycle emissions due to tableware made from conventional plastics, which are disposed of by a combination of incineration and landfill according to the European average (presumed food remnants making them unsuitable for recycling), and biodegradable bioplastics, which are industrially composted along with the food remnants.

We assume each set of tableware consists of a dinner plate and cup, a knife and fork, and a paper napkin and tray mat, all manufactured to the same size and thickness, but may differ in weight due to their respective material densities. A full list of assumptions and details of the analysis can be found in the original article [113].

The total emissions for 1,000 sets of conventional polystyrene tableware is 221 kg CO_2e, as compared with 109 kg CO_2e for the biodegradable bioplastic tableware, a saving of 112 kg CO_2e, around the emissions of a flight from Paris to Geneva. Note that much of the comparative advantage of the bioplastics comes from their end-of-life treatment; their production is significantly more resource-intensive than conventional plastic tableware.

It is difficult to compare these figures to those for reusable tableware, since reliable, peer-reviewed studies that allow quantitative comparison between all three types of tableware are hard to come by. For the purposes of comparison, however, we include here the emissions cost of 1,000 dishes and cups from a 2015 study by Italian plastics company Pro.mo [114]. They put the total emissions due to reusables at 26 kg CO_2e, with the emissions due to conventional plastic dishes and cups (polypropylene in this case) at 79 kg CO_2e.[a]

Note that these figures are specific to the electricity and energy mix of the European market, which has a large impact on the dominant emissions in all cases: for production in the case of bioplastics, production and incineration for conventional plastics, and washing for reusables.

[a]We do not quote their estimate for bioplastics, since they do not consider the composting of bioplastics, but rather assume they are disposed of by incineration and landfill, in a similar way to conventional plastics.

5 Sustainability Projects

To do

The aim of this section is to give examples of how our communities' expertise has been and can be applied to problems in climate and environmental science, and to sustainability projects.

6 Technology

Another aspect of sustainability of HECAP are the the experiments and accelerators themselves and their impact from cradle to grave. This is recognised in the European Strategy for Particle Physics [115]. It divides the topic into three aspects: Energy efficient technologies, Energy efficient accelerator concepts and General sustainability aspects. The first two focus on the biggest impact of accelerators: the energy consumption during their operation. One on the very direct technological level, the other one on the development of new accelerating concepts with smaller energy requirements. These topics are discussed more in depth in other sections of the Strategy. The third one broadens the view to an overall sustainability beyond energy:

> "A carbon footprint analysis in the design phase of a new facility can help to optimize energy consumption for construction and operation. For cooling purposes accelerator facilities typically have significant water consumption. Cooling systems can be optimized to minimize the impact on the environment. For the construction of a facility environment-friendly materials should be identified and used preferably. The mining of certain materials, in particular rare earths, takes place in some countries under precarious conditions. It is desirable to introduce and comply with certification of the sources of such materials for industrial applications, including the construction of accelerators. A thoughtful life-cycle management of components will minimize waste."

Recommendations — Technology

Individual actions. Make a critical assessment of the environmental impact of materials, construction and the operational lifecycle an integral part of the design phase for all new infrastructure. Be proactive in seeking out new innovations and best practice.

Group actions. Focus on environmental sustainability in all aspects of the design and operational phases of projects, through engagement with industrial partners who exemplify best practice and sustainable approaches. This may include appointing a dedicated sustainability officer to oversee this focus.

Institutional actions. Ensure that sustainability is a requirement in design and operation at all stages, from initial proposals, design reports, review and approval processes, and the setting of standards.

- Require risk analysis for new developments, which includes not only safety but also environmental sustainability.
- Provide designers and operators with easy to use tools to see if an improvement is also a financial advantage.
- Reward innovations that minimize or eliminate environmental impacts, not just those that reduce costs.
- Establish an exchange with initiatives and other institutes, which includes the designers, operators and decision-makers of projects, setups and infrastructure.
- Propagate the transfer of knowledge between groups and the expansion of knowledge of technical staff.

6.1 Life-Cycle Assessment

The methodology of a life-cycle assessment can be used to analyse the resources used to build, run and decommission an accelerator or experiment and the respective emissions. The ISO-Standards ISO 14040 and ISO 14044 are made to provide a standardised procedure for the analysis. Depending on the goal and scope of the analysis, the life-cycle inventory comprises the quantification of all input and output flows. This includes raw materials, consumables, energy, products, waste, emissions, discharges to water and soil contamination.

Such calculations to estimate a variety of impacts have been attempted by at least two facilities:

- The European Southern Observatory (ESO) [116]

- The GRAND Project, a multi-decade astrophysics experiment [117] — This led to a full issue of the Nature Astronomy Journal on climate change [118].

There are online tools and auditing agencies who provide help with the analysis. As an example for the quantification of material, the analysis of a 1 cm^2 silicon wafer (thickness = 775 μm, diameter = 300 mm, weight = 0.128 kg) as identified in 2000 is given in Tables 6.1 and 6.2 [119]:

Table 6.1: Inputs & Outputs of silicon wafer production. [119]

Inputs	Quantity	Outputs	Quantity
Hydrogen chloride HCl (hydrochloric acid)	0.00675 kg	Co-products: Si in other co-products	0.000286 kg
Graphite (as electrode material)	0.000163 kg	Co-products: Silicon tetrachloride	0.00415 kg
Wood chips	0.00183 kg	Co-products: Si residues for solar cells	65.2×10-6 kg
Petroleum coke	0.000597 kg	Polished silicon wafer	1 cm2
Quartz	0.00487 kg		
Electricity	0.385 kWh		
Dry wood	0.00398 kg		

Table 6.2: Emissions of silicon wafer production. [119]

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

6.2 Initiatives

In addition to the general recommendations made above, we list a number of references below with further information, inspiration and support for the challenges of improving sustainability in the development and operation of research technology:

- The International Committee for Future Accelerators (ICFA) has the specific panel "Sustainable Accelerators and Colliders" [120]
- Every 2 years since 2011, the ESSRI workshop is taking place: Energy for

Sustainable Science at Research Infrastructures [121]. The sixth workshop is planned for September 2022.

- Innovation Fostering in Accelerator Science and Technology (I.FAST) [122] is an EU-project in which the "WP 11 – Sustainable concepts and technologies" is aimed to increase sustainability. The current participating institutes are CERN, DESY in Germany, ESS in Sweden, GSI Helmholtz Centre for Heavy Ion Research in Germany, PSI in Switzerland and STFC in the United Kingdom.
- Energy Recovery Linacs, such as the Powerful Energy Recovery Linac for Experiments (PERLE) [123], which provides an electron beam of approximately 1 GeV energy, and the Cornell-BNL ERL Test Accelerator (CBETA) [124].

To do

Subsection on the use of gases in detectors and cooling systems.

7 Travel

Transport accounted for almost a fifth of total global emissions in 2016 [125], and is the sector that saw the highest growth in pre-COVID years. Demand for car, rail and air transport is expected to continue to increase over time, with increasing global population and income levels.

Unsurprisingly walking and cycling are the most carbon-efficient means of transportation, with train travel next best for distances beyond where the former are practicable. A quantitative comparison between these and other alternatives requires the specification of further details, such as distance travelled, fuel efficiency of the vehicle and the number of passengers carried, and the underlying electricity mix for the country of travel. In the UK for instance, driving alone in a medium-sized petrol-fuelled car yields smaller GHG emissions than air travel for distances shorter than 1000 km, whereas flying in economy class beats driving over longer distances [126] (data taken from [127]).[8] For a detailed comparison of GHG emissions of various forms of transport within France, see Table 7.2.

Passenger transport constitutes a significant portion of the emissions of a HECAP researcher (see Figure 1.3), including short daily commutes between the home and the workplace and longer distance business travel. When and how we travel are not always free choices, being constrained to some degree by existing transport infrastructure, local geography, our research, finances and family responsibilities. Universities and HECAP institutions, with their large and progressive workforce, can help tip the balance in favour of the more environmentally sustainable option with a judicious combination of policy, incentives, on-site infrastructure and advocacy, as detailed below.

[8] These estimates include a 'radiative forcing' factor of 1.9 for air travel, which account for the larger warming effect due to aeroplanes emitting GHGs high in the atmosphere.

Recommendations — Travel

Individual actions. Choose environmentally sustainable modes of transport for necessary and discretionary travel, amalgamating trips where possible.

Group actions. Consider and facilitate alternatives to in-person attendance that minimise travel emissions and diversify participation, including hybrid, virtual or local hub formats.

- For hybrid or virtual events facilitate engagement and interaction by using the appropriate software, equipment and infrastructure.
- For regular in-person conferences, consider making every *n*-th occurrence virtual.
- Merge conferences with overlap in attendees and consider travel emissions when selecting conference location.

Institutional actions. Where travel is necessary, encourage, incentivise and enable students, staff and visitors to travel by more environmentally sustainable means, and despite potentially higher costs. Advocate for better regional sustainable transport infrastructure.

- Provide bicycle-friendly infrastructure, such as covered, secure bike parking and on-site showers.
- Subsidise costs of public transport for work commutes and disincentivise the use of private cars for commuting where viable alternatives exist.
- Where public transport is sparse, provide shuttle services for daily commutes, encourage and facilitate car pooling, and provide on-site charging stations for electric vehicles.
- Push campus travel agents to include multi-modal travel options in their route searches, especially for international travel.
- Refrain from using extent of travel as an indication of quality in hiring decisions.
- Implement carbon budgets for discretionary business travel (with exceptions for early-career researchers), using carbon offsetting only as a last resort.

7.1 Commuting

Typically, changes in commuting patterns are affected by life circumstances, including changes in education, employment and residence [128]. The viability of the enironmentally sustainable mobility, like walking, cycling and taking the train, depends crucially on characteristics of the home and workplace locations, including the distance between them, and their local environment. These properties are seen to influence the relative importance of commuting and business emissions for different HECAP institutions.

For example, CERN, Fermilab, and ETH Zürich have wildly different CO_2 emission profiles due to personal transportation. While emissions due to commuting were roughly equal to those for business travel at Fermilab, commuting outweighed business travel for CERN, and conversely, business travel swamped commuting emissions for ETH. This reflects the unique environment and characteristics of each these research centres.

ETH is located in an urban centre and is well connected to the local public transport. In 2008 only 1,700 tCO_2e were recorded for commuting, with 7.5 to 10 times larger emissions attributable to business travel (using numbers from 2006–2012). It is unclear if the commuter emissions include only the ca. 10,000 employees, or also ca. 20,000 students, but regardless the emissions per capital are significantly smaller than those for Fermilab or CERN.

The latter two have more rural settings, with a 77 % majority of CERN employees commuting by car from France. Fermilab's commuter emissions [129] of about 6,000 tCO_2e are approximately on par with business travel emissions,[9] whilst CERN quotes 5,836 tCO_2e of commuter emissions compared to 3,330 tCO_2e business travel emissions for its approximate 4,000 staff members. The small amount of travel emissions compared to emissions from commuting reflects to some extent the status of CERN as scientific centre, where it is expected for other members of the community to travel to and where travel is easier to avoid, also because the experiments are located at CERN. Whilst ETH, Fermilab and CERN face different boundary conditions, all three of them, and HECAP institutions in general, should aim to reduce emissions from commuting, even if these contribute to their overall budget to a different degree.

This reduction requires an interplay of institutional and individual actions: while institutions cannot force employees to more environmentally sustainable commuting habits, they can incentivise them through various measures, from the availability of bicycle-friendly infrastructure such as showers and secured/covered parking to financial incentives for greener transportation. They can also allow employees avoid long commutes by formalising telecommuting options, which have become more normalised since the start of the COVID-19 pandemic, and use their standing to push local authorities towards better public transit/cycling/carpool infrastructure. Individuals and groups can, on the other hand, push for these actions at the institutional

[9] In a typical year, Fermilab's approximately 1,900 staff members commute an average distance of 15.6 miles each way mostly by car. This translates into 5,987 tonnes of CO_2 when assuming 250 working days per years and using 404 g of CO_2 per mile as per US Environmental Protection Agency [79]. This is only 5 % less than Fermilab's emissions from air travel, calculated from 8.2 million (or 42 %) fewer miles flown in 2020 using 200 g per air km [130].

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 also 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. Requires a subscription of more than 6 months and once suspended, a cooling-off period of 9 months is required in order to be eligible for re-subscription (problematic if employee is posted abroad for a few months).
Fermilab	Shuttle service to and from Chicago Metra trains for all employees	Only works at specific times (e.g., two connections in the morning and two in the afternoon). Connects to the Metra station with the slower trains.
France	Public transit subsidy or 200 €/year for all employees who cycle or carpool	Honors system for the 200 €/year. The roughly 50 % reimbursement on public transport subscription is very helpful, though its adoption 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). This is independent of the means of transport and also applies to cyclists or pedestrians, but is more advantageous for people with longer commutes who are less likely to use eco-friendly means of transport.
University of Sheffield	Bike to work scheme for all employees	Possibility to borrow an e-bike (or a bike) for free for 2 months in order to test commuting by bike. Ability to rent bikes throughout the semester and to buy re-conditioned bikes. Over 1,400 cycle parking spaces available throughout campus and at the residences. Service to provide free bike checks and at-cost servicing and repairs for staff and students funded by the university. (All UK universities.) Financial help 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.)

Table 7.1: Institutional/country-wide measures to encourage sustainable commuting amongst employees. This is a non-exhaustive list; similar initiatives are also offered by other employers.

level. Table 7.1 collects some means by which ETH, Fermilab and other academic and HECAP institutes promote 'green' transport. An estimate of the emissions per distance of different forms of transport in France is presented in Table 7.2.

	Vehicle	emissions (g CO_2e/km)	Fractional uncertainty (±)
Personal transit	bicycle	5.0	0.7
	electric bicycle	10.9	0.5
	electric scooter	24.9	0.5
	electric car	103.4	0.7
	hybrid car	182.8	0.7
	motorbike	202.8	0.6
	diesel-powered car	209.6	0.6
	gasoline-powered car	240.1	0.6
Mass transit	subway	3.5	0.2
	tramway > 250,000 inhabitants	4.0	0.6
	commuter rail (RER/transilien)	5.1	0.2
	tramway =< 250,000 inhabitants	5.7	0.6
	rail (< 200 km)	18.0	0.6
	bus >250,000 inhabitants	135	0.6
	bus 100,000–250,000 inhabitants	146	0.6
	bus <100,000 inhabitants	156	0.6

Table 7.2: 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. [131] — see, in particular, Ref. [132] — and assumes the electricity comes from the French grid, which is a factor of 10 less carbon-intensive than other countries [133]. Public-transit figures are per-person.

7.2 Business Travel

A global scientific endeavour such as HECAP will mandate some amount of long-distance travel, e.g. to experimental sites, or to build close working relationships. However the current academic culture which rewards hyper-mobility is neither environmentally sustainable, nor equitable to all scientists. Visa rules and prohibitive long-haul travel costs can make participation in conferences extremely challenging, especially for researchers from the Global South. Moreover, the freedom to travel can be heavily restricted for people with disabilities, health impairments or caring responsibilities. For example, the burden of childcare is still unequally distributed, and this burden falls predominately on female shoulders [134].

Emissions from commercial aviation is a long-recognised problem, contributing 2.5% of CO_2 emissions and 3.5% of 'effective radiative forcing' (a closer measure of aviation's impact on warming as explained above) [135] in 2018 (see Figure 7.1). Note that the majority of these emissions derive from the one-tenth of the world's population that can afford air travel. Almost all HECAP scientists belong to the 4% of the population taking international flights, and many fall within the 1% classified as the most frequent flyers [136]. These statistics highlight the inequalities inherent in travel emissions generally.

More troubling is that global aviation statistics belie the significance of business travel emissions for many HECAP researchers, which are comparable to, and in some cases even dwarf, their direct and indirect emissions (see Figure 1.3). This is clearly in tension with the push to net zero emissions, particularly given we do not expect the aviation sector to decarbonise at the same rate as the rest of the transport sector.

Emissions related to conference travel have been studied in detail and dominate conference-related emissions [137, 138], contributing annual emissions equivalent to the total annual transportation emissions for Geneva (800 kilotonnes CO_2). However, the CO_2 emissions for a single conference trip amount to about 7% of an average individual's total CO_2 emissions. This might be even worse for HECAP researchers, for whom frequent trips to experimental sites and meeting venues to undertake international collaborations are common.

Discussions about curbing business travel are highly charged, as active engagement with other members of the scientific community is integral to scientific practice. Any changes that we make to HECAP travel culture have to be considered in the context of other aspects of our working practices, such as hiring decisions, where any curbs on travel may disproportionately impact early career researchers. At the same time, the reprioritisation of business travel and a move toward a greater share of virtual/hybrid formats can have a positive impact both on the climate and on inclusivity.

For necessary travel, sustainable alternatives to air travel should be prioritised where possible, keeping in mind that the increased travel time and costs of sustainable travel as compared with air travel could make this choice difficult for researchers with caregiving responsibilities, or limited travel budgets. In case study Case Study 7.1, we compare emissions, travel time and cost of different modes of travel to CERN, from various starting points within Europe, for CMS week in January 2022. HECAP institutions and funding bodies are beginning to implement more sustainable travel policies, including travel top-ups for green travel; we highlight two examples in Best Practice 7.2 and Best Practice 7.1.

If the community is to rethink this travel culture and move toward more hybrid/virtual modes of engagement, we must recognise that these require additional planning to maximise engagement, which amounts to much more than streaming the in-person event format. It is also important to appreciate that virtual participation requires an internet-ready device and stable connection, and devices with which to connect, which may not be universally available in lower income countries. A possible remedy for this might be the concept of hub conferences, where the conference has several locations spread globally (e.g., Ref. [139]). In Case Study 7.2 we study travel emissions and participation in the context of the last 5 ICHEP conferences, and assess the reduction in emissions from optimising the conference location, moving to a hub model, or hybrid/virtual forms of attendance.

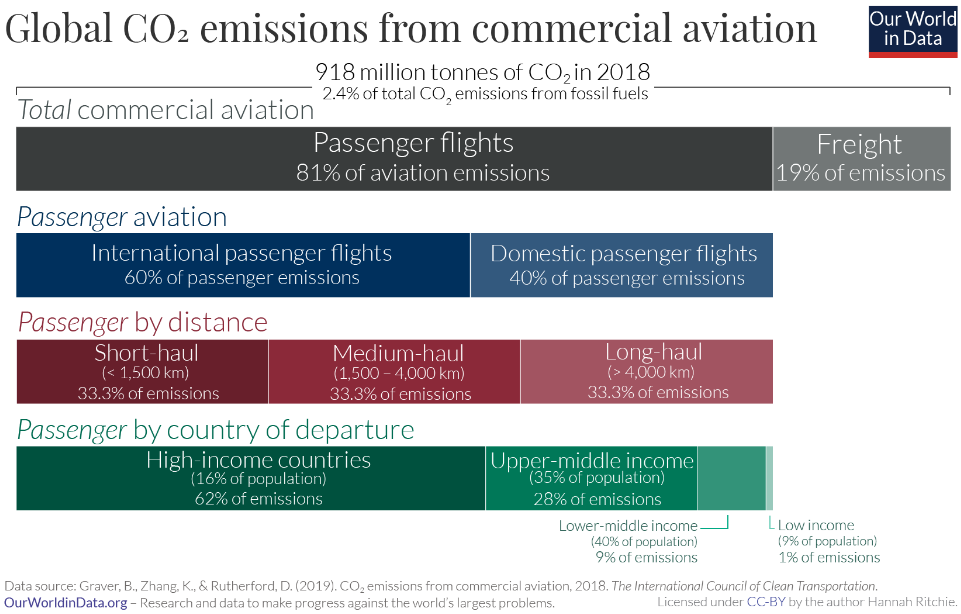

Figure 7.1: Global CO_2 emissions from commercial aviation, reproduced from Our World in Data [140], based on data from Ref. [141].

Case Study 7.1: Travel to CERN

The itineraries in Table 7.3 were found for travel to CERN for, e.g., CMS week, 24th–28th January 2022, as found on 30th November 2021[a]. Although emissions were significantly smaller for rail travel as compared with travel by car or air, as expected, this must be weighed against the increased travel time, and in many cases, cost, of rail travel. Note that the air travel times are underestimated as they do not include travel to the airports which are usually distant from the city centres, or the usual buffer time required for check-in and security formalities. For itineraries that include sleeper trains, the additional cost of the train could offset a night's hotel accommodation at origin or destination.

[a]Prices and carbon footprint rounded to nearest whole number. For prices not given in euros, currency conversions were made using Google currency converter. Carbon footprints for one-way travel were calculated using Ref. [142] and then doubled, using all default assumptions, except for toggling on the climate factor for flights. Precise departure and arrival information was not used for calculation of the flight footprint. Since some airports are not included as possible destinations, the footprint was calculated from the central train station in the origin city to the central train station in the destination city, and the footprint of travel to the airport is assumed negligible (in comparison to the flight). Train fares quoted are for the most convenient train journeys from the central station in the origin city to the central station at the destination. For longer journeys, preference was given to itineraries with overnight trains to maximise efficiency per euro spent, assuming savings on an additional night in a hotel. For all overnight trains, quoted prices include reservation in shared sleeper cabin. Female-only occupancy can be specified. Note that in many cases there may be a limited number of 'super saver' tickets that are available for purchase ahead of time. Air fares were for the 'best' option available on Skyscanner [143], with inbound flight arriving in time for an assumed midday start of meetings at CERN, and outbound flight departing after 15:00 hours on Friday. Flight prices were taken directly from the airline where possible, and include a standard-sized cabin bag, but not necessarily a checked bag. Durations include flight time only and do not include airport check-in times.

Table 7.3: Comparison of modes of travel to CERN from different origins.

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
> 1200 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

Case Study 7.2: Comparative study of travel carbon footprint for ICHEP conferences (2012–2020)

Based on the study of the annual meetings of the American Geophysical Union (AGU) in Ref. [130] and the methodology and software tools employed therein, we undertake a survey of the past five editions of the International Conference for High Energy Physics (ICHEP) with the aim of assessing the GHG emissions of conference travel to ICHEP, as well as the (geographical) diversity of participants.

ICHEP is a biannual conference with a large and steadily growing participation, of order 1000 researchers, and a location that alternates mainly between Europe, America and Asia. We study the 5 most recent instances, with locations in Melbourne, Australia (2012), Valencia, Spain (2014), Chicago, United States, (2016), Seoul, Korea (2018) and Prague, Czech Republic (2020, fully virtual). At the time of writing the 2022 conference, to be held in Bologna, had not yet begun.

Methodology Participant details were taken from the Indico conference system registration pages [144]. The departure location for each participant was assumed to be the city of their affiliation, save for cases where it was clear that the participant was based in Geneva, as is often the case for members of LHC collaborations. Direct travel to and from the conference was assumed. Distances were calculated as the great circle distance using coordinates obtained with Nominatim from the OpenStreet Map data base. Rail, car or bus travel was assumed for all journeys with distances of less than 400 km, with air travel assumed for longer distances. 'Short-haul' was defined as travel distances of less than 1500 km; distances up to 8000 km are 'long-haul' and longer distance still were classified as 'super long-haul'.

Table 7.4: Total number of participants of recent ICHEP conferences and the GHG emissions per participant The corresponding numbers for the AGU Fall Meeting[130] are shown for reference.

	AGU Fall Meeting 2019	ICHEP Melbourne 2012	ICHEP Valencia 2014	ICHEP Chicago 2016	ICHEP Seoul 2018	ICHEP Prague 2020 (virtual)
Number of participants	24009	764	966	1120	1178	2877
GHG emissions per participant [kg CO_2e]	2883	8432	1902	2699	2648	0

Table 7.4 shows the average GHG emissions per participant for the ICHEP editions alongside those for the 2019 AGU Fall Meeting for reference. With the exception of the 2012 Melbourne edition of ICHEP, the per capita emissions were significantly lower for ICHEP, which is a "travelling" conference, as compared with the stationary AGU Meeting, which always takes place in San Francisco. This indicates that moving a conference series between continents naturally reduces the travel-related emissions as participants tend to wait for the conference to be held near them to make the trip. Comparing the geographical distribution of home insti-

tutes for each conference reinforces this conclusion. Note that ICHEP Melbourne (2012) was the first and only ICHEP conference taking place in Oceania.

The emissions for two typical ICHEP conferences, one in Europe (Valencia) and the other further removed, in Asia (Seoul) are displayed as a function of travel distance in Figure 7.2 below. Due to the remote nature of the conference location, a large fraction of attendees at the Seoul conference had to fly super-long-haul to get there, giving rise to the majority of the emissions. Emissions for the remaining half of the attendees was nearly negligible. This was not the case for Valencia, where as many attendees travelled short haul travel or less. It is also clear that the bulk of the emissions is due to long-haul or super-long-haul air travel.

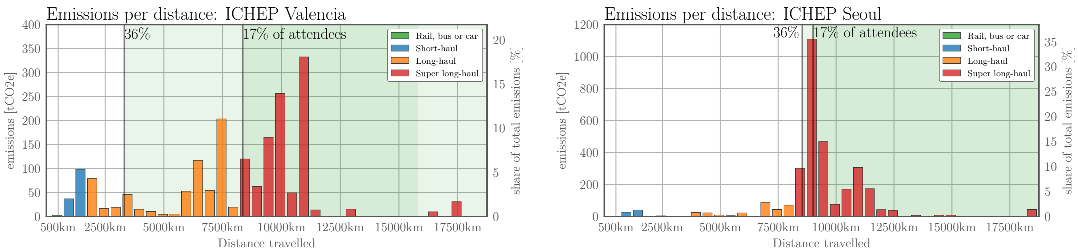

Figure 7.2: Emissions per distance for the different ICHEP editions shown in tCO_2e (left axis) and as share of the total emissions. Additionally, the emissions caused by the 17 % and 36 % participants furthest away are shaded in green.

Reference [130] investigated possible optimizations of the conference location for the given participant distribution in order to reduce emissions.[a] Note this is a slightly artificial construction because of the basin of attraction phenomenon discussed above, where participant distribution is self-selecting, based on the conference location. Unlike the AGU example, where moving the conference location to the middle of the country, rather than on a coast, significantly decreased the travel-related emissions, we found that the ICHEP locations were already pre-optimised, and further optimisation yielded at most a 10.2 % reduction of GHG emissions. (The real outlier again was Melbourne, where the majority of participants had to fly super long-haul, and for which a 70.7 % reduction would be achievable given the same participants by changing the location). If instead we optimised the location using participants from all 5 ICHEPs, the optimal location would be close to Amsterdam.

Further emissions reductions are only possible with a hub-based conference, and mandatory virtual participation above a certain distance from the hubs. Ref. [130] trialled hubs in Chicago, Seoul and Paris, with virtual attendance for all participants with origins greater than 2000 km from the hubs. Having found that Chicago, Seoul and Paris were not far from the optimal locations for the respective ICHEP conferences, we did the same, for the total ICHEP participation over the 5 conferences. Simply using a 3-hub model can reduce the carbon footprint of the conference to around 15–35 % of a traditional one. Adding compulsory virtual participation for more distant participants reduces the carbon footprint further by 5–15 % of a traditional conference with 10–25 % of the participants attending virtually. As a test case, and without any prior optimization, we chose Rio de Janeiro, Johannesburg, and Kolkata as alternative hubs. This, however, increased virtual participation to

95 %, mainly due to the strong European participation in HEP and the remoteness of Johannesburg from Western Europe. Switching Paris for Johannesburg reduced the footprint to about 10 % of the nominal one, with 40% of participants attending virtually. While the virtual fraction is still relatively high, it might be acceptable in a bid to include more remote HEP communities (like Melbourne) while keeping the emissions low.

Finally, one might expect a fully virtual conference to be more inclusive then in-person ones, especially for underserved participants, such as those with care-giving responsibilities, limited travel funding, or visa problems. We studied this by classifying participants by the human development index (HDI) [145] of their country of affiliation, and dividing them into four categories (low, medium, high and very high HDI[b] The share of participants in these categories for each of the ICHEP conferences is shown in Figure 7.3. Indeed, in addition to enjoying the largest number of participants (by a factor of 2) the virtual ICHEP in Prague had the largest proportion of participants from countries with high or medium human development index, although it was not clear how much of this increase was due to its virtual nature, as opposed to a steady increase in physics participation from high and medium-HDI countries. There was virtually no participation from low HDI countries in any of the ICHEP conferences studied.

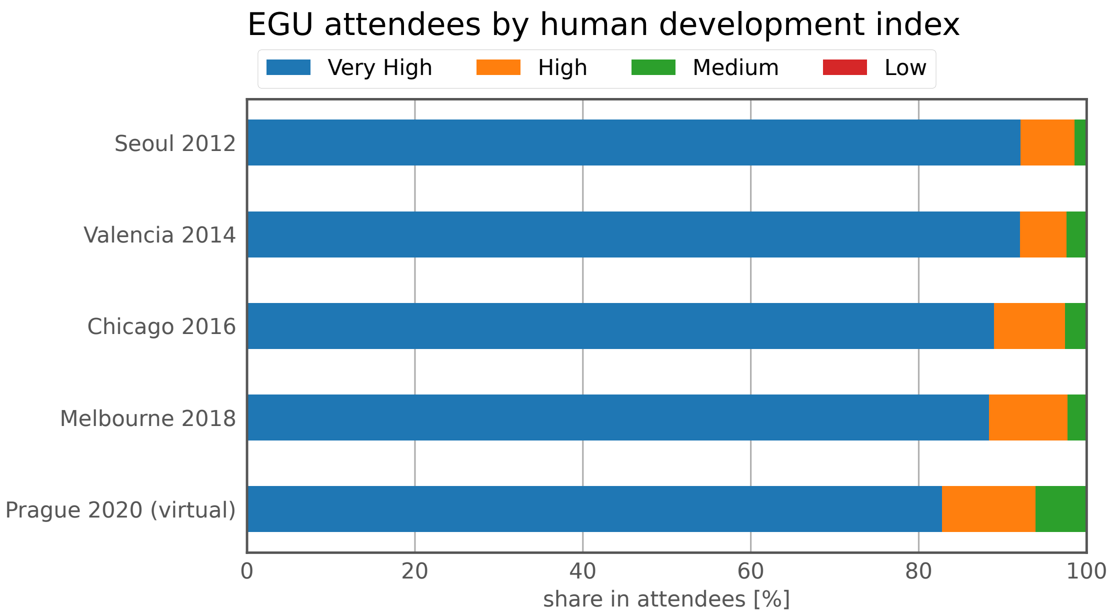

Figure 7.3: The fraction of participants, categorised by human development index, HDI [145] attending the last 5 instances of ICHEP.

[a]Optimizations were carried out with a grid spacing, and hence resolution, of 1 degree longitude and latitude

[b]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. [145].

Best Practice 7.1: Green travel top-ups on Erasmus+

The EU mobility and training programme Erasmus+ has implemented funding top-ups for environmentally sustainable travel, which is more costly than point-to-point air travel in many instances, in particular between hubs for low-cost airline. See Table 7.5 for exact supplements for participants who receive travel funding, as excerpted from the 2022 programme guide [146]). Moreover green travel over large distances can be more time-consuming. The programme allows for this by providing travel support for an additional 4 days of travel.

Table 7.5: Green travel supplements for Erasmus+ participants receiving travel support. [146]

Travel distance (km)	Standard travel (EUR/participant)	Green travel (EUR/participant)
10 - 99	23	
100 - 499	180	210
500 - 1999	275	320
2000 - 2999	360	410
3000 - 3999	530	610
4000 - 7999	820	
>8000	1500	

Best Practice 7.2: Internal regulations to reduce the impact of business travel at DESY

The regulations at DESY have been based on the goal of preserving the excellence of science and career opportunities while reacting to the necessity to save CO_2 and other emissions. With its directive for business trips adopted in 2021, DESY relies on the climate policy principle Avoid - Reduce - Compensate.

Avoid: The number of business trips will be reduced by 30 % compared to the situation before the start of the COVID-19 pandemic. This means that all travel planning is reviewed to identify whether the trip is needed to achieve the intended purpose, whether a virtual meeting could be just as beneficial, whether rotational changes between presence and digital are possible, and whether and how appointments can be bundled. In addition to CO_2 savings and travel time, it should also be considered how much of the time spent traveling and for travel planning can actually be used as working time, and what costs are incurred or saved. Ultimately, digital meetings also contribute to a better flexibility of family and work life. They also reduce travel-related risks.

Reduce: For some time now, it has already been possible to use the train instead of the plane, even if the costs were higher. With the new directive, the use of the train is now mandatory if the destination can be reached within six hours total travel time. It should also be noted that the usable working time during the trip for rail travel is given as at least 50 % of the travel time (depending on the transfer frequency) and for flying it is assumed to be about 25 % of the travel time.

Compensate: Until recently, compensation was not possible under the Federal Travel Expenses Act. However, since September 2020, there is a new regulation on the reimbursement policy for carbon offsets from the German ministry of science, whereby also grant recipients like DESY are allowed to offset their CO_2 emissions for business trips. Starting in 2021, DESY will compensate the consequences of unavoidable air travel. There are established systems through which the climate-damaging effects of travel can be offset. The money goes to climate protection projects, including energy efficiency, biogas or biomass, solar energy, and environmental education. The selection of the compensation projects can be steered by DESY.

8 Waste and Resources

The generation of waste is a direct consequence of material consumption and is aggravated by inefficiencies in the various stages of production, distribution, usage and disposal or recycling of consumables. The generation of unnecessary waste products has severe impacts on life on the land and sea, often destabilizing local ecosystems and contributing to climate change indirectly resulting in a destabilization of the global ecosystem. Accumulations and inefficient disposal of waste products also directly affects the health of individuals and communities, when ground water and air are polluted with toxic agents, leading to a large cost in terms of lives lost and disease burden on society. In an attempt to curb the footprints left by the generation of waste, the concept of a circular economy has been proposed [147]. This, however, does not maximise the reduction of waste, since, even a fully circular economy has some dissipation, and signatures of this energy waste need to be addressed separately and reduced [148–150].

Around 3% of global GHG emissions is due to solid waste disposal, the organic component of which decomposes in wastewater and landfills, producing methane and nitrous oxide [151]. The amount of waste landfilled in the EU has dropped by 60% in the last two decades, partly due to an increased legislative focus on alternative treatment methods such as recycling and composting, and partly due to more widespread landfill gas recovery [152].

A growing proportion of our waste output is e-waste, powered products with electrical components that are discarded into the waste stream, particularly after being illegally shipped to developing countries without the infrastructure for safe recycling [153, 154]. In addition to releasing hazardous chemicals into the environment, improperly treated e-waste contributes to global warming through failure to recuperate valuable mined materials, and direct release of GHGs including refrigerants (see Figure 8.1 for statistics on global E-waste generation and disposal in 2019). Exploding demand for digital devices, fuelled by their fast obsolescence and difficulty to repair has also given rise to a boom in the mining industry and consequently the economy in resource-rich countries, where working conditions are usually unsafe and unpleasant, causing deforestation and pollution [154].

While the generation of waste products is universal, discussions specific to the HECAP communities are provided below.

Recommendations — Waste and Resources

Individual actions. Reduce, reuse and recycle on a day-to-day basis.

Group actions. Reduce waste in the management of group consumables, as per the recommendations for institutions below.

Minimise waste generated in conference events and avoid single-use plastics.

- Keep any conference gifts digital e.g., e-vouchers/discounts for local restaurants or activities. Distribute sustainable stationary on a need-only basis.
- Make banners, posters and nametags plastic-free and reusable, and share leftover resources with future events.
- Prioritise catering with reusable, washable tableware. For outdoor events with informal catering, use biodegradable tableware with industrial composting of waste.
- Provide alternatives to printed timetables and welcome packs, e.g., by making use of a well-designed conference app (see, e.g., Whova[155]).

Institutional actions. Critically assess waste generation and management for the design, operation and decommissioning of infrastructure projects.

Institute sustainable purchasing, usage and end-of-life policies for materials, and electrical and electronic equipment, including reuse/reclaiming of materials, recycling, or donation where viable.

- Prioritise the purchase of equipment with replaceable parts.
- Provide an institutional pool of infrequently-used equipment to avoid redundancy in purchasing.
- Set appropriate collection and recycling targets.
- Provide a forum where personnel can list unwanted items for reuse within the institution.
- Decrease the size of mixed waste bins, and increase the size, availability and prominence of recycle bins.

8.1 Reduce, Reuse, Recycle

In order to determine the optimal path for reducing the waste generated by the academic community, one has to first understand the scope of what waste means for different subfields. From there one can identify the sources of waste generation, especially when consumption can be a driver for waste. After making such identifications concrete actions can be defined for reduction of consumption, reduction of waste by re-use and recycling of the waste generated. Once these policies have been developed institutions and departments can be approached with these tailored recommendations, which can then be implemented.

The waste produced through the activities of HECAP research can be classified into the following three categories, based on the duration of their use, which can help in building strategies for reducing them through policy decisions:

- Short-term and regular use
  - Paper: journal articles, official documents, circulars and newsletters, books
  - Plastics: stationary, organizational aids (clips, binders, folders)
  - Essential consumables: food, chemicals
  - Energy: buildings, transportation, computation, running facilities
- Short-term and irregular use
  - Conference gifts
  - Conference supplies
  - Allied footprints of conferences, workshops and meetings
- Long-term use
  - Waste generated during the construction, operation and decommissioning/dismantling of infrastructure, i.e., experimental facilities.
  - Electronic waste: computers, tablets etc.
  - Furniture

To do

Further discussion of each of the above, their impact and potential strategies to reduce, reuse, recycle.

Best Practice 8.1: Plastic-free 2019 conference of the Australian Marine Sciences Association

Taken from Ref. [156]

In response to the growing problem of plastic pollution, the Australian Marine Sciences Association undertook to make their 2019 conference 100% plastic free. Concrete measures they implemented for their O(600) delegates included:

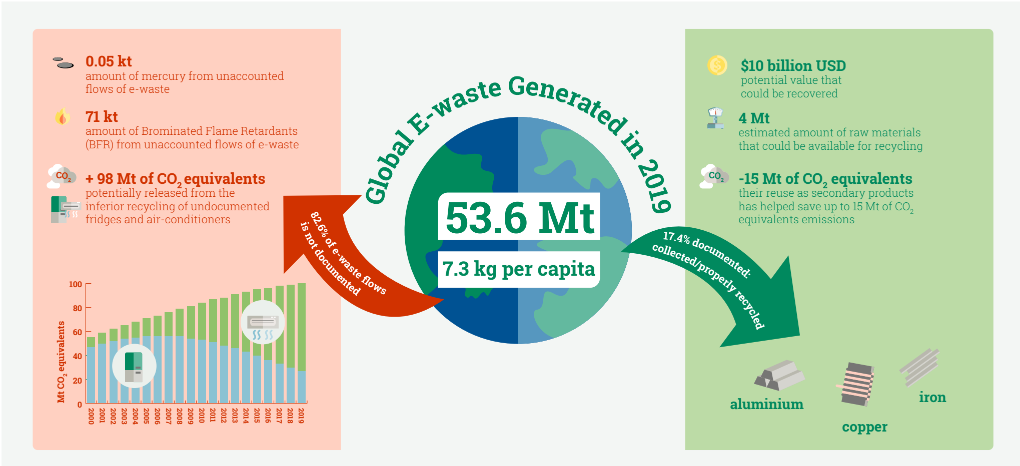

Figure 8.1: The generation of global e-waste in 2019. About 82.6% of e-waste goes undocumented highlighting the importance of recycling of e-waste. Source: Global E-waste Monitor 2020.

- plastic-free cardboard name badges with bamboo lanyards and metal clips
- fabric tote bags give-aways with conference logo
- no printed envelopes for registration packs, no printed conference abstracts
- any printing necessary was done on sustainably-sourced paper, using a solar-powered printer
- sustainably-sourced pencils instead of pens, with sharpening stations provided
- no packaged sweets
- delegates were asked to bring reusable water bottles, or pre-register to buy them at the conference
- water jugs with glassware provided at back of each presentation room
- reusable, washable plates, cups silverware and glassware for all meal and coffee breaks
- vegetarian catering for tea breaks

These measures were implemented without affecting the budget, although some solutions reportedly took a fair amount of planning and forethought, and clear communication with the event organizer and providers.

To do

Discussion of plastic waste, including microplastic polution.

8.2 Resources

To do

Discussion of sustainable sourcing of raw materials.

Acknowledgments

This initiative was conceived at the workshop “Sustainable HEP”, which was organised by Niklas Beisert, Valerie Domcke, Astrid Eichhorn and Kai Schmitz, and hosted by CERN and held online 28 to 30 June 2021.

The authors thank Micah Buuck, Astrid Eichhorn, Stefan Fredenhagen, Paul Laycock, Salvatore Rappoccio and Jan Rybizki for invaluable input.

The authors thank Jessie Muir (https://www.jessiemuir.com/, https://orcid.org/0000-0002-7579-770X) for producing the individual, group and institution icons for the recommendations.

To do

Include estimate of the CO_2 emissions from the writing of this document, based on hours on zoom, hours editing on Google docs, overleaf etc., number of websites opened.search engine searches and screen time on our laptops.

A Supplementary data for Figure 1.3

Tables **??** contain the raw data that was used to produce Figure 1.3. Each set of data was taken from a publicly-available environmental report issued by (members of) the institution in question; the original documents are referenced below.

Our approach differs from existing estimates of the GHG footprint per researcher in the divisor used to compute this quantity. We shared the emissions per resource equally by the total number using that resource, whether it be total number of employees, or research staff, or in the case of large laboratories like CERN, the number of Users, rather than using the same divisor throughout. For instance, while we divide the commuting emissions for each institute by the total number of employees, we assign the business travel emissions solely to the research staff, assuming the support staff have negligible long-distance travel. For concreteness we have colour-coded the per-researcher estimates in Table A.1 by the denominators used in their computation, with the colour key provided in Table A.2.

Sector	Emissions (tCO_2e)							
	CERN		MPIA		ETHZ DPHYS		Nikhef	
	Institute	Researcher	Institute	Researcher	Institute	Researcher	Institute	Researcher
Scope 1 (direct)	78,169	4.4	446	1.4	0	0	150	0.7
Scope 2 (indirect)	10,672	2.0	779	2.4	570[a]	0.9	0	0
Travel (business)	3,330	1.0	1,280	8.5	1,449	3.2	785	3.3
Travel (commuting)	5,836	1.1	139	0.9	1,700	0.2	146	0.7
Food	738	0.2	16	0.1				
Computers, supplies			64	0.4	497	0.3		
Waste treatment	2,194	0.5						
Total	100,939	9.2	2,724	13.3	4,216	4.6	1,082	4.8

CERN data for 2019 taken from [8–10], MPIA data for 2019 from [11], ETH data from 2018 taken from [12], Nikhef data from 2019 from [13].

Table A.1: Average annual GHG emissions (tCO_2e) for researchers at various HECAP institutions, by sector. Colour-coding corresponds to key below for staff type that was used in the divisor to compute the emissions per researcher.

[a]This corresponds to the total ETHZ Scope 2 emissions rescaled by the ratio of DPHYS employees to total ETHZ employees.

Employee type	CERN	MPIA	ETHZ DPHYS	Nikhef
Total staff	5,235	320	630	350
Research staff	3,430	150	450	350
Users	17,663			

Table A.2: Institute employee statistics, color-coded by type. The same color codes are used in the researcher numbers above to show which staff statistics were used as the divisor in each case.

To do

Add more details on what emissions contributions are included in each estimate.

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Acronyms and Abbreviations

ALLEA All European Academics. 12

BFE Swiss Federal Department of Energy. 35

CERN European Organization for Nuclear Research. 7

CO_2e CO_2 equivalent. 7, 26

CPU Central Processing Unit. 24

CSCS Swiss National Supercomputing Centre. 27

DC Data Centre. 26

ETH Zürich Eidgenössische Technische Hochschule Zürich. 7

FCC Future Circular Collider. 12

GHG Green House Gas. 7

GPU Graphics Processing Unit. 24

HEP High Energy Physics. 24

HL-LHC High-Luminosity Large Hadron Collider. 21

HPC High Performance Computing. 21

HTC High-throughput Computing. 21

IAEA International Atomic Energy Agency. 33, 37

IPCC Intergovernmental Panel on Climate Change. 7

IRIS-HEP Institute for Research and Innovation in Software for High Energy Physics. 24

LHC Large Hadron Collider. 21

MPIA Max Planck Institute for Astronomy. 7

NGO Non-government Organization. 35

PCC CERN Prévessin site Data Centre. 26

PUE Power Usage Effectiveness. 26

PV Photovoltaic (Panel). 35

QCD Quantum Chromodynamics. 21

SDG Sustainable Development Goal(s). 15

SESAME Synchrotron-Light for Experimental Science and Applications in the Middle East. 36

tCO_2 metric tonne CO_2. 12

UHVDC Ultra High Voltage Direct Current. 34

UN United Nations. 8

WLCG Worldwide Large Hadron Collider Computing Grid. 24

Best Practices

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Figures

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