European Commission

Marie Skłodowska-Curie Actions Green Charter

Guidance Material for researchers and research managers

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Introduction

The Marie Skłodowska-Curie Actions (MSCA) fund bottom-up research in all fields of science and across disciplines, based on scientific excellence and competitive funding. The programme supports the careers, skills development, and international mobility of researchers at all stages of their careers, with a strong focus on the development of excellent doctoral and post-doctoral research and training programmes. It is open to both academic and non-academic organisations and to researchers from all over the world.

The European Commission is committed to tackling climate, environmental and biodiversity challenges, in line with the EU Green Deal[1], the United Nation's 2030 Agenda[2] and the Sustainable Development Goals[3]. As an organisation, the European Commission is also determined to act as a front-runner in the transition towards a climate neutral society, by setting out an ambitious and realistic plan to achieve climate neutrality by 2030[4].

In light of the role of the MSCA programme supporting the future generations of researchers at the highest level, the MSCA Green Charter lays down a set of non-binding guiding principles that promotes the mainstreaming of environmental considerations in all aspects of research planning and implementation, throughout the life cycle of a project. The Charter seeks to help reduce environmental harm caused or induced by MSCA-funded projects, to raise awareness of environmental sustainability, and to serve as a catalyst in promoting sustainable practices in research.

All participants in MSCA-funded projects are encouraged to adhere to the principles of the Charter as much as they can without compromising the scientific excellence of their project, nor their freedom to choose what to investigate in a bottom-up manner.

This document contains guidance, concrete examples and other resources which can serve as a source of inspiration for researchers and research managers wishing to adopt or promote sustainable research practices aligned with the principles of the MSCA Green Charter. A separate document offers guidance targeted at research groups, organisations, and consortia. While all recommendations will not apply to all research settings or projects, these guidance documents can help our community better understand what can be done in practice to integrate environmental sustainability principles in research work.

This guidance has been elaborated thanks to the collective work of a group of stakeholders and experts coming from different parts of the research community, including representatives of researchers at different career stages, research managers, research performing and funding organisations, sustainability experts, as well as MSCA coordinators, fellows and alumni.

1 Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal (COM(2019) 640 final): https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX-:52019DC0640.

2 United Nations, 2030 Agenda for Sustainable Development: https://sdgs.un.org/2030agenda

3 United Nations. The 17 goals: https://sdgs.un.org/goals

4 Greening the European Commission: https://commission.europa.eu/about/service-standards-and-principles/modernising-european-commission/greening-european-commission_en

1. Travel, events and meetings

Mobility - through secondments, workshops, and conferences - remains central to research and career development, offering important opportunities for skill-building, knowledge exchange, and network expansion. At the same time, frequent travel and events come with an environmental impact and carbon footprint. As climate change intensifies[5], it becomes increasingly important to consider adopting sustainable approaches to travel and events and integrating environmentally conscious habits and skills into the research culture, while preserving the vibrant exchange of ideas that fuels scientific progress. Facilitating this shift involves individual researchers and project consortia exploring changes in mobility patterns and event planning, and organisations working towards embedding sustainability into their policies.

Several challenges complicate achieving a meaningful shift on this issue. These challenges can consist in lack of awareness, logistical and budgetary barriers, or individual and organisational approaches that prioritise cost and efficiency exclusively, without taking into account the environmental impact of travel or the availability of sustainable alternatives - such as rail travel, hybrid conferences, and longer research stays. At the same time, while digital collaboration offers solutions, it cannot fully replace the value of in-person engagement.

This section aims to offer researchers and research managers useful tools to make informed, climate-conscious choices when planning research related travel, events and meetings without compromising their research objectives.

Attending events: travel and mobility

Researchers attend events such as project meetings, workshops and conferences. As actors of mobility, their individual choices will impact the environmental footprint of attending one event. Yet, these choices are often limited within a framework defined by the organisation's rules. Adjusting mobility and travel policies at the organisational level can greatly facilitate green mobility for researchers.

Recommendations:

- **Consider the need for mobility**: whether within a research group or at individual level, consider adopting a GHG quota per year or per project. For each event, consider the actual need and added value of attending in-person vs online, and prioritise attendance to local events where possible. This is particularly relevant for intercontinental trips, where flying cannot be replaced by low-CO2 mobility.
  - ✓ A report by Young Academy (2020) on the flying behaviour in Dutch universities notes that academics travel for multitude of reasons, including networking, disseminating their own work, learning about new trends in their discipline and doing fieldwork. Travelling less was seen as potentially negative for their careers, especially for early career researchers who often have not yet established their networks. Tailored approach might be needed for researchers at different career phases. However, research (Kreil, 2021) suggests that opinions differ amongst academics on whether reduced academic travel negatively impacts their work.
- **Find out how to reduce CO2 emissions**: consult the existing travel policies and guidelines of your organisation, which may include travel recommendations (taking train vs plane), including policies for sustainable travel. If no such document exists, you may consult the sustainability office for guidance. As a personal initiative, you can track the CO2 emissions of your travel, as data are often provided by the travel agencies, or using tools such as Labo1point5, EcoPassenger or Greentripper. Establish a threshold under which you systematically prefer trains over planes, which can be based on duration of the trip (e.g. 6 hours) or distance (e.g. 700 km). Such threshold may already be implemented by your organisation based on governmental rules.
  - ✓ Examples of resources provided by organisations and other useful tools:
    - ✓ A train map, by the University of Twente
    - ✓ A travel decision tree, by the University of Groningen
    - ✓ The Travel Policy by the University of Auckland emphasises that travel needs to be essential for university's strategic objectives

    Useful tool:

    - ✓ Flying less in academia was developed by 4 partner organisations in Germany. The project itself offers comprehensive guidance from brief videos to modular lectures in a toolbox, GHG emission monitor.
- **Optimise your travel plan**: combine trips, e.g. laboratory visits, conferences and meetings within the same travel phase, as much as possible.

5 https://www.weforum.org/stories/2023/11/carbon-budget-run-out-six-years/

- **Optimise mobility**: once on location, use public transport, rent a bike or walk while staying in the city you are visiting. If you need to take a taxi, try to share the ride.
- **Collect data on your travel**: data collection - starting with the CO2 emissions of your transport mode - is the best way to have an objective vision of your impact and see how to adjust choices in the future.
- **Raise awareness**: share your experience with your colleagues, provide feedback to your organisation where possible.

Organising events

Whether it is a small project meeting or a large conference, the choices made regarding the planning and organisation of an event have an impact. The following recommendations are addressed to the people operationally organising the event, whether they are a **researcher, research manager, consortium member**, the **organisation**[6], or a team composed of all of the above.

Planning phase

- **Implement and apply Sustainable Event Guidelines**. Create or use a sustainability checklist, to ensure you cover all aspects related to sustainability.
  - See for instance: 7 steps for Greener events and Guidelines for sustainable meetings and events (European Commission)
  - You may also apply for green event certification schemes available in your country (e.g. The National Research Fund of Luxembourg uses Green Business Events. Additional examples available in Science Europe's survey report)
- **Reduce unnecessary travel by promoting online or hybrid events**: wherever possible, offer an option to join online to reduce travel while ensuring inclusivity. Consider encouraging online participation with dedicated incentives (e.g. prize for best online presentation instead of or alongside prizes for in person presentations).
- **The selection of the location**: prioritise venues easily accessible by low-carbon transport. In the context of a MSCA consortium, consider the travel options of all your attendees to decide the best locality in which to host the event. Consider sustainability as a criterion for the choice of the venue: favour places that are well insulated and avoid unnecessary heating, or which provide water fountains, etc.
- **The choice of catering**: prefer sustainable caterers that use local ingredients and propose plant-based meals. Consider choosing a vegetarian menu for your event or, at least, finding alternatives to red meat. Request to the caterer that they avoid single-use plastic, if they provide cutlery, cups and plates.
- **Avoid food waste**: work with the caterer to optimise food quantities based on attendance. Wherever possible, provide compost bins for any food waste. Ensure that untouched food can be donated or redistributed (e.g. using apps such as Too Good to Go). Secure ways of having food remain untouched, i.e. cover food containers with transparent lids/covers whenever possible so that food remains accessible to event attendees yet at least partially protected and less exposed.
- **Minimise waste**: as much as possible, avoid single use glasses, cups, plates and cutlery. Prefer tap water or returnable glass bottles over plastic. Avoid unnecessary printed materials. Reuse conference materials from previous events (e.g. stands, banners, signage).
  If you plan to offer goodies to your attendees or gifts to the speakers or organising team, choose a provider that uses recycled and/or recyclable materials, or select local edible gifts. At the end of the event, collect lanyards used for the name badges, to reuse them. Wherever disposables cannot be avoided for logistics reasons, favour recyclable and compostable items.
- **Offer guidance to your attendees**: share information about low-carbon travel, recommend hotels with environmental labels and restaurant with sustainable values, that are easily accessible by public transport. Encourage the use of public transport, for instance by purchasing passes for your attendees if funding is available.
- **Communicate your intention** to minimise the environmental impact of the event with attendees at the planning/invitation stage.
- **Estimate the likely carbon footprint** of the event at planning stage using calculators (e.g. from myclimate).

Operational phase

- Communicate with attendees to help them understand how they can adhere to the sustainability principles implemented during the event (e.g. in the welcome speech, at the welcome desk if there is one). Ensure **adequate signs are available to clearly indicate best practices**, such as clear signs on bins explaining what to throw in which; a map that indicates available water fountains, etc.
- Avoid **printed programmes**; instead, privilege an online document available with a QR code, or using

6 For more details on what can be done by organisations and consortia, see the MSCA Green Charter Guidance material for research groups, organisations and consortia

a conference app for large events. Provide a digital map of the building and eliminate paper-based surveys or evaluations.

- **Make sustainability part of the event**: invite attendees to engage in the conversation around sustainability, for instance using online live surveys during one of the sessions (e.g. Slido, Kahoot, Mentimeter, Vevox). You can ask them questions related to their own sustainable engagement while attending, what action they took to reduce the environmental impact of participating this event, what actions they can still undertake, or what they would expect from the organisers in terms of sustainability initiatives. Consider **non-material gifts** (e.g., donations, experiences) or **consumables** (e.g., drinks, food, cosmetics) to thank the organisers and speakers.

Post-event phase

- **Data collection** is key to evaluate the sustainability of your events. One simple way to do so is to send a short survey to the attendees or include sustainability questions in the satisfaction survey if one is already planned. Furthermore, collect data on waste by working with the subcontractors (caterer, venue providers) to identify weaknesses and optimise in the future.
- **Estimate the actual carbon footprint** of the event at post-event stage using calculators (see for instance this CO2 calculator).
- **Make Sustainability part of the event's Close Out**: consider proposing to attendees to engage in the conversation around sustainability using collaborative tools. Ideas for questions could be: How did you consider sustainability during this event? Did you succeed in achieving environmentally friendly practices during your participation in the event?

Training on sustainable events and mobility

While some team members may have some pre-existing notion on sustainability from their personal interests, it is unrealistic to expect everybody to be able to implement sustainable practices related to mobility and event planning.

Sustainability can be incorporated as part of the early-stage researcher's training and career development plan. Organisations may make training, tools and materials on sustainable mobility available to researchers and research managers, who often have a key role to play on the organisation of events. Researchers may also actively seek training on sustainable practices, and suggest it to their group leader, project coordinator or organisation if it is not proposed by default.

Organising and attending events: practical examples

Fictitious Story: **Organising an Event**

Peter had always seen sustainability as intrinsic to his role as event organiser, aiming to ensure gatherings leave a positive impact on people while minimising harm to the planet. When he was tasked with organising an MSCA end-of-project conference, he saw this as an opportunity to implement eco-friendly practices.

Planning Phase: Peter started by creating a comprehensive sustainability checklist. He ensured that the event followed guidelines that promoted sustainable decision-making and reduced unnecessary travel. Understanding the carbon footprint of travel, Peter made the event hybrid, encouraging online participation by offering incentives for virtual attendees. When selecting a venue, he chose a location that was easily accessible by public transport and with sustainability certifications. He collaborated with a caterer that provided plant-based meals, minimised food waste and avoided single-use plastics. He recommended hotels with environmental labels to attendees.

Operational Phase: At the registration, attendees were reminded of the sustainability objectives of the organisers and invited to be proactive about reducing and sorting waste. Instead of printed programs, Peter introduced QR codes that provided instant access to schedules. Resources and name tags were designed to be reusable. Single-use plastics were discouraged, and water stations were set up to encourage attendees to refill reusable bottles. During the opening speech, Peter reminded guests about the event's sustainability goals and encouraged them to adopt similar practices in their professional lives.

Post-Event Phase: After the event, Peter collected and analysed data on emissions generated from both in-person and virtual participation. He sought feedback from attendees on how sustainability efforts could be improved for future events, to help shape better strategies for minimising environmental impact in future gatherings.

Additional examples and resources:

- European Commission internal guidelines for sustainable meetings and events: https://green-forum.ec.europa.eu/news/guidelines-sustainable-meetings-and-events-2024-07-15_en
- Mobility guidance on Green Travel: e.g. https://www.tudelft.nl/studenten/mijn-studie-ik/onderwijs/study-abroad/before-your-stay-abroad/green-travel
- Sustainable events checklist together with a list of useful tools (such as a footprint calculator): e.g. https://www.universityofgalway.ie/sustainability/studentsresources/resources/sustainableeventchecklist/
- A comprehensive training, a toolbox and GHG monitoring tool: e.g. https://flyingless.de/en/
- Evaluate alternatives for your travel routes: e.g. https://ecopassenger.org/bin/query.exe/en?L=vs_uic
- Articles: numerous open access articles have explored the impact of reduced travel in academia, including: Kreil (2021), Does flying less harm academic work? Arguments and assumptions about reducing air travel in academia - ScienceDirect); Katz-Rosene (2023), Spiral-scaling climate action: lessons from and for the academic flying less movement; Eriksson et al (2020), On the Necessity of Flying and of not Flying | Proceedings of the 7th International Conference on ICT for Sustainability; Wenger et al (2025), Conference air travel's relevance and ways to reduce it - ScienceDirect.
- Reports: various reports provide an overview of developments in academia with respect to train travel (e.g. Flying high but flying less | De Jonge Akademie), practical tips on reducing travel and mobility by adjusting infrastructure, creating clear guidelines (e.g. Green Guide for Universities), or putting in place nudging techniques (e.g. The Little Book of Green Nudges | UNEP - UN Environment Programme).
- General sustainability training addressed to students: e.g. short videos from Ecole Polytechnique.
- Courses covering leadership, management, and research: e.g. EMBO practices and resources, including, funding for virtual meetings and encouraging hybrid events, covering additional costs and providing sustainability badges for reducing environmental impacts: How do you reduce the environmental impact of scientific meetings? – Blog – EMBO. See also "Organising an efficient hybrid meeting needs extra effort" blog post from EMBO.

Fictitious Story: **Attending and Travelling to an Event**

As Mary prepared to attend the MSCA end-of-project Conference, she set her mind on making sustainable choices at every step.

Planning Phase: Before booking her trip, Mary carefully considered whether attending in person was necessary. Since networking opportunities and hands-on workshops were crucial for her work, she decided to go but ensured she minimised her carbon footprint. She opted to take the train instead of flying, as the travel time was under six hours. She combined this trip with a nearby research visit, thereby maximising the efficiency of her travel. She selected a hotel with an environmental label and close to the venue.

Operational Phase: At the conference, Mary followed sustainable habits. She brought her reusable water bottle and coffee cup, avoiding single-use plastics. She chose plant-based meals and minimised food waste by taking only what she needed. She avoided printed materials, using digital schedules and QR codes. When she met a new acquaintance, she exchanged digital business cards rather than using printed cards. Throughout the event, Mary made a conscious effort to use public transports.

Post-Event Phase: After the conference, Mary calculated her travel emissions and compared them to previous trips. She provided feedback to the organisers, suggesting future green initiatives such as composting food waste.

2. Research practices and resource-intensive research settings

While scientific research is a driver of innovation and societal progress, research practices can rely on large amounts of energy, water, and single-use materials. The following practical recommendations can help integrating sustainability into everyday research practices, with a focus on resource-intensive research settings. Sustainability in research still being an emerging field, links are included where available to relevant open-access resources, tools and training, some of which may undergo further development as the field matures. This section also introduces concepts and frameworks such as circular economy, life cycle assessments and green chemistry.

The recommended measures can not only help to reduce the environmental impact of certain practices; several of them can also reduce costs, enhance research quality, foster collaboration and improve efficiency.

Partnering up & getting started

To embed sustainability in research, collaboration between researchers, within research groups, consortia, and organisations is essential. A culture of sustainability can be fostered through training, accessible resources, support from green teams, and formal recognition.

At an individual level, a key recommendation is to seek training opportunities and connect with local sustainability groups or networks.

Planning a research project

Sustainability principles can be applied throughout all phases of research projects, from literature review and hypothesis formulation to experimentation, analysis, collaboration and dissemination.

A key recommendation for researchers and research managers is to include sustainability in the planning phase of a research project by conducting thorough literature reviews and developing a sustainability plan with concrete action areas (notably including the recommendations in this document and related guidance materials).

Quantifying environmental footprint

Assessing the environmental footprint of research helps identify impact hotspots. While full greenhouse gas inventories or biodiversity impact assessments are complex, standard metrics (e.g., energy use, water, materials, waste) can be monitored more easily. Establishing a baseline of metrics at a project's start enables researchers to set measurable targets and evaluate progress - ideally with adequate support from their research group or organisation. Standardised reporting templates or shared spreadsheets can help compare resource use and waste across projects and organisations, enhancing transparency and best practice exchange.

Recommendations:

- Identify impact hotspots early and use footprint assessment tools where available.
- Apply principles of life cycle assessment [*see section on principles below*] when evaluating impacts.
- Use simple tools like plug-in energy monitors to track lab equipment consumption and highlight savings opportunities.
- Measure and analyse the quantity and quality of waste.

Examples and resources:

- **Toolset to quantify and mitigate carbon footprint:** (initially limited to France, European version under development) https://labos1point5.org/
- **Carbon calculator**: (under development) https://www.epfl.ch/schools/sv/school-of-life-sciences/about-us/sv-sustainability-office/co2-calculator/
- **Waste assessment**: https://www.embopress.org/doi/full/10.1038/s44319-024-00360-x
- **Life cycle assessment of malaria trial**: https://journals.plos.org/sustainabilitytransformation/article?id=10.1371/journal.pstr.0000131
- **University-wide carbon footprint highlighting labs**: https://ethz.ch/en/the-eth-zurich/sustainability/facts-and-figures.html#treibhausgase
- **Biodiversity footprint**: https://www.nature.com/articles/d41586-022-01034-1

Reducing the environmental footprint of resource-intensive research activities

The following non-exhaustive list of measures aims to inspire immediate action to reduce the environmental impact of research activities, with a focus on resource-intensive research settings.

Recommendations:

- Turn off or hibernate non-essential instruments when not in use.
- Use cold storage efficiently (e.g., -70 instead of -80C, defrosting, cleaning filters, and removing expired samples).
- Reduce hazardous chemicals by using safer alternatives.
- Downscale experiments where possible and appropriate.
- Close fume hoods when not in use to reduce energy demand.
- Share data and use open-access platforms to reduce redundancy.
- Reduce, reuse and recycle lab consumables wherever possible.
- Consider replacing continuous water cooling with air-cooled condensers or closed-loop systems and minimise usage of laboratory-grade water (e.g. distilled, deionized, ultra-pure).
- Ensure that HVAC and vacuum systems are regularly serviced.
- Use affordable plug-in power meters or smart monitors on lab equipment like freezers, centrifuges, and incubators provide real-time consumption data, to identify overconsuming devices and justify upgrades.

Examples and resources:

- **Metering, purchasing, operations guide**: https://www.ucl.ac.uk/sustainable/sites/sustainable/files/sustainable_lab_equipment_guide_-_metering_purchasing_operations.pdf
- **Plastic recycling**: https://greenlabsaustria.at/recycling-lab-plastic/
- **Single use vs glass calculator**: https://apps.labos1point5.org/ecolabware
- **Cold storage**: https://www.kcl.ac.uk/assets/policyzone/estates/cold-storage-management-sop.pdf
- **Solvent eco-impact metric for chemists:** https://pubs.acs.org/doi/10.1021/acs.oprd.4c00546#:~:text=This%20metric%20leverages%20a%20comprehensive,and%20guide%20sustainable%20development%20initiatives.

Going further: definitions, principles, metrics and frameworks for sustainable research practices

The following definitions, principles, metrics and frameworks can help researchers and research managers understand more deeply how to implement sustainable research practices in their work.

Environmental footprint

- **Carbon footprint** (CO_2-equivalents): summarises all greenhouse gas emissions from energy use (electricity, heating), production of materials, and any transport or refrigeration.
- **Biodiversity footprint**: estimates direct and indirect upstream and downstream impacts on biodiversity losses associated with activities.

Standard metrics

- **Energy consumption**: monitoring the electricity or fuel used by major equipment (such as freezers, centrifuges, and fume hoods). Recording energy use per experiment highlights high-consumption devices and potential savings (for example, by switching to more efficient models or optimising usage patterns).
- **Water usage**: measures direct water use (e.g. in baths or equipment cooling) and the embedded water in reagents (especially ultrapure water). By evaluating water usage and conservation (such as reusing rinsing water or closed-loop systems), teams can reduce demand for water resources.
- **Material use and waste generation**: tracks the mass of chemicals, plastics, and other materials used per experiment, as well as the weight or volume of waste produced (hazardous or general). Quantifying material flows helps identify unnecessary consumption and supports waste reduction efforts.
- **Baseline**: establishing a baseline of metrics at a project's start enables researchers to set measurable targets and evaluate progress. Standardised reporting templates or shared spreadsheets can help compare resource use and waste across projects and organisations, enhancing transparency and best practice exchange

Environmental Impact Assessment

Assessing the environmental impact of research is key to systematically make research activities more sustainable. By analysing energy and material flows from input to output, Life Cycle Assessment (LCA) is a method to support data-driven decision-making in laboratory management. Integrating LCA early in research design enables the identification of environmental hotspots, encourages efficient experimental planning, and supports ecological accountability enabling researchers to identify and minimise overall environmental impact. At the same time, LCA can be resource intensive or rely on unavailable data. Involvement of lab management and/or of the organisation is also an important enabler of success. Where there are limitations, it is recommended to apply LCA to the extent it is feasible. This section emphasises the role of LCA in laboratory-scale sustainability and provides suggested actions for applying LCA methodologies across research disciplines.

Key steps for applying LCA in a research context include:

1. **Define scope and boundaries:** Clarify which life-cycle stages are included (for example: raw material extraction, manufacturing of reagents and equipment, use-phase energy, and waste treatment).
2. **Inventory analysis:** Collect data on energy and material inputs and outputs for each stage (e.g. electricity consumption of instruments, quantities of chemicals and solvents, volume of water used, and waste generated).
3. **Impact calculation:** Use recognised environmental impact categories (such as carbon footprint in CO_2-equivalents, freshwater ecotoxicity, or human toxicity) to quantify the environmental burdens of the experiment or process.
4. **Interpretation:** Identify "hotspots" or steps with the highest impact and explore alternatives. For instance, if ultra-low freezers or autoclaves dominate the carbon footprint, consider more efficient equipment or modified protocols (such as reducing sterilisation frequency where adequate).
5. **Software Tools:** To perform these steps efficiently and in alignment with ISO 14040/14044 standards, specialised LCA software is recommended. Widely used tools in academic research include SimaPro (commercial), GaBi and OpenLCA.

Defining System Boundaries

Clearly defining system boundaries is essential to ensure that LCA results are meaningful and comparable. In laboratory research, system boundaries should typically include the following stages:

- **Upstream processes:** Production of chemicals, laboratory consumables (e.g. plasticware, reagents), and manufacturing of equipment.
- **Use phase:** Energy and resource consumption during experiments (e.g. heating, cooling, instrument operation), along with any on-site chemical usage.
- **Downstream processes:** Treatment and disposal of waste (e.g. recycling of chemical waste, degradation of products, or final disposal).

The system boundaries of an LCA should align with the specific goals and context of the research project. For example, a bench-scale experiment may warrant a boundary encompassing all stages from reagent synthesis to waste disposal - a cradle-to-grave approach that captures the full life cycle. Conversely, an instrument evaluation might adopt a cradle-to-gate perspective, assessing impacts from raw material extraction through manufacturing, use-phase energy, and decommissioning, without including downstream effects such as product use or disposal beyond the laboratory.

A well-defined and justified boundary ensures that the LCA results are both scientifically robust and practically meaningful, accurately reflecting the real impact of the research activities under evaluation.

Green chemistry

Green chemistry is an area of chemistry focused on lowering the environmental and health impacts of chemical production. At the core are the twelve green chemistry principles, which aim to enhance safety, efficiency, and sustainability in chemistry. They are summarised below.

- **Waste prevention:** Plan experiments to minimise by-products and overuse of chemicals. Follow the EU waste hierarchy: avoid creating waste whenever possible, then seek reuse or recycling before disposal. For instance, dispense and store only the exact quantity of reagent needed and design synthetic routes that generate fewer side products.
- **Safer chemicals and solvents:** Whenever feasible, substitute hazardous reagents and solvents with lower-toxicity alternatives. Use water or bio-based solvents in place of volatile organic solvents and consult solvent selection guides or eco-impact metrics to make informed choices.
- **Energy-efficient processes:** Conduct reactions under mild conditions (ambient temperature and pressure) when possible. Use catalysts or enzyme-mediated reactions to lower energy requirements. For example, microwave or photochemical techniques can shorten reaction times and reduce heating needs.
- **Renewable feedstock:** Source materials from renewable or recycled resources rather than petroleum-based inputs. For example, use biomass-derived chemicals or recycled polymers as starting materials, aligning with the principle of using renewable inputs.
- **Maximise atom economy:** Choose reaction pathways where most of the input atoms end up in the final product. High atom-economy processes generate less waste by design. Catalytic methods and multi-component reactions are strategies to improve atom efficiency.
- **Scale-down experiments:** Perform micro-scale experiments where scientifically valid. Smaller reaction volumes and sample sizes reduce reagent consumption and hazardous waste and often improve safety by limiting the quantity of harmful substances handled.
- **Recycle and reuse:** follow waste management principles. Implement solvent recovery systems (e.g. distillation setups) to purify and reuse common solvents. Clean and reuse glassware or plasticware where possible. Establish take-back or recycling programs for plastics and chemicals through collaboration with organisational services.
- **Design for degradation:** When creating new materials or compounds, prefer designs that break down into non-toxic substances after use. This reduces long-term environmental impact and aligns with the principle of designing chemicals with minimal persistence.**Real-time monitoring:** Use in-line or on-line analytical techniques (such as FTIR, NMR, or UV-Vis spectroscopy) to follow reactions in real time. This avoids over-processing or repeated trial runs, saving reagents and energy while ensuring optimal control.
- **Safer-by-design:** Ensure that new procedures and products are inherently safer for human health and the environment. Minimise use of substances with known toxic or bio accumulative properties, prevent unsafe by-products, and design experiments to avoid extreme hazards.

On sustainable chemistry, see also: https://mediatheque.lindau-nobel.org/recordings/42562

3. Data, hardware and software

Sustainable practices for research data

During the research process, the different types of information generated and used as source for analysis, discussion or calculations that support research findings are known as research data[7] The data comes from observations, experiments, simulations, surveys, interviews, recording, digitalisation, compilation of existing data and its analysis, among other sources. Moreover, in the digital era, the amount and speed of data generation has been increasing markedly. In this context, issues about data quality, storage, and sharing, among others, become central.

The data lifecycle is shown in Figure 1.

Figure 1. Data lifecycle[8]

7 Research Data Management – UCD Policy. https://www.ucd.ie/history/t4media/Research%20Data%20Management%20Policy.pdf

8 German Council for Scientific Information Infrastructures (RfII): The Data Quality Challenge. Recommendations for Sustainable Research in the Digital Turn, Göttingen 2020, 120 p.

The following principles and recommendations can help researchers improve the sustainability of their practices by acting on research data management.

- Ensure the data is stored, retained, made available for use and reuse, and disposed of according to best international practices, in compliance with legal obligations and the requirements of funding bodies and publishers.
- Ensure the **data quality and describe data** that supports findings, **share data**, to enable other researchers to verify their results and build upon them, **avoiding unnecessary duplication of experiments** (physical and computational), which would increase the carbon footprint of research.
- Critically assess the energy impact of computational analyses and simulations, avoid multiple copies of datasets, and consider batch processing to reduce grid load.
- Follow the FAIR principles for research data. FAIR stands for Findable, Accessible, Interoperable, and Reusable[9].
- Store research data following applicable legal and ethical standards, along with the guidelines set by funding organisations, publishers, and any relevant national policy (see for example the National Policy Statement on Ensuring Research Integrity in Ireland[10]).
- Develop clear procedures for handling research data, in line with your data management plan requirements, looking at collection, storage, use, access, retention, and destruction. In collaborative projects, define protocols and responsibilities. For research involving personal data, identify necessary measures to meet data protection obligations.
- Plan for the data's custodianship at the University or through third-party services after research completion, or upon departure or retirement. Agree with the Head of School/Institute Director on data location and storage. Ensure any agreement involving personal data aligns with the communication provided to and reasonable expectations of research participants.

Sustainable hardware practices

This section focuses on the environmentally responsible use of hardware devices within research settings, emphasising actions researchers and research managers can take, sometimes with the assistance of computing facility personnel, during operations involving Information and Communication Technologies (ICT) equipment, in order to reduce their environmental footprint.

Digitalisation and the growing use of ICT into research workflows offer new efficiencies and opportunities for collaboration. However, while the digital transformation of science has the potential to lower environmental impact in certain areas, evidence suggests that the real environmental outcome depends heavily on how those technologies are used and managed during their life cycle[11].

The environmental impacts of hardware during the usage phase are primarily associated with:

- **Energy consumption during operation**: Research hardware is often continuously left on, even when not in active use. This leads to significant electricity consumption and as a result, contributes to greenhouse gas emissions, particularly if the electricity source is carbon-intensive[12].
- **Inefficient power settings and lack of awareness**: Many devices are used without enabling energy-saving features such as sleep modes, low-power settings, or automated shutdown schedules. Research environments can be vulnerable to such inefficiencies especially when equipment is shared and continuously running[13].
- **Limited repair and upgrade culture**: Upgrading components (e.g., adding RAM or replacing hard drives) may be more efficient than replacing entire devices prematurely, which increases the total environmental load associated with electronics use.
- **Underutilisation of shared resources**: High-performance computers and laboratory instruments are sometimes underutilised because of a lack of coordinated scheduling or awareness of existing infrastructure, resulting in energy and hardware inefficiencies.
- **Electronic waste (e-waste):** When equipment becomes obsolete and researchers consider discarding it, avoid increasing levels of e-waste through proper reuse, donation or recycling planning.

9 https://www.go-fair.org/fair-principles/

10 Policy Statement on Ensuring Research Integrity in Ireland, Revised Edition 2024. National-Policy-Statement-on-Ensuring-Research-Integrity-in-Ireland-Dec-2024.pdf

11 Hilty, Lorenz M., et al. "The relevance of information and communication technologies for environmental sustainability–a prospective simulation study." Environmental Modelling & Software 21.11 (2006): 1618-1629.

12 Center for Sustainable Systems. (2021). Information Technology: Energy Consumption and Environmental Impacts. University of Michigan. Retrieved from https://css.umich.edu/publications/factsheets/built-environment/information-technology-factsheet

13 Hischier, R., Coroama, V. C., Schien, D., & Ahmadi Achachlouei, M. (2015). Grey energy and environmental impacts of ICT hardware. In ICT innovations for sustainability (pp. 171-189). Springer International Publishing

Some organisations emphasise that responsible research conduct should include sustainable hardware usage practices as part of their broader sustainability and research data management frameworks[14],[15]. These frameworks highlight the importance of extending device lifespan, optimising energy use, and supporting user behaviour change to embed environmental sustainability into daily research activities.

By adopting sustainable usage practices—such as enabling power management features, turning off equipment when not in use, upgrading rather than replacing devices and sharing computing infrastructure, researchers can significantly reduce their energy consumption and associated carbon emissions. These practices also align with organisational goals for sustainability and responsible resource management, contributing to a broader culture of environmental responsibility in science.

The main barriers to more sustainable hardware use in research include lack of awareness or training, limited technical support for repairs or upgrades, behavioural inertia, and the absence of clear guidance tailored specifically to researchers. Overcoming these challenges relies not only on technical solutions but also on organisational support and sustained awareness-raising efforts.

Adopting energy-efficient practices, optimising device settings, and using available tools and resources allows researchers to minimise the environmental footprint of hardware during its usage phase. These actions can also reduce operational costs, extend device lifespans and contribute to broader organisational sustainability goals[16]. The following recommendations provide actionable steps to achieve sustainable hardware usage in research settings.

Energy-efficient usage practices

Implementing energy-saving measures during the operational phase of hardware can lead to measurable reductions in energy consumption:

- **Enable power management settings:** Configure all devices (desktops, monitors, lab computers, equipment, etc.) to automatically switch to sleep or hibernate after short periods of inactivity. For example, screens can turn off after 5 minutes and devices enter a sleep mode after 10–15 minutes. This approach can reduce idle energy use by more than 60%[17].
- **Conduct routine maintenance:** Clean hardware regularly to prevent dust build-up, which can lead to overheating and higher energy use. Periodically check fans and ventilation to ensure efficient operation.
- **Promote awareness:** Encourage research teams to shut down or unplug devices when not in use and share simple guides on configuring power-saving settings.

Repair, upgrade, and extended use

Extending the life of hardware significantly reduces the embedded carbon footprint associated with its production:

- **Opt for repairable equipment:** Choose devices with modular designs and available spare parts. Platforms such as iFixit provide repairability scores to help identify user-serviceable models[18].
- **Make use of warranties for repair:** Investigate the possibility to repair devices, checking if they are still within their warranty period, instead of opting for an early replacement.
- **Encourage internal reuse:** Help establish and take part in internal transfer schemes within departments or labs to redistribute underused but functioning hardware to researchers in need.

Shared resources and scheduling

Efficient use of computing resources across research units helps minimise redundant energy use:

- **Centralise high-performance computing:** Rather than operating multiple underutilised machines, researchers can leverage shared servers or cloud platforms for simulations, modelling, and data processing — for example, for applications training machine learning models on just 10% of the dataset using shared infrastructure has been shown to significantly reduce energy consumption while

14 UCD. (2020). Research Data Management Policy. University College Dublin. Retrieved from https://www.ucd.ie/history/t4media/Research%20Data%20Management%20Policy.pdf

15 UCD. (2024). Report of the President September 2023 to August 2024. University College Dublin. Retrieved from https://www.ucd.ie/president/t4media/UCD%20Report%20of%20the%20President%20September%202023%20to%20August%202024.pdf

16 Podder, S. K., Karuppiah, M., Thomas, B., & Samanta, D. (2022, February). Research initiative on sustainable education system: model of balancing green computing and ICT in quality education. In 2022 Interdisciplinary Research in Technology and Management (IRTM) (pp. 1-5). IEEE.

17 Koomey, J., Berard, S., Sanchez, M., & Wong, H. (2010). Implications of historical trends in the electrical efficiency of computing. IEEE Annals of the History of Computing, 33(3), 46-54.

18 Bakker, C., Wang, F., Huisman, J., & Den Hollander, M. (2014). Products that go round: exploring product life extension through design. Journal of Cleaner Production, 69, 10-16.

maintaining performance[19]. It can also be applied to IoT-based service allocation in edge computing[20].

- **Coordinate use of specialised equipment:** Schedule and share high-energy lab instruments (e.g., workstations, microscopes) to avoid idle running time.
- **Enable remote access:** Implement virtual desktops and remote login solutions so researchers can run computing tasks without needing multiple on-site systems.

Responsible end-of-life management

Ensure proper end-of-life handling, in accordance with organisational channels and guidelines.

Training

- **Workshops on sustainable practices**: Attend sessions focused on energy efficiency and responsible hardware usage.
- **Online courses**: Enroll in courses that cover sustainable IT practices and environmental impact reduction.
- **Organisational seminars**: Participate in university-led seminars that promote sustainability in research operations.

Sustainable software practices for AI research

This section focuses on the adoption of environmentally responsible approaches throughout the lifecycle of artificial intelligence (AI) software development, deployment, and maintenance. As AI becomes increasingly integral to various sectors, its environmental footprint, particularly in terms of energy consumption and carbon emissions, has garnered significant attention.

The rapid advancement and deployment of AI models, especially large-scale ones, have led to substantial energy and water demands. Training state-of-the-art AI models can consume vast amounts of electricity, contributing to increased greenhouse gas emissions and straining existing power infrastructures[21], and also consume large amounts of water, contributing to the global freshwater scarcity[22].

The operational phase of AI models, encompassing inference and real-time data processing, also contributes to ongoing energy usage. As AI applications become more pervasive, the cumulative energy and water required for their continuous operation creates sustainability challenges[23].

In response to these concerns, the concept of "Green AI" has emerged, advocating for the development of AI systems that are not only effective but also energy-efficient and environmentally friendly[24]. This approach emphasises the importance of considering energy consumption and carbon footprint as primary metrics alongside traditional performance indicators.

Implementing sustainable software practices in AI research involves several strategies:

- **Energy-efficient algorithms**: Design and/or use algorithms that require less computational power on sufficient performance levels, as appropriate for the task, rather than unnecessary overperformance. A shift toward sufficiency helps prevent rebound effects that can arise when efficiency gains lead to increased overall consumption.
- **Model optimisation**: Employ techniques such as model pruning, quantisation, and knowledge distillation to reduce model size and complexity, thereby lowering energy requirements while ensuring performance remains adequate for the intended purpose.
- **Efficient infrastructure**: Leverage hardware and cloud services optimised for energy efficiency, and use data centres powered by renewable energy sources.
- **Monitoring and reporting**: Track energy consumption and carbon emissions associated with AI workloads to identify areas for improvement and promote transparency[25].
- **Use assessment**: Evaluate or re-evaluate whether a large AI model, or AI solution, is indeed needed for a given task. In some cases, simpler computational methods or non-AI alternatives may provide sufficient outcomes for that task.

19 Yagiz, M. A., & Goktas, P. (2025). LENS-XAI: Redefining lightweight and explainable network security through knowledge distillation and variational autoencoders for scalable intrusion detection in cybersecurity. arXiv preprint arXiv:2501.00790. https://doi.org/10.48550/arXiv.2501.00790

20 Agrawal, K., Goktas, P., Sahoo, B., Swain, S., & Bandyopadhyay, A. (2024, December). IoT-based service allocation in edge computing using game theory. In International Conference on Distributed Computing and Intelligent Technology (pp. 45-60). Cham: Springer Nature Switzerland.

21 Luccioni, A. S., Viguier, S., & Ligozat, A. L. (2023). Estimating the carbon footprint of bloom, a 176b parameter language model. Journal of Machine Learning Research, 24(253), 1-15

22 https://www.forbes.com/sites/cindygordon/2024/02/25/ai-is-accelerating-the-loss-of-our-scarcest-natural-resource-water/

23 Strubell, E., Ganesh, A., & McCallum, A. (2020, April). Energy and policy considerations for modern deep learning research. In Proceedings of the AAAI Conference on Artificial Intelligence (Vol. 34, No. 09, pp. 13693-13696).

24 Schwartz, R., Dodge, J., Smith, N. A., & Etzioni, O. (2020). Green AI. Communications of the ACM, 63(12), 54-63.

25 Lacoste, A., Luccioni, A., Schmidt, V., & Dandres, T. (2019). Quantifying the carbon emissions of machine learning. arXiv preprint arXiv:1910.09700. https://doi.org/10.48550/arXiv.1910.09700

By integrating these practices, researchers can mitigate the environmental impact of AI technologies, contributing to broader sustainability goals and ensuring that the advancement of AI aligns with ecological considerations.

Optimise model efficiency

- **Implement efficient algorithms**: Choose algorithms that require less computational power without compromising performance. For instance, replacing traditional convolutional neural networks with more efficient architectures like MobileNets can reduce energy consumption[26].
- **Model compression techniques**: Apply methods such as pruning, quantisation, and knowledge distillation to reduce model size and complexity. These techniques can lead to faster inference times and decreased energy demands[27].
- **Use pre-trained models**: Leverage existing pre-trained models that match the task requirements, and fine-tune them instead of training models from scratch. This approach conserves computational resources and minimises redundant training cycles.
- **Task-specific models**: Whenever possible, use models designed or adapted specifically for the intended task instead of relying on overly general-purpose architectures. Task-specific models often require fewer parameters and less computation, resulting in lower energy usage and more efficient deployment.

Efficient resource use

- **Dynamic resource allocation**: Employ dynamic resource allocation strategies, such as auto-scaling in cloud environments or using local and national shared compute resources, to match computing power with actual demand. This helps prevent over-provisioning and reduces energy consumption.
- **Schedule training during off-peak hours**: Training models during times when renewable energy sources are more available or when energy demand is lower can reduce the carbon footprint associated with energy consumption.
- **Monitor and profile energy consumption**: Employing tools to track the energy usage of models helps identify inefficiencies and areas for improvement.

Sustainable data management

- **Data minimisation**: Collecting and using only the data necessary for AI models to function effectively reduces storage and processing requirements, thereby lowering energy consumption.
- **Efficient data storage**: Implementing data compression and deduplication techniques minimises storage space and energy consumption[28].
- **Lifecycle management**: Regularly reviewing and deleting obsolete or redundant data frees up resources and reduces unnecessary energy use[29].

By integrating these practices into AI research and development workflows, researchers can significantly reduce the environmental impact of their work while maintaining high performance and innovation standards.

Training

Equipping researchers and developers with the necessary knowledge and skills is key to successfully implementing sustainable AI practices. Both the environmental impacts of AI and practical steps to reduce them are relevant.

- **Understanding environmental impacts of ai systems**: Follow seminars or webinars focused on the carbon footprint of AI, including lifecycle assessments of training and deployment stages.
- **Green software engineering principles**: Attend workshops on green software development, including efficient coding practices, algorithm selection, and profiling energy consumption.
- **Using monitoring tools**: Take hands-on training for sustainability tracking tools such as CodeCarbon, CarbonTracker, and Green Algorithms to enable evidence-based decisions on AI energy use.
- **Sustainable data handling**: invite research teams to work on strategies for data minimisation, storage lifecycle planning, and avoiding unnecessary duplication to reduce emissions linked to data management.

Examples of training resources

- https://greensoftware.foundation/
- https://github.com/mlco2/codecarbon
- https://www.green-algorithms.org/
- https://github.com/samuelrince/awesome-green-ai

26 Howard, A. G. (2017). Mobilenets: Efficient convolutional neural networks for mobile vision applications. arXiv preprint arXiv:1704.04861.

27 Cheng, Y., Wang, D., Zhou, P., & Zhang, T. (2017). A survey of model compression and acceleration for deep neural networks. arXiv preprint arXiv:1710.09282.

28 Hilty, L. M., Arnfalk, P., Erdmann, L., Goodman, J., Lehmann, M., & Wäger, P. A. (2006). The relevance of information and communication technologies for environmental sustainability–a prospective simulation study. Environmental Modelling & Software, 21(11), 1618-1629.

29 Coroama, V. C., & Hilty, L. M. (2014). Assessing Internet energy intensity: A review of methods and results. Environmental Impact Assessment Review, 45, 63-68.

Sustainable Practices for Computational (non-AI) Research & General-Purpose Computational IT service use

The topic of Sustainable Practices for Computational (non-AI) Research & General-Purpose Computational IT service use is about quantifying the **environmental impact of computational research**, creating a culture of **sustainability awareness** in computational research, and promoting adoption of efficient approaches to reduce the impact of computational IT service use.

The construction of **digital twins**, i.e. computational models of physical systems to test their responses in silico, can be a powerful strategy to harness digitalisation for improved research sustainability, although the quantitative evaluation of the net impact of the actual implementation can be complex. The evaluation of the sustainability opportunities is application dependent. Measuring the net-impact of implementing digital twin solutions in reducing and avoiding greenhouse gas emissions across different sectors is covered by the guidance and science-based methodologies released by the European Green Digital Coalition and will therefore not be further expanded here[30].

Modelling, simulations and computer-assisted analysis have accelerated several branches of research, from computational chemistry for materials science and drug design, to large scale linguistic text analysis. Progress is enabled by access to ever-increasing computational power, also through local and regional/national **High-Performance Computing** (HPC) facilities. More broadly, accurate monitoring of the environmental impacts of **data analysis** is a key condition for sustainable research, as computational algorithms increasingly require more hardware and energy resources.

Computational research may also play an indirect role in addressing climate challenges, for example by advancing energy storage technologies or enabling climate modelling that informs emissions reduction policies. However, the extent of such benefits is difficult to quantify, and they are generally not included in emissions estimates for computational research.

Recommendations for general computational IT services used in research work (email, writing documents…)

- Ensure that searches powered by generative AI models have a true added value, as these searches tend to have a larger CO2 footprint than conventional search engines[31].
- Keep software up to date, assuming that the updated version will be optimised and more energy efficient than previous versions.
- Minimise software running in the background needlessly to reduce energy consumption.
- Delete unnecessary emails and files with a focus on large emails/attachments and bulk deletions rather than time consuming message-by-message deletions.
- Unsubscribe from mailing lists that are no longer relevant.
- Set up collaborations in ways that minimise energy usage, such as:
  - ✓ prioritising virtual meetings over travel. While keeping video off during conference calls can slightly reduce energy use, maintaining video is often valuable for engagement and may ultimately prevent additional travel-related emissions.
  - ✓ Leverage cloud collaboration software to limit storage for multiple versions of the same document.
  - ✓ Agree on collaboration platforms and software to avoid multiple licenses and improve interoperability.

Green software

Green software use is carbon-efficient software use, meaning that it emits as little carbon as possible. The carbon **emissions of software** can be reduced in at least three ways:

- **Energy efficiency**, i.e. consuming the least amount of electricity possible;
- **Carbon awareness**, i.e. doing more when the grid is cleaner; and
- **Hardware efficiency**, i.e. using the least amount of embodied carbon possible.

An overarching guiding mindset for sustainable software development and use is that of **sufficiency**, i.e. designing

30 https://digital-strategy.ec.europa.eu/en/news/measuring-impact-digital-solutions-climate

31 https://iea.blob.core.windows.net/assets/ddd078a8-422b-44a9-a668-52355f24133b/Electricity2024-Analysisandforecastto2026.pdf

and using algorithms that require less computational power on sufficient performance levels appropriate for the task rather than unnecessary overperformance.

Measuring the carbon emissions of computational jobs

In addition to the impact associated with the hardware used in computational research [*see section on hardware above*], the main environmental impact of software use is related to the **power drawn by computers during the calculations**. The carbon footprint of a task depends on the **total energy used** by the computer and the amount of greenhouse gases emitted to produce this energy, called carbon intensity. The definition of carbon footprint metrics for software is an active area of research, which is likely to evolve and produce more accurate and sophisticated metrics and tools in the future.

Estimating energy consumption

The energy consumed by a computational activity can be estimated from the **power draw of processing cores** (which depends on the CPUs and/or GPUs model and % utilisation during the computation), the quantity of **memory available**, the **runtime**, and the efficiency of the computing facility (measured by its **power usage effectiveness**, or PUE)[32].

- **Online calculators**, such as GreenAlgorithms[33], or Datavizta can guide researchers in gathering the necessary information and making these estimates.
- Alternatively, it is possible to **embed a package** or **use a library** to track computing usage to produce carbon footprint estimates. Examples include CodeCarbon, JoularJX for Java and software “PowerMeters” built with the PowerAPI.
- When using a **HPC facility**, server-side tools such as GreenAlgorithms4HPC can be useful to provide the estimated carbon footprint a posteriori **based on server logs**.

A **challenge** in using carbon footprint calculators is accessing all the information required. For example, power usage effectiveness is measured and reported inconsistently by different computing facilities, and may not be possible to measure when computations run from a laptop or desktop computer. In case of unknowns, users can ask the facility administrators to provide their best estimates and/or account for this uncertainty by calculating a range of best-case/worst-case scenarios related to the uncertain quantities.

Estimating carbon intensity

Carbon intensity refers to the amount of greenhouse gas emissions released per unit of energy produced. It is related to the energy mix powering the computations.

This has regional as well as hourly variations (e.g. solar power unavailable at night).

Various resources make country electricity grid emission factors data available, such as:

- The Carbon Database Initiative
- ElectricityMap

Online calculators use these sources to include carbon intensity in the calculation of the carbon emissions related to a computation.

Knowing carbon intensity allows researchers to apply **carbon-aware strategies**, i.e. responding to shifts in carbon intensity by increasing or decreasing demand. If flexibility is possible, a higher workload can be performed when the carbon intensity is lower and paused when it is higher.

Discipline-specific guidance

In addition to general principles, discipline-specific studies are emerging in numerous fields, that can serve as guidance for researchers to assess the environmental impact of their computational work, such as in the case of Bioinformatics[34] and Computational Chemistry[35].

Green computing principles

Algorithm optimisation

Increasing the efficiency of an algorithm is a core pillar of green computing, resulting in reduced use of computational processing units and memory minimisation. This can be pursued in several ways:

- Favour algorithms with lower time complexity, such as using binary search over linear search for sorted data.
- Consider using more efficient programming languages instead of energy-intensive ones for high-impact applications. For example, C, C++, Rust, and

32 Lannelongue, L., Inouye, M. Carbon footprint estimation for computational research. Nat Rev Methods Primers 3, 9 (2023). https://doi.org/10.1038/s43586-023-00202-5

33 Lannelongue, Loïc, Jason Grealey, and Michael Inouye. "Green algorithms: quantifying the carbon footprint of computation." Advanced science 8.12 (2021): 2100707. https://doi.org/10.1002/advs.202100707

34 Jason Grealey, Loïc Lannelongue, Woei-Yuh Saw, Jonathan Marten, Guillaume Méric, Sergio Ruiz-Carmona, Michael Inouye, The Carbon Footprint of Bioinformatics, Molecular Biology and Evolution, Volume 39, Issue 3, March 2022, msac034, https://doi.org/10.1093/molbev/msac034

35 Schilter, Oliver, Philippe Schwaller, and Teodoro Laino. "Balancing computational chemistry's potential with its environmental impact." Green Chemistry (2024).

Java score higher than Python for all combination of sustainability objectives in comparative studies (reduced time, energy, and memory requirements)[36].

- Reduce the media file size where possible, to contribute to lower memory use.
- The power drawn from memory mainly depends on the memory available, not the actual memory used, and the memory available is often the peak memory needed for one/few steps of the algorithm. Optimising these steps can significantly lower the overall energy required for the process.

Profiling CPU/GPU/memory usage can help identify the parts of the algorithms that are more resource-intensive and would yield the largest reduction in energy consumption through optimisation. Open source and proprietary profiling/performance analysis tools are available for various operating systems and programming languages, and are typically available to users in HPC environments.

Moreover, HPC support staff often provides help to optimise algorithms, and they can provide a valuable contribution in optimising your algorithms on their system.

A **challenge** that arises with achieving more efficient algorithms is that they can create a rebound effect: instead of reducing computing usage, more calculations are performed, which often results in increased carbon footprints.

It is important to highlight that in order to consolidate the sustainability outcomes of increased efficiency it is important to also consider **sufficiency**, i.e. designing and using algorithms that require less computational power on sufficient performance levels appropriate for the task rather than unnecessary overperformance.

Reduce the number/size of computations

"Think twice, compute once"

- Limiting the number of times an algorithm runs is an effective way to reduce carbon footprint. For example, parameter fine-tuning can be limited to the minimum necessary and smaller-scale examples can be used for debugging.
- Check if the data you want to generate does not already exist and ensure to make your results available and reusable by others.

Minimise data transfer and storage

[*On the impact of data used in computations and their storage see section above on Data.*]

Edge computing helps minimising data transfer and storage energy costs by processing data locally, reducing the need to query central storage and lowering the overall power consumption of data centres. While the power consumption from storage is usually minimal at the scale of one computation, if central storage is constantly queried by the algorithm, this can become an important factor in power draw. Moreover, at the scale of the data centre, storage represents a significant part of electricity usage and data is often stored for years beyond the compute time, therefore research projects relying on large databases should assess the long-term carbon footprint of storage.

Move computations to greener facilities

[*On the impact related to cloud computing providers and data centres, see sections above on data, hardware and software*] Carbon intensity and PUE information (when available) can be used by researchers to assess whether it would be beneficial to move computations to a different facility in a low-carbon country, as a greener alternative to local data centres. A **challenge** can be the economic cost associated to using cloud providers in low-carbon countries instead of local or cheaper but less sustainable facilities.

Minimise technical debt

Legacy systems and inefficiently written code result in technical debt, consuming excessive resources for updates and debugging, and making reuse more difficult.

Normalise reporting of environmental impact of computational research

Upon completion of a project, its total carbon footprint can be reported and acknowledged in publications to raise awareness.

- See for example the following paper acknowledgments on carbon impact: "We used GreenAlgorithms v.1.0 to estimate that the main computational work in this study had a carbon impact of at least 2,660 kg of CO2 emissions (CO2e), corresponding to 233 tree-years."

A reporting framework for the environmental impact of research activities is discussed in the work by Sweke et al.[37]. They suggest including a table of carbon emissions in publications, for example using the template provided in Scientific Conduct.

36 Pereira, Rui, et al. "Ranking programming languages by energy efficiency." Science of Computer Programming 205 (2021): 102609. https://doi.org/10.1016/j.scico.2021.102609

37 Sweke, R., Boes, P., Ng, N. et al. Transparent reporting of research-related greenhouse gas emiss[illegible] the scientific CO2nduc[illegible] mun Phys 5, 150 (2022). https://doi.org/10.1038/s42005-022-00930-2

4. Facilities & infrastructure

Facilities

Facilities can be defined as utilities and services such as heating, water, electricity, wastewater, cooling, cleaning and maintenance (see uses of the term e.g. here and here).

This section addresses **facilities** as they relate to research processes and provides recommendations as to how researchers and research managers as well as project coordinators can be empowered to reduce their environmental impact with respect to the use of utilities and services in the course of a research project.

Research practices involving facilities are considered for three key phases: Planning, Operation, Decommissioning/ Close out.

Planning phase

- Participate in consultations to contribute to the formation of realistic environmentally sustainable measures that support the research work. Indeed, Planning of facilities should reflect the needs of the end users as determined by the consultations.

Operational phase

- As users of infrastucture, become familiar with the instructions concerning the building or installation (provided by the organisation) and ensure that your usage of services and utilities is consistent with existing plans to minimise environmental impact.
- Where processes as part of Environmental Management Schemes and/or eco-label initiatives are in place, researchers should adhere to the recommended practices and contribute to reporting, evaluation and expansion of the infrastructure that they use.
- Where formal processes are not in place at an organisation, research groups can enact positive change by following good practices at the level of their project.
  - ✓ See for instance the case studies described at https://www.mygreenlab.org/.
- Local nudging campaigns with posters may incite lower utility consumption. There have been for instance "Switch off campaigns" aiming to switching off non-critical lighting, heating and ventilation systems or putting them into lower power modes outside peak hours.

Decommissioning/Close out

- If long term storage or samples, materials under specific conditions or data is required post project, make sure that the requirement is well-understood and that the duration is clearly defined. The volumes of materials or data maintained should be minimised as much as possible. [*see also section above on research data*]

Infrastructure

Infrastructure in this section is treated on the organisational level and refers to the planning, construction, and management of physical infrastructure including buildings, fixed installations and generally permanent structures in organisations. This section does not address technical infrastructure that is used specifically for research.

Infrastructure is a major factor in organisations' greenhouse gas emissions and broader environmental impact. Globally, the building and construction sector accounts for 37% of global emissions – more than any other sector[38]. In the EU, this number was 35% in 2021[39]. The EU is pursuing greening of its buildings sector, notably through the Energy Performance of Buildings Directive[40] and the Energy Efficiency Directive[41], with the aim to "achieve a highly energy efficient and decarbonised building stock by 2050.[42]"

Moreover, green procurement is an essential aspect of the sustainable transformation of research and higher education [*see section on procurement in the MSCA*

38 https://www.unep.org/resources/report/building-materials-and-climate-constructing-new-future

39 https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-energy

40 Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast)

41 Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast)

42 https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

Green Charter guidance Material for research groups, organisations and consortia].

While organisations are directly in charge of infrastructure, research groups as well as individual researchers can play a role in encouraging and supporting their organisations to implement more sustainable measures.

The following recommendations consider research in distinct phases of Planning, Operation, and Decommissioning

Planning phase

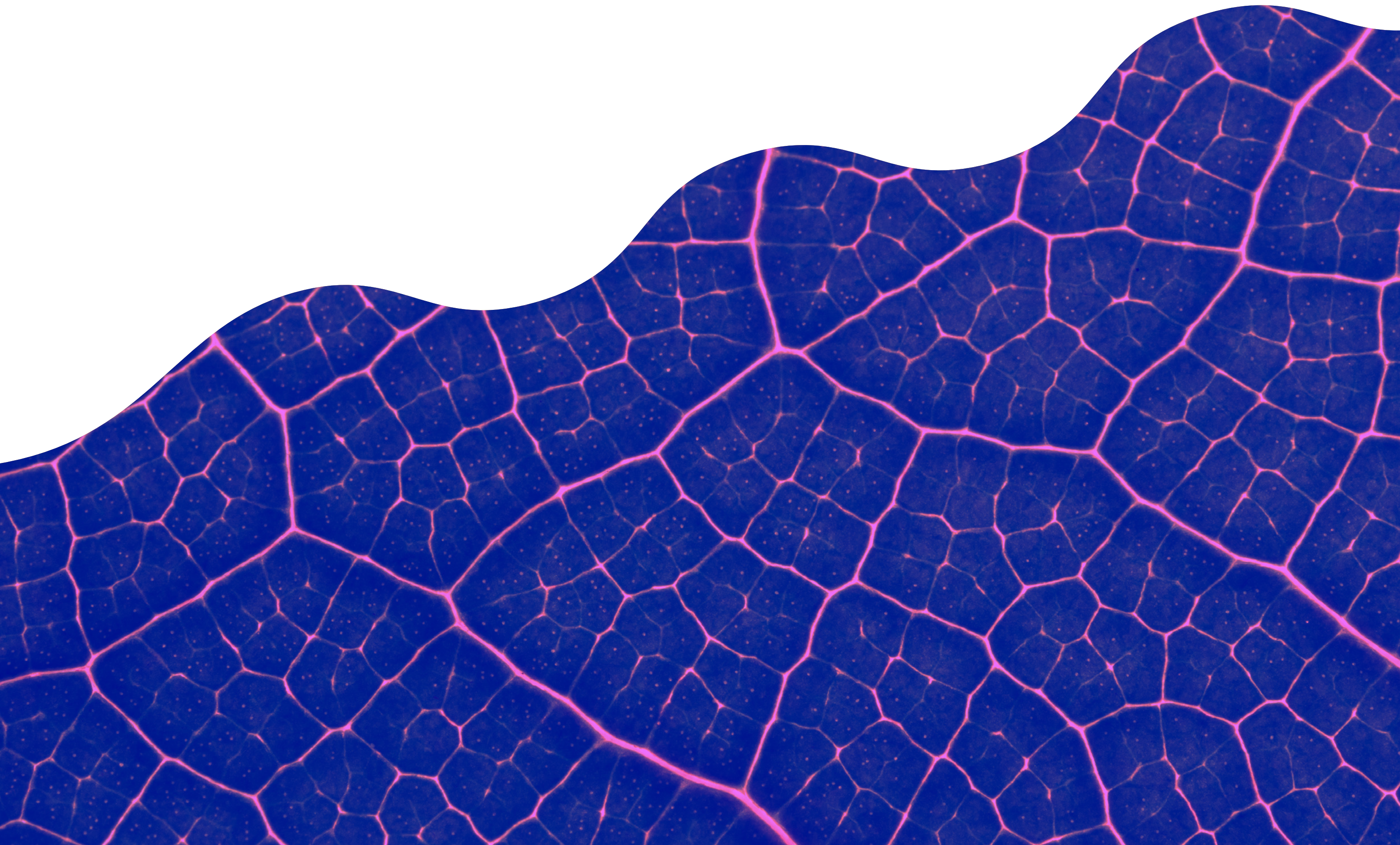
- Consider **alternatives** (within and external to organisation) before new purchase or installation of fixed infrastructure e.g. sharing existing space, collaborating, identifying existing spaces that may be easily repurposed reducing unnecessary refurbishment and associated carbon footprint
- Consider consulting with funders regarding the **availability** of existing infrastructure (on international collaborations on infrastructure, see also https://www.oecd.org/en/publications/optimising-the-operation-and-use-of-national-research-infrastructures_7cc876f7-en.html)

Operational phase

- Users of infrastructure should become **familiar** with the information about the building or installation they wish to use and ensure that that usage is consistent with any applicable guidelines for the minimisation environmental impact.
  - ✓ Where processes as part of an Environmental Management System and/or certification initiatives are in place, researchers are encouraged adhere to the recommended practices and contribute to reporting, evaluation and expansion with regards to the infrastructure they use.
- Where formal processes are not in place, following good practices at a project level can achieve positive change.

Decommissioning

- Promote the reuse of infrastructure within your community and organisation.
- Consider and advertise post-project usage alternatives for the infrastructures.



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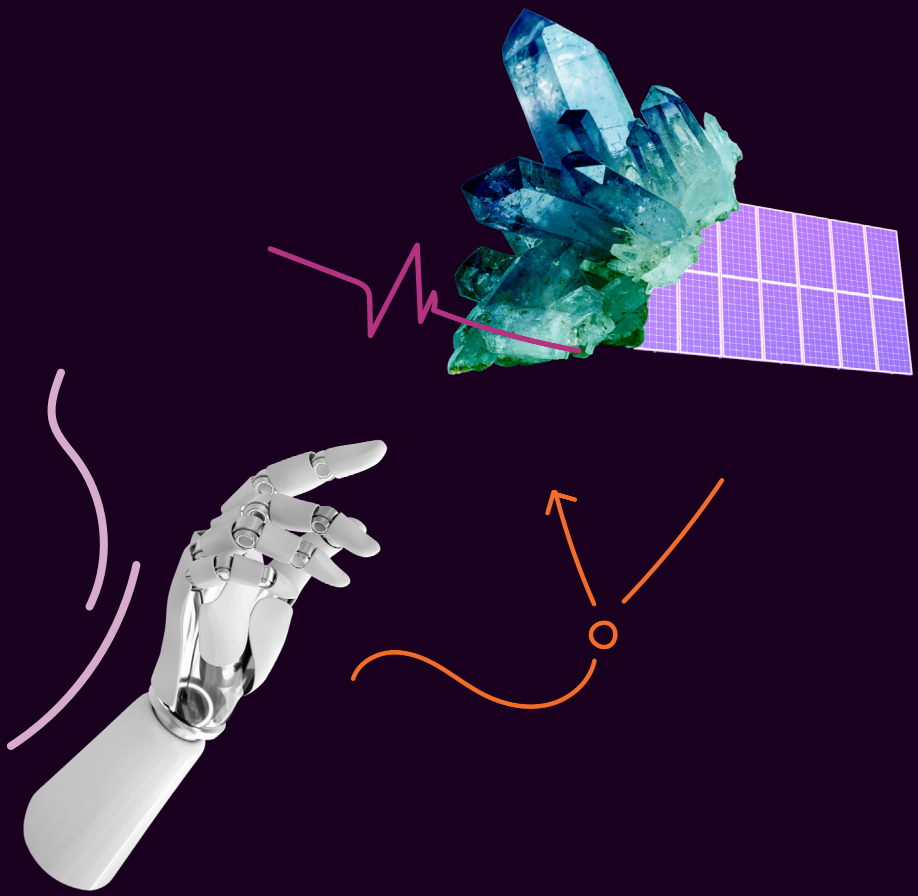

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