Driving innovation together

Framework for Sustainable High-Performance Computing in Research and Artificial Intelligence

Justifying the use of HPC in the Era of Climate Change

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Introduction

This report provides insight into sustainability of resource-intensive technologies - in this case high-performance computing (HPC) - and offers a framework for sustainable HPC application for research and Artificial Intelligence (AI). Section 1 is dedicated to addressing the complexity of the concept “sustainability”, and the tensions within (UN, 2012; Bourban 2024). It offers an analysis of bases, motivators and virtues of sustainable action. The bases of sustainability are inspired by the tripartite conceptualization of sustainability not just as environmental, but also economic and social endeavors that when balanced together create a more sustainable future (UN, 2012). The motivators of sustainable action serve as a guide of sustainable behaviour by realizing that sustainability is related to feelings of caring about the environment, but also turning those feelings into practical actions by competing in sustainability, just as we do currently in efficiency or productivity (Backus, 2020; WEF, 2020) The virtues of sustainability showcase sustainable action as empowerment and resilience to climate change, and help individuals and businesses realize their responsibility and potential for acting more sustainably.

This holistic approach aims to propose three definitions of sustainability that accommodate three key areas of development: personal (UN, 2012), business and technological (Bourban, 2024). The end-goal is to provide HPC research communities with a basic understanding of what it means to be sustainable, but more importantly how we can be empowered and in control of sustainable action.

Section 2 provides insight into how this approach to sustainability can help us in justifying the use of resource intensive technologies – such as HPC – in the era of climate change. This section introduces HPC not only as an invisible cloud technology, but as a material and physical entitiy that requires natural resources for its performance (Brevini, 2022).

The main part of this report is in section 3 that devises a **Framework for Sustainable HPC Application in Research and AI**. This entails analyzing elements of HPC that precede its sustainable action. One crucial element is understanding HPC as material and physical technology, and the other is justifying the resource-intensiveness of that technology amidst the era of climate change. Through materializing HPC and offering technological sustainability as prerequisite for its justification, a framework that allows for making HPC more sustainable is proposed. The framework consists of technical and behavioral tools, both equally important in creating a more environmentally friendly world in which technologies and nature can coexist in symbiosis. Rather than understanding sustainability as hindering technological development, or technologies as inherently unsustainable and bad for the planet, the end-goal is to have a balanced outlook that allows for nourishment or our natural enviroments and ability of technological development for future generations.

1 The Complexity of Sustainability

Sustainability is a complex, multifaceted topic that has been on the rise since its mention in the economic theories from the 80s (Bourban, 2024). Forty years later, it is still not clear what the term encompasses entirely and there is no “once size fits all” approach. Sustainability is versatile, robust, and it is meant to suit the purpose of that which is trying to be sustainable. This report is no different in that respect. It is not the goal to provide one or more definitions that are completely true for everything. Instead, the goal is to focus on what it is we want to make sustainable and what are the values and virtues we want to have while doing that. That is why instead of a top-down approach of deciding on a definition to apply, I propose a bottom-up approach of deliberating on which bases, values and virtues we should consider when being sustainable. On that basis, we can provide definitions that are more of a “call to action” in nature, rather than purely theoretical.

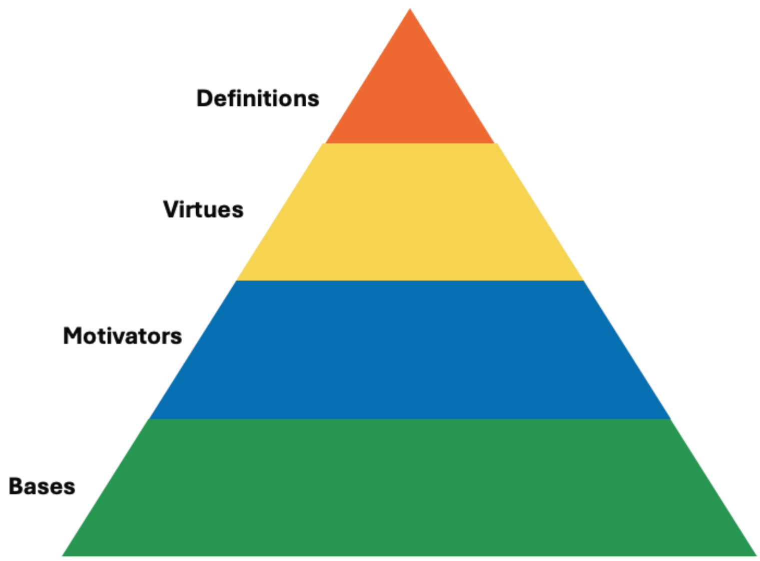

Figure I, The Complexity of Sustainability

1.1 Bases of Sustainability

Inspired by the UN tripartite approach to sustainability (UN, 2012) as economic, social and environmental. For sustainability to be achieved, all three must be balanced and reinforce each other. The three pillars are described as:

1. Environmental Sustainability: Protecting and preserving the natural environment, including natural resources, ecosystems, and biodiversity.

2. Economic Sustainability: Ensuring long-term economic growth and development that is financially viable and equitable.

3. Social Sustainability: Promoting social justice, human well-being, and the development of inclusive and cohesive communities. (UN, 2012)

I propose adding a fourth base as 'technological sustainability'. This idea was inspired by the work of ethicists in sustainability (Bourban et al, 2024). Bourban mentions that future generations should not only have enough resources, but also productive capacity and technical knowledge. However, there is no specification what is meatn by technical knowledge in this case.

In her paper on sustainability of AI, Wynberghe (2021) notes that whether AI can be considered sustainable or not will be dependent on two things: a) whether AI is created in a sustainable fashion and b) whether AI can be used to make us more sustainable.

Inspired by these relevant notions by Bourban (2024) and Wynsberghe (2021) I propose to define technological sustainability in two crucial aspects:

1. Using and creating technologies sustainably &
2. Preserving the knowledge necessary to build sustainable technologies and enact sustainable practices.

Figure II, Bases of Sustainability

Adding technological sustainability emphasizes the need to preserve and transmit critical technical knowledge that enables sustainable practices, while also ensuring that technological development continues to evolve in alignment with long-term ecological and social welfare. Specifically, it entails three important aspects:

1. Preserving and transmitting the technical knowledge necessary to enact sustainable practices
2. Developing new technologies in a sustainable manner

3. Ensuring that both the use and creation of technologies align with environmental, economic, and social sustainability goals.

Adding technological sustainability ensures that current and future generations attain adequate levels of technical knowledge in order to maintain the other three systems in the most sustainable way possible. The puzzle picture is not only aesthetic, but symbolic of the fact that one of these 'sustainabilities' should not be seen in isolation. Rather, they complement each other and are preconditions for each others existence. For example, it will be very hard to provide future generations with technical knowledge on how to lessen water pollution if water becomes a resource we may not even have anymore. It can also be understood the other way around that the access to water as a resource is dependent on our technical knowledge and capabilities on water treatment.

1.2 Motivators for Sustainable Action

The three primary motivators listed – competitiveness, care, and practice – are presented in effort to encourage sustainable action and behavior. These motivations work in symbiosis, reinforcing and complementing each other.

- Competitiveness as a motivator means that individuals and businesses should strive to outperform one another in their sustainability efforts. By competing to be more environmentally responsible, socially aware, and economically efficient, organizations can drive innovation and set new standards for sustainable practices. This competitive drive encourages the actual implementation of sustainability measures, rather than mere lip service (WEF, 2020).

- The most important motivator is the understanding of sustainability as intrinsically good and the genuine care for the Planet (Jax et al, 2018). This care-based motivation prompts individuals and businesses to prioritize environmental protection and social responsibility, even in the absence of external pressures or competitive forces. It reflects a deeper, values-driven commitment to sustainable action.

- Finally, the motivation to put sustainability into practice is crucial. Individuals and businesses must translate their care for the planet into tangible, measurable actions. This could involve simple choices, such as an individual opting for a restaurant that minimizes plastic waste, or more complex organizational strategies, such as a business implementing energy-efficient technologies and sustainable supply chain practices.

By embracing these three interconnected motivations – competitiveness, care, and practice – individuals and businesses can create a culture of sustainable action that benefits both the environment and their own long-term success. This holistic approach empowers actors to take ownership of their sustainability efforts and drive meaningful change within their respective spheres of influence.

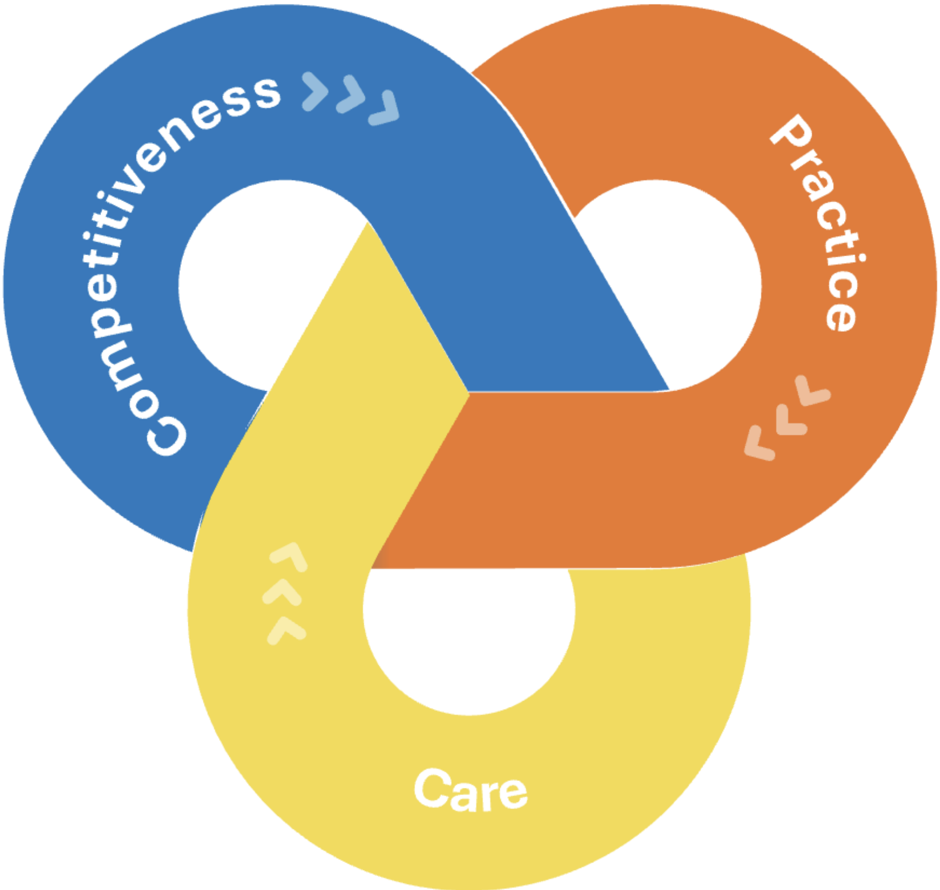

Figure III, Motivators for Sustainable Action

1.3 Virtues of Sustainable Action

Being or acting sustainably can be understood as acting in good faith and with good manners. When something is characterized as good, it can be argued that such character is virtuous. It possesses a certain set of characteristics that are good and beneficial. If sustainability is then understood as intrinsically good, there must also be certain virtues that promote sustainability. The virtues listed below are aimed at providing individuals and businesses with a sense of control and empowerment over being sustainable, as sustainability can often be an overwhelming topic to grasp.

By making sustainability pragmatic and resilient, we can "choose our battles" and aim to do action where we are most effective. For example, it is hard for an individual to criticize a business based on the unsustainability of their model, but the individual can still make a choice to not be a client of such a business and be in control to choose other providers that align more with their values of sustainability. Being aware of your position as an individual relates to understanding that if you have power or control over sustainability decisions, you should act in a way that will benefit others who are burdened by climate change, but are not in the same position to make an impact.

Figure IV, Virtues of Sustainable Action

1.4 Three Definitions of Sustainability

The process of defining something encompasses the idea that to define something is to provide a basis on which an action can be taken, on which something can be done. Therefore, the hands-on approach and the importance of "practicing what you preach" is crucial in this report when it comes to sustainability.

The three proposed definitions relate to three areas that can be understood universally in the intersection between technological development, society and the environment. The first definition is a simple reflection of what an individual should understand sustainability as. It helps grasp the bigger picture and understand the scope under which sustainable action can be taken. This definition is a result of research on sustainability in relation to humans and Planetary boundaires, as well as international policies on sustainability such as the United Nations Sustainable Development Goals (Bourban, 2024, UN 2012).

Sustainability is an **intrinsic value that requires balancing social, economic and technical needs** with the environmental capabilities of our world. It must consider preservation and livelihood of both **human and non-human environments and actors.**

The second definition empowers business to think about providing sustainability just like providing efficiency and speed as their services. Sustainability should be embedded and understood as a service benefit, and not just a by-product or a box to tick off. This way, businesses show care about the quality of their service, the values of their client and the environmental well-being of the Planet. This definition is a result of engagement in a corporate work settings, and is inspired by insights from interviews with experts on creating sustainability policies such as Albert Henkel's SURF Green ICT Maturity Model (2015). It is mostly driven by the idea that we should compete in acting more sustainably as businesses, as we compete in being the most efficient.

Sustainability **must be competitivee in the corporate culture and be understood as a service benefit.** By competing to be more sustainable as businesses we show deep care about our clients, theirs and our values and our environments.

The final definition opens up space for the next chapter of this report and relates to the practice of sustainability and the necessity of preserving adequate levels of technical knowledge for future generations, so that they can maintain social, economic and environmental sustainability in the ways that benefit them the most. This technological sustainability emphasized the need to think about two important things: 1) how can we use technologies for sustainability & 2) how can we make our technologies in the most sustainable way possible. This definition is inspired by Bourban's (2024) insight into the connection between sustainability and technical knowledge, and by Wynsberghe's (2021) idea of sustainability as a twofold concept.

Sustainability must ensure that **future generations** have access to clean water, air and forests and that they can acquire adequate **levels of technical knowledge to maintain those ecosystems in the most sustainable way possible. This means guiding technology manufacture to be respectful of environmental goals and boundaries.**

2 Sustainability and High-Performance Computing (HPC)

The emphasis on technological sustainability provides basis on which action for more sustainable technological practices – in this case computation – can be taken. Taking into account the current state of climate change and the role technologies play, it is worthwhile to start considering how we can minimize their impacts.

High-performance computing (HPC) is a useful technique of speeding up and scaling digital research. It provides great benefits not only in the scientific area of research, but also for more commercial purposes such as training AI models for everyday use. The robustness, speed and connectivity offered by HPC is a great asset to maintaining technological development and furthering scientific advances.

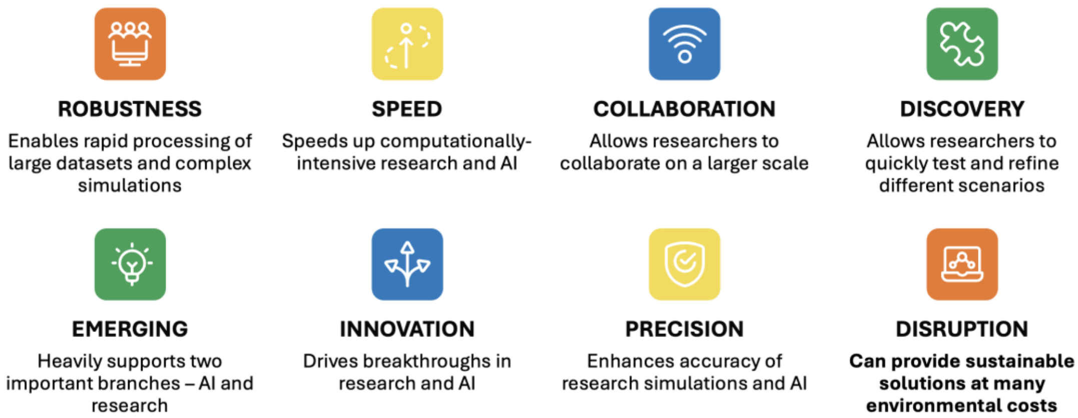

Figure V, The benefits of HPC

However, in the past decade questions of sustainability of HPC has been put on the spotlight. The most discussed are the energy and CO2 footprint of supercomputers. With about 35% of the procurement tenders, putting environmental sustainability as the second most important factor after performance (Ludema, Freeman 2023). This disruption prompted a bigger discussion on how can we mitigate these negative aspects, but still keep using HPC for the better. This report aims to provide a framework that can aid those efforts.

2.1 Justifying the use of HPC in the Era of Climate Change

In the context of justifying the use of HPC in the era of climate change, the concept of justification can be understood as the reasoning, and evidence-based arguments that support the continued use and development of HPC technologies in a way that is aligned with the urgent need to address climate change and environmental sustainability. The justification should be grounded in basic understanding of the trade-offs and potential unintended consequences associated with HPC use.

It should also acknowledge the ethical considerations and the need for responsible governance and oversight to ensure the sustainable and equitable deployment of HPC resources.

The justification of HPC use in this context would involve demonstrating three aspects:

1. How can HPC directly contribute to sustainable research?

2. How can impacts of HPC on the climate be mitigated by technological adjustments?

3. What behavioral changes can HPC providers, facilitators and users take into account to make their use of HPC more sustainable?

These elements are the basis and the idea behind the development of this framework. The aim is to reach an understanding that through justifying the use of HPC amidst climate change we do not fall into the destructive narrative that technological production can never be sustainable. On the contrary, and in relation to virtues of sustainability, through justification we can feel empowered and more responsibile for using HPC in a more sustainable way and to achieve sustainability. The first step is to understand the materiality of HPC, so that we can see which elements of HPC directly off-set its environmental sustainability.

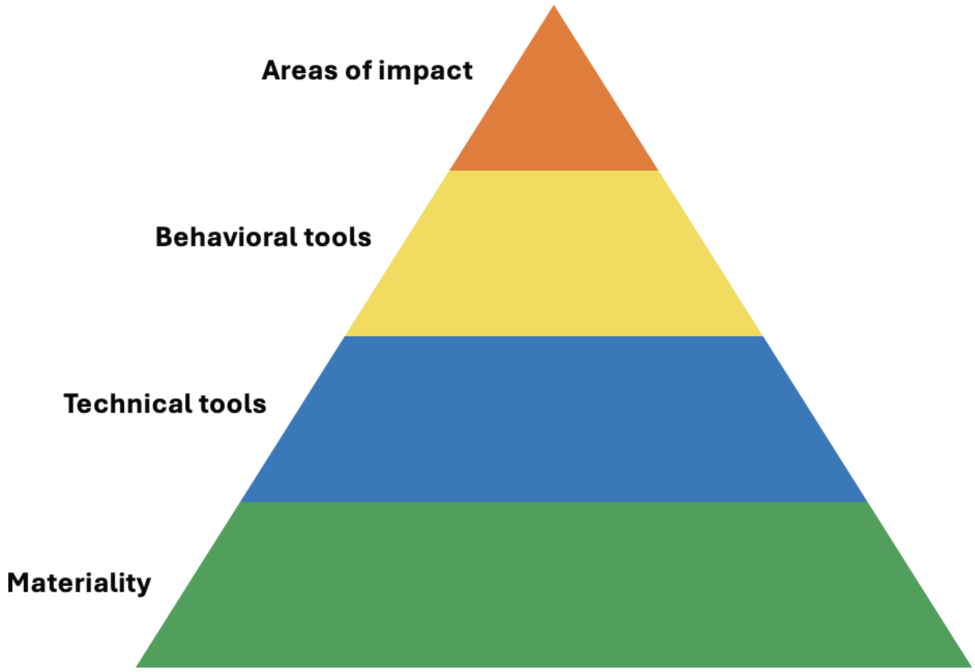

Figure VI, Justifying the use of HPC

2.2 Materializing High-Performance Computing

Before providing tools that answer the question of *how* can we justify HPC, it is important to ask ourselves *why* does HPC inspire and require justification. One crucial element is that the materiality of HPC, as is the case with many technologies, is not discussed often enough (Brevini, 2021; Wynsberghe, 2021). Technologies, especially those that work hidden from plain sight, are seen as invisible entities whose work is done "somewhere over there" or "in the cloud". To unravel this discourse, we need to see HPC for its physical properties. This means materializing HPC and recognizing that computation does not happen primarily between the chips and servers, but that it begins with the process of extracting material to create those chips and servers that computation is done through in the first place.

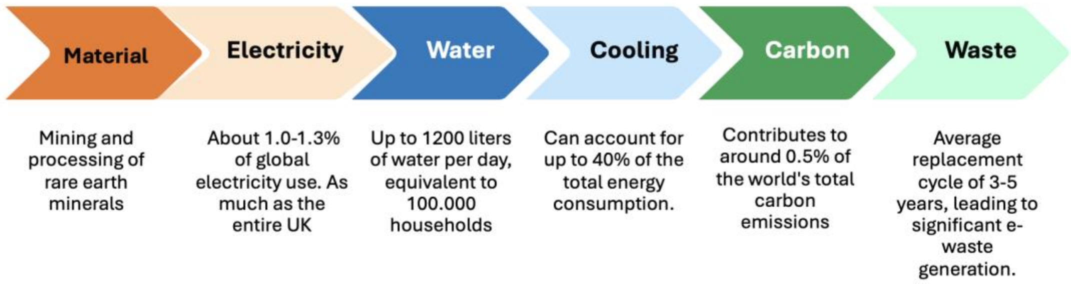

Figure VII, Materializing HPC

Material extraction is just the beginning process of materializing HPC. Other aspects such as massive water and energy consumption, carbon footprint the size of a European country (Rakov, Ham 2023), cooling inefficiencies and lack of proper waste management give us an ever bigger incentive to start thinking about how we can minimize these numbers.

HPC systems are situated in the world and have real world impacts. This means our behaviours and actions using these systems, have real environmental impacts. To make these numbers more relatable, consider that one computation task, such as training a large language model, can be equivalent to:

- Flying from New York to Los Angeles and back again around 200 times in terms of carbon emissions (Strubell et al, 2020)
- The annual energy consumption of a small town with a population of around 1,000 people (Brevini, 2021)
- The water usage of a small city with a population of around 10,000 people for a day (Li et al, 2023)

3 Framework for Sustainable HPC in Research and AI

Having understood the materiality of HPC, we have a basis on which we can determine what kind of tools are necessary to minimize or off-set the environmental costs of distributing, facilitating and using HPC. This framework consists of three elements. The first two are responsible for providing adequate tools that are distributed between three actors in step 3.

Three steps:

1. Technical tools
2. Behavioral tools
3. Areas of Impact

The actors relevant for this framework are:

a) Distributors of HPC: The organizations or entities responsible for delivering, installing, and supporting HPC systems to end-users. They act as intermediaries between the providers and the end-users, often providing additional services like maintenance, training, and technical support.

b) Facilitators of HPC: The organizations that enable the adoption and utilization of HPC by providing access, support, and expertise to users. They act as intermediaries between the HPC infrastructure and the research community, facilitating collaboration, knowledge sharing, and innovation.

c) End-users of HPC: The researchers, scientists, and other professionals who utilize the HPC resources provided by the facilitators to conduct their work which often includes large-scale operations that require robust power and scale offered by HPC.

3.1 Technical Tools

Technical tools are related to measurements, metrics, statistics and other tangible elements that provide information and enable action for the sustainability of HPC software and hardware. Technical tools help service providers and facilitators compete in the sustainability race, and give users a sense of autonomy and control over the environmental impacts in their research.

The technical tools are divided between:

1. **Hardware optimization tools:** These tools help providers and facilitators asses and optimize the environmental footprint of HPC hardware either through directly installing more sustainable material hardware or software tweaks that help hardware run more sustainably. The proposed tools in this frameworks are listed below. However, there are a lot more tools that are not included but are also encouraged if they serve the purpose of lessening the environmental footprint of HPC.

Energy Product Assessment Tool (EPEAT) – EPEAT is a global eco-labeling system that helps purchasers identify and select more sustainable electronic products, including key HPC components such as CPUs, but also computers, monitors, televisions, printers, and other IT equipment.

Life Cycle Assessment (LCA) – Helps distributors and facilitators to evaluate the environmental impact of HPC systems throughout their entire life cycle, from the extraction of raw materials to the disposal or recycling of components, enabling more informed decision-making and the adoption of sustainable practices in the distribution and facilitation, and use of HPC.

Product Impact Tool – Allows HPC distributors and facilitators to conduct a comprehensive assessment of the environmental and social impact of HPC-related products and services, including the hardware, software, and supporting infrastructure. This tool can help identify areas for improvement, inform sustainable procurement and deployment decisions, and drive the adoption of more responsible practices across the HPC value chain.

Ethical OS Kit – Helps HPC distributors and facilitators proactively identify and mitigate potential ethical risks and sustainability concerns associated with the hardware components and supply chains of HPC systems, enabling more responsible and environmentally-conscious procurement and deployment decisions.

EcoLife – This unique framework promotes the strategic combination of new and existing HPC hardware to optimize resource utilization and reduce the overall carbon footprint of HPC systems, providing a holistic approach to evaluating and improving the environmental sustainability of HPC infrastructure. EcoLife is unique in a way that it uses software tools to co-optimize carbon footprint and performance (Jiang et al, 2024).

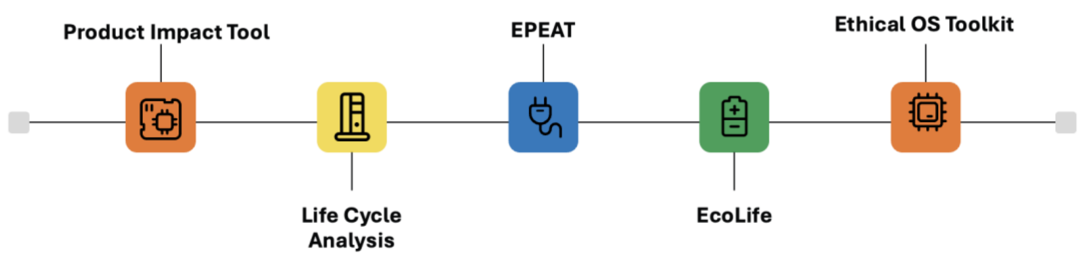

Figure VIII, HPC hardware optimization tools

2. **Software optimization tools:** These tools help distributors and facilitators assess and optimize the environmental footprint of HPC software. For end-users, these tools provide the means to actively monitor, analyze, and optimize the energy consumption and environmental impact of the computational workloads they run on HPC systems.

Energy Awareness Runtime (EAR) – This software is a management framework that optimizes the energy and efficiency of a cluster of interconnected nodes in a supercomputer. Nodes are individual computers or servers that are connected together to form a high-performance computations. Optimizing these nodes is important because it enables faster processing, improved efficiency, and increased overall performance of the HPC system.

Green Code Initiative (GCI) – Coding communities like the Green Coding Initiative on GitHub can be particularly valuable for HPC end-users in supporting software sustainability. These communities provide a platform for researchers and developers to share best practices, open-source tools, and innovative techniques for writing more energy-efficient and environmentally-conscious code. By engaging with these communities, HPC users can stay up-to-date with the latest advancements in green software development, access a wealth of resources and expertise, and collaborate with like-minded individuals to implement sustainable coding practices within their own HPC-powered research and applications.

CodeCarbon – A Python package that seamlessly integrates into HPC software, can enable distributors, facilitators, and end-users to seamlessly measure the carbon emissions associated with the execution of their code. By providing real-time insights into the CO2 footprint of their computational workloads, it allows actors to identify opportunities for optimization, such as hosting infrastructure in regions with renewable energy sources or implementing more energy-efficient coding practices.

OpenLCA: This open-source platform provides life cycle assessment (LCA) specifically designed for evaluating the environmental impact of software, making it a valuable tool for HPC distributors, facilitators, and end-users. By integrating this open-source LCA solution into their HPC workflows, actors can conduct thorough analyses of the resource consumption, emissions, and other sustainability metrics across the entire life cycle of their software.

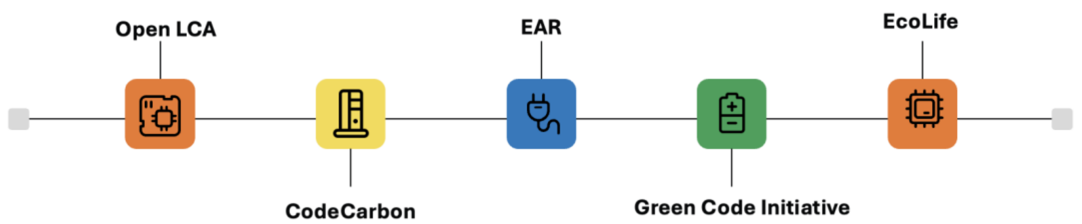

Figure IX, HPC software optimization tools

3.2 Behavioral Tools

Behavioral tools entail personal or collective initiatives that help using HPC in a more sustainable manner. Behavioral tools equip HPC distributors, facilitators and end-users with the right mindset to feel included and responsible for sustainable action. The list below contains, but is not limited to, key points that are beneficial in boosting behavioral change and empowerment towards more sustainable HPC distribution, facilitating and use. These tools go beyond technical solutions with the goal to nurture a culture of environmental responsibility and collective action among different HPC actors.

The key behavioral changes that can boost sustainable HPC are:

1. Training distributors, facilitators and end-users in the areas of HPC, sustainability and the intersection of the two, for example by organizing seminars or workshops
2. Understanding sustainability both as care and practice, for example by motivating actors through empowering their role and responsibility for sustainable action
3. Prioritizing sustainable research, for example by providing more computation time for research that directly offsets environmental harms caused by HPC
4. Awarding sustainable research, for example by offering monetary compensation in organizing sustainable competitions such as 'Hacking The Global Goals' hackaton aiming to tackle UN Sustainable Development Goals
5. Empowerment through responsibility and control, for example by setting clear goals for sustainable targets (i.e. make cooling use less of the total energy) and fostering collective action by reassuring actors that they have control over how this process is done
6. Doing more with less is a method that has benefits by restricting resources. It is noted that when resources are scarce, individuals tend to get more creative and resource-mindful when looking for solutions. In this case, resource distributors and facilitators can initially provide less computation time, and then extend it per request.

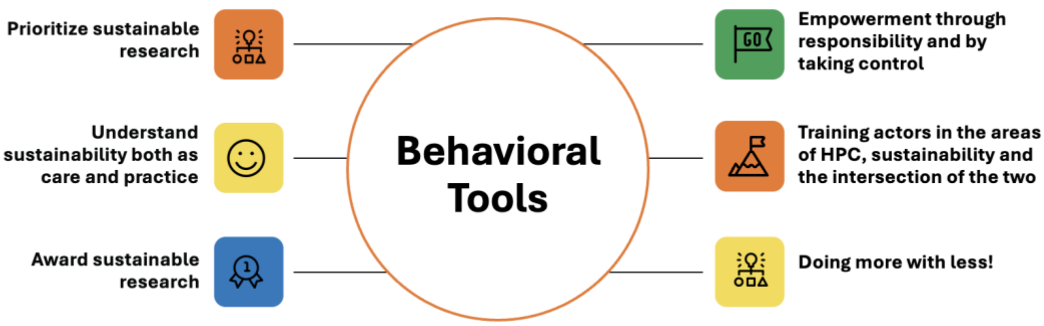

Figure X, HPC behavioral tools

3.3 Areas of Impact

This section divides areas of impact between three key actors. HPC providers, HPC facilitators and end-users. The areas of impact allow each actor to take action by using one or more of the tools. The aim of this division is to distribute responsibility and empower each actor in their own mission towards sustainable HPC application and use. However, it should be noted that this is a limited table and that actors are encouraged to fill it out on their own accord while of course being mindful of basic technological tools and behavioral ones. Alongside, actors are strongly encouraged to be mindful of the sustainability motivators and virtues, as they can help ground and guide their decisions towards sustainable action. Most importantly, the aim is not to be rigid in the framework itself but to feel empowered and in control and work together in achieving sustainability.

RESOURCE DISTRIBUTOR	RESOURCE FACILITATOR	END-USER
Insist on SDG reporting	Implement technical tools	Position your research
Incentivize sustainable research	Train staff & researchers	Calculate the environmental costs
Insist on supply chain reporting	Seminars, workshops	Make use of optimization tools
Devise policies for researchers to follow while applying for compute time	Organize sustainability competitions	Understand sustainability as your responsibility
Prioritize sustainable research	Award sustainable research	Be in control and take action

Figure XI, Areas of Impact between HPC actors

By distributing the areas of impact and the corresponding tools across the three key actors, this framework aims to instill a sense of responsibility and control. Rather than feeling overwhelmed or helpless in the face of the environmental challenges posed by HPC, each actor can identify the actions they can take, the tools they can leverage, and the positive impact they can have.

3.4 Recommendations

This framework is designed to be flexible and adaptable, encouraging HPC distributors, facilitators, and end-users to go beyond the suggested tools and areas of impact, and to continuously explore new ways of enhancing the sustainability of HPC. The goal is to foster a culture of innovation, collaboration, and a shared commitment to environmental stewardship, where every contribution, no matter how small, is valued and celebrated. Therefore, feel free to add technical and behavioral tools that fit your specific business while keeping in mind the virtues and motivators of sustainability. Ideally, you strive to accommodate all of the four sustainability bases. Try and organize a workshop with the above tables and graphs, and leave some slots empty. Ask your staff which tools are missing and more importantly which tools you can directly use to make impact with. It is highly recommended to speak to companies and businesses in the same branche and take inspiration from their approach, especially if they have successfully hit certain sustainability targets such as less CO2 by a certain year, or if they have implemented a sustainability policy that is bringing positive results. Keep in mind that although sustainability is complex, it is also in all of our ability and responsibility to take action as much as we can.

Acknowledgements

Writing and coming up with ideas is seldom a solitary process. It involves not only what the individual knows, but also what she experiences and lives through with the environment and the people in it. This framework is a mirror of that experience, and an attempt to preserve those people and their environment in the best conditions possible.

Technologies are permeating almost every aspect of our lives, thus becoming almost unavoidable in a modern society. High-performance computing is one of the pillars enabling most popular technologies, specifically boosting important branches of digital research and AI development. During my time at SURF I understood that the value HPC brings has to be regulated not only from administrative standpoints, but also environmental ones – which may be even more important in the long-term.

Apart from my visit to Snellius, I had the chance to talk to some amazing people from and outside of SURF. The insights and advice I have gotten provided support in my research, as well as made me realize even more how indispensable human knowledge and ways of its distribution are. Supercomputing or AI may be fast and efficient, but they can never capture the nuance, complexity and importantly the smell of coffee breaks that accompany inspiring conversations.

With that in mind, I would like to thank these incredible people for their valuable contribution to my research. I would also like to thank them for making my time at SURF a wonderful and a worthwhile step forward in my career.

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Visualisations
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Figure 4: Created PowerPoint slide from the SURF template; Virtues of Sustainable Action
Figure 5: Created PowerPoint slide from the SURF template; The Benefits of HPC
Figure 6: Created PowerPoint slide from the SURF template; Justifying the use of HPC
Figure 7: Created PowerPoint slide from the SURF template; Materializing HPC
Figure 8: Created PowerPoint slide from the SURF template; HPC hardware optimization tools
Figure 9: Created PowerPoint slide from the SURF template; HPC software optimizations tools
Figure 10: Created PowerPoint slide from the SURF template; HPC behavioral tools
Figure 11: Created PowerPoint slide from the SURF template; Areas of Impact between HPC actors

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