EuroHPC JOINT UNDERTAKING

DECISION OF THE GOVERNING BOARD OF THE EuroHPC JOINT UNDERTAKING No 08/2025

Amending the Joint Undertaking's Multi-Annual Strategic Plan 2021-2027 (Amendment No 3)

THE GOVERNING BOARD OF THE EUROHPC JOINT UNDERTAKING,

Having regard to Council Regulation (EU) 2021/1173 of 13 July 2021 on establishing the European High Performance Computing Joint Undertaking and repealing Regulation (EU) 2018/1488[1], (hereinafter, "the JU Regulation"),

Having regard to the Statutes of the European High Performance Computing Joint Undertaking annexed to the Regulation (thereinafter " JU Statutes") and in particular Articles 1(o), 7(4)(a), 7(5)(a), 7(6)(a), 7(7)(a), 9(4)(a), 13(1)(a), 14(1)(a), and 18 thereof,

Having regard to Decision of the Governing Board of the EuroHPC Joint Undertaking No 24/2021 of 21 November 2021 approving the Multi-Annual Strategic Programme 2021-2027,

Having regard to Decision of the Governing Board no 09/2024 of 12 April 2024 approving the Multi-Annual Strategic Programme 2021-2027 (Amendment No 2),

WHEREAS

(1) Article 1(o) of the JU Statues provides that the EuroHPC Joint Undertaking shall define the Multi-Annual Strategic Programme,

(2) By Decision No 24/2021 of 21 November 2021, the Governing Board approved the Multi-annual Strategic Programme, further amended by the means of the

[1] OJ L 256, 19.7.2021, p. 3–51.

Governing Board Decision No 08/2023 of 15 June 2023 (Amendment No 1), and by the means of the Governing Board Decision No 09/2023 of 12 April 2024 (Amendment No 2),

(3) In accordance with Articles 13(1)(a) and 14(1)(a), the Research and Innovation Advisory Group ("RIAG") and the Infrastructure Advisory Group ("INFRAG") of the EuroHPC Joint Undertaking contributed to the amendment of the Multi-annual Strategic Programme by providing their inputs,

(6) During the 45th Governing Board meeting, the Governing Board discussed and endorsed the amendment

HAS ADOPTED THIS DECISION:

Article 1

The Governing Board approves the amended Multi-Annual Strategic Programme 2021-2027 annexes to this Decision.

Article 2

This Decision shall enter into force on the date of its adoption.

Done at Luxembourg, on 26 February 2025.

For the Governing Board

Rafal Duczmal

The Chair

Annex I: Multi-Annual Strategic Programme 2021-2027 (Amendment no 3).

EuroHPC Joint Undertaking Multi-Annual Strategic Programme (2021 – 2027)

2025 revision by INFRAG and RIAG

Document Revision Status

Multi-Annual Strategic Programme (MASP 2021 -2027)

Version	Status	Date
0.0	First Draft, based on Strategic Orientations	GB discussion: 3-4 June 2021
0.1	Comments included from CH, DE, ES, SE, DK, IE, FI, EC,	July 2021
0.2	Second Draft based on feedback provided	August 2021
0.3	Third draft based on feedback provided	GB meeting 16/09/2021
1.0	Final version	October 2021
2.0	Draft Revision – JU version	April 2023
2.1	Comments from INFRAG and RIAG	May 2023
2.2	Comments included from DE, FR, SE, DK, NL, NO, EC	June 2023
2.3	INFRAG & RIAG inputs Different suggestions + comments + insets	Until 6-7 Feb 2024
2.4	Review on Feb 8 JU+INFRAG+RIAG – various changes – then final changes by RIAG and INFRAG after Feb 8	End of changes Feb 16
3.0	Final version for the submission to GB	19 February 2024
3.1	Final version with comments from DE	22 March 2024
4.0	INFRAG & RIAG inputs – first draft	December 2024
4.1	INFRAG & RIAG version shared with JU	22 January 2025
4.2	INFRAG & RIAG – final draft	7 February 2025
4.3	INFRAG & RIAG – after f2f meeting	7 February 2025
5.0	Final version shared with JU for the submission to GB	12 February 2025

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1 Executive Summary

In 2025, five years since it started full operations, the EuroHPC Joint Undertaking (**EuroHPC**) **has created one of the world's most powerful and versatile open infrastructures for High Performance Computing (HPC), Quantum Computing (QC), and Artificial Intelligence (AI)**. It operates a large fleet of petascale, pre-exascale and soon exascale HPC systems as well as QC platforms. At the same time, EuroHPC funds a multitude of Research and Innovation (R&I) projects that are crucial to advance European HPC/AI/QC technologies and applications plus support education, training and international cooperation.

EuroHPC is currently extending its portfolio with additional Artificial Intelligence (AI) systems and services in the form of the AI Factories (AIFs) and with a strong initiative to federate infrastructure and services. Due to the growing importance of AI, strong support for the AIFs was given recently, which RIAG and INFRAG agree upon. However, this required reprioritization of activities, postponing post-exascale deployments earmarked at the end of the second regulation, and pushing out plans for QC deployments. It remains to be seen how the deployment of the upcoming *Gigafactories* [1], which should happen within the realm of EuroHPC, will impact the global budget distribution. In particular, it is crucial to **invest on the adaptation of software and applications** to exploit the computational capabilities of GPU systems, in order **to reach** a reasonable **Return on Investment (ROI) from the deployed infrastructures**.

One of the key contributions of EuroHPC is to **strengthen European sovereignty**, supporting the development and adoption of European HPC solutions. In this context, Research and Innovation (R&I) activities in the technology pillar should continue with a much stronger commitment for the adoption of the developed solutions in the deployment of EuroHPC infrastructures, whilst seeking for international collaboration where useful and appropriate.

Looking ahead, INFRAG and RIAG recommend strengthening **the support for the HPC community.** It is critical to **rebalance the distribution of funding across the Pillars**, which is currently strongly focused on the deployment of HPC/AI/QC systems and **dedicate more effort to the development of European hardware and software technology, applications, and skills**.

INFRAG and RIAG agree on these main recommendations per Pillar:

Infrastructure: New HPC systems should be deployed after the two exascale systems (including upgrades or renewals of the first multi-petascale machines), to address the needs of HPC users. In addition, the next generation of QC systems (delivering improved fault tolerance) should be deployed and their proper integration with the HPC/AI infrastructure must be ensured to accelerate take-up and quantum application development.

AI Factories: INFRAG and RIAG welcome the new AI-optimized supercomputers which are complemented by a set of high value services, advise to procure the systems in a phased approach to benefit from new AI-oriented acceleration technologies, and to ensure variety both in the selected hardware and software solutions. Furthermore, AI and HPC applications must be developed, enhanced and refined to efficiently make use of the AIFs platforms (convergence is key).

Federation and Hyperconnectivity: The new federation platform is welcomed by INFRAG and RIAG, which encourage swiftly extending it to the AIFs and QC systems, as well as private data centres and cloud services. This would enable European Cloud providers to offer an end-to-end sovereign Cloud, supporting the full spectrum of use cases from open research to commercial activities. In that sense, INFRAG and RIAG urge the launch of a call towards creating an AI Sovereign Cloud. In this context, it is important that solutions are put in place to share and transfer data between the different data repositories, platforms and European data lakes.

Technology: in the context of strong geopolitical tensions with ever stricter export regulations of overseas technologies, INFRAG and RIAG encourage EuroHPC to increase the development of European hardware and software technologies, in synergy with other entities (such as Chips JU and Quantum Flagship). Such investments will be essential in the field of processors and accelerators (ARM and RISC-V based), disruptive technologies (like neuromorphic and cryogenic computing), quantum processors (shifting focus to fault tolerant quantum processors and memories), networking technologies, cooling, and integration. Investments in software technologies should be continuous, leading to capable and efficient European HPC/AI/QC software stacks that integrate layers from system software up to programming models and frameworks, with particular emphasis on supporting European processors. Meeting ambitious energy and carbon footprint reductions will require concerted advances across all hardware and software layers.

Applications: Europe is a world-leading player in HPC applications. To maintain this position, increased support of scientific and industrial applications development, targeting flagship applications as well as emerging codes, and of the related associated application communities is instrumental. This requires a continuous support to the communities in their effort for developing, porting and optimizing their applications – established ones as well as novel and emerging applications, in particular to accelerated technologies. Support should be devoted to expanding supercomputing usage to new fields (digital twins, agriculture, smart cities, humanities, urgent computing supporting public or private decision making) and creating hybrid HPC, QC and AI workload. It should also further strengthen effective collaboration of scientific researchers with HPC/AI software engineers. This cross-fertilisation is crucial for sustaining performant applications at the exascale level. On the AI applications side, INFRAG and RIAG recommend that EuroHPC should promote the development of open-source models. Emphasis should be first and foremost on developing and maintaining several multi-modal foundation models, focusing efforts on fine tuning such models to as many domains as possible.

Skills & Usage: support for educating and training future HPC/AI experts and end-users should be increased (extending the EuroHPC Master's programme by at least 10x ambition in terms of trainees and covering HPC, AI and QC). User support across HPC, AI and QC should also be strengthened by federating and expanding existing initiatives.

International Cooperation: EuroHPC should continue to develop and strengthen relations with other countries to support cross-fertilisation of ideas between researchers as well as promotion of EU technologies, applications and skills.

Additionally, **EuroHPC** shall ensure that its **activities** are carried out **in close cooperation** and coordination **with those organized by the European Commission (EC)**, in particular in the areas of **Chips JU**, **AI**, **cybersecurity**, **data** infrastructure, **cloud**, and **quantum computing**.

Finally, before starting its third term starting in 2027/2028 into the so-called post-exascale era, INFRAG and RIAG advise EuroHPC to develop a clear-cut **Roadmap for future key use cases in science and industry** launching an extensive bottom-up effort involving all relevant stakeholders. Objectives should be to assess the needs and expectations of (old and new) end user communities, identify relevant scientific, industrial and societal challenges, and survey planned and emerging HPC, AI, QC and disruptive technologies. A Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of the last period should be performed, benchmarking against other regions on the planet, **aiming at determining the best European definition of *post-exascale***.

2 Introduction

The **EuroHPC Joint Undertaking** (hereafter, EuroHPC) was established in 2018 by Council Regulation No. 2018/1488 and is fully in operation since 2020. In its few years of existence, EuroHPC has become the vehicle to expand infrastructures, research and innovation in High Performance computing (HPC) and Quantum Computing (QC) in Europe. Recently, the scope has been extended to fully cover all aspects of Artificial Intelligence (AI), with the introduction of the new pillar on AI-Factories (AIFs), see Section 4.2.

EuroHPC is financed by the European Union (EU), complemented by national and private member contributions [2]. Full information on the history, role and scope of EuroHPC, is given on its website [3].

2.1 Mission

EuroHPC aims to establish a federated, energy-efficient HPC/AI/QC infrastructure, and foster European Research and Innovation (R&I) in the fields of HPC, QC, and AI. These HPC/AI/QC systems and solutions are mandatory to address grand challenges in science and society, including climate change, medicine and health, renewable energy supply, and industrial progress, amongst many others. Supercomputing, understood as the sum of Hardware (HW) and Software (SW) HPC/AI/QC solutions, accelerates drug discovery, personalised medicine, and sustainable product design while reducing costs and environmental impact. EuroHPC ensures widespread access to HPC/AI/QC resources, trains skilled professionals, and drives solutions for Europe's digital and climate transitions, enabling Europe's leadership in science, industry, security, and economic development.

2.2 Strategy

EuroHPC coordinates European and national resources to deploy world-class exascale supercomputers and foster a sustainable, inclusive, and innovative HPC ecosystem. It focuses on advancing research, industrial competitiveness, and EU digital sovereignty[2] by developing cutting-edge supercomputing infrastructure and promoting carbon-efficient technologies. EuroHPC also supports scientific excellence, collaboration, and skills development while minimizing environmental impact. Its goals include enhancing the EU’s HPC supply chain, enabling access for diverse users, and integrating HPC/AI/QC systems with data and cloud services. By aligning with Horizon Europe and global sustainability goals, EuroHPC addresses scientific, societal, and industrial challenges effectively. To achieve its goals, EuroHPC is organised in 7 pillars (see Figure 1): Infrastructure, AI Factories, Federation and Hyperconnectivity, Technology, Applications, Skills & Usage, and International Cooperation. These areas are tightly interlinked with each other. Section 4 describes the strategy for each of the pillars, and Section 5 the cross-sectional topics that link them.

[2] Sovereignty is an important part of EuroHPC’s mandate, and often referenced topic in the MASP. Therefore, a definition and the associated objectives of sovereignty are included in Section 3.

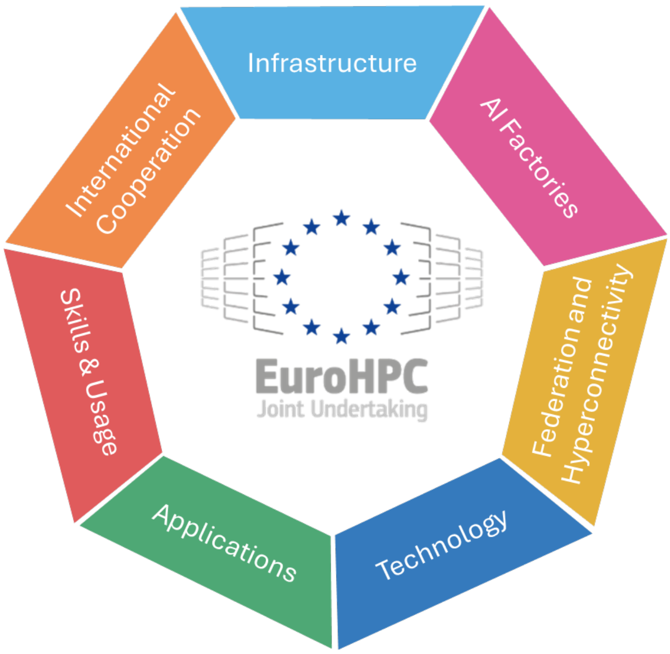

Figure 1: Seven Pillars of EuroHPC

EuroHPC coordinates activities across pillars via an annual work programme approved by the its Governing Board (GB), which is defined following the Multi-Annual Strategic Programme (MASP). It ensures R&I outputs are deployed, disseminated, and monitored for HPC infrastructure and technologies. Progress is shared through events, communications, and the Annual Activity Report. Operating until 2033 under current regulations, EuroHPC oversees grant implementation, project completion, and supercomputer operations.

2.3 Multi-Annual Strategic Programme (MASP 2021-2027)

The Multi-Annual Strategic Programme (MASP) is aligned with the mission set out in the updated EuroHPC Council Regulation [4], and lays out the mid-and long-term strategy of EuroHPC based on which the annual work programmes are formulated. The MASP is created by the two advisory groups in EuroHPC: the Research and Innovation Advisory Group (RIAG) and the Infrastructure Advisory Group (INFRAG), who also consult external experts whenever their expertise is deemed necessary. It is then provided to the Executive Director of EuroHPC and presented for approval to the EuroHPC Governing Board (GB).

The first MASP was formulated in 2021, and updates were done in 2023 and 2024. The present document is the 2025 update of the MASP, based on the latest issue from 2024. For a review of the previous issues of the MASP, we refer to the relevant location in the EuroHPC website [5].

2.4 State of Play

This section gives a brief summary of the status of different developments in EuroHPC until end 2024, pillar by pillar.

2.4.1 Infrastructure

Since 2021, EuroHPC has procured petascale, pre-exascale HPC systems, and quantum computers, with Europe's first exascale system, JUPITER, to be operational by 2025 [6]. The rise of AI Factories (AIFs) in 2025 introduces challenges to prepare users for future exascale and AI-optimised systems and services while continuing support for traditional HPC workloads, including fostering hybrid HPC/QC, advancing AI for science, industry, providing public/private cloud access, and supporting large-scale instruments, public services, and urgent computing, while developing skills and defining a European post-exascale vision.

Key actions launched between 2021 and 2024 include:

- **Exascale Systems:** JUPITER call launched in 2021, with operations set for 2025. A second exascale system, Alice Recoque, integrating European technologies, aims to start in 2026.
- **Pre-exascale Systems:** LUMI became operational in 2022, Leonardo in 2023, and MareNostrum5 in 2024 [7].
- **Petascale Systems:** MeluXina, Karolina, Discoverer, Vega, and Deucalion are now all operational.
- **Quantum Computing:** Through the HPCQS project 2 quantum simulators will be available in 2025 in France and Germany and 6 hosting entities have been selected in 2022, with systems expected to be in operation by 2025 [8]. A second call in 2024 added Luxembourg [9] and the Netherlands [10], with operations planned for 2026. EuroHPC has also set up a joint project aiming for HPC/QC common integration among Hosting Entities.

To ensure seamless implementation, EuroHPC organises regular meetings with HPC and QC hosting entities to foster collaboration and share best practices.

2.4.2 AI Factories

In 2024, EuroHPC introduced an AI pillar to deploy an AI-oriented supercomputing infrastructure, including AI-tailored services and potentially experimental AI facilities, targeting startups and Small and Medium Enterprises (SMEs). September 2024 saw the launch of calls for AI Factories, with rolling selections until 2025 [11]. These calls support hosting entities of AI-optimised or upgraded EuroHPC supercomputers and establish AI Factories. With €1.5 billion in funding, the first AI Factories will start in 2025 in seven countries (Finland, Germany, Greece, Italy, Luxembourg, Spain and Sweden), involving consortia from 17 European nations [12].

2.4.3 Federation and Hyperconnectivity

A competitive dialogue procurement for deploying federation services (authentication and authorisation infrastructure, data transfer, peer review, meta scheduling, etc.) across HPC sites was launched in 2023 with the selection proposal from CSC-IT in December 2024 and a progressive effective launch of the federation services starting January 2025. Extensions of this call or new calls are expected to expand the federation to AIF and QC infrastructures.

Furthermore, in 2022, EuroHPC launched a call for tender to establish a study on hyperconnectivity [13] to assess what would be the best solution to interconnect EuroHPC systems and provide the related connectivity services. The study including needs and requirements from computing centres, data infrastructures, end user communities, National Research and Education Networks (NRENs), and GEANT was presented to the GB in October 2024 for a procurement of network capacities and services launched end of 2024.

2.4.4 Technology

EuroHPC has supported European HPC technology development through a large number of initiatives, e.g. the SEA projects [14] or the European Processor Initiative (EPI) [15]. EPI, a cornerstone project (2018–2025), focuses on European sovereignty in HPC and chip technologies, producing the Rhea General-Purpose Processor (GPP) and proof-of-concept European RISC-V accelerator technology. While the accelerator developments will continue in DARE (see bullet below), there is no current funding path for the continuation of the EPI Arm GPP. However, Arm processor development should continue in Europe, given the growing Arm-based ecosystem in the data centre and HPC environment predicted by all market analysists.

In the Technology area, in 2023 and 2024 EuroHPC has launched:

- A call focused on developing HPC algorithms for exascale systems [16], to enable the creation of novel algorithms to tackle complex computational challenges and improve time and energy efficiency for critical applications.
- An Innovation Action in low latency and high bandwidth interconnects will support the R&I technology development of innovative and competitive European HPC inter-node interconnection technology [17]. This has been awarded to the NET4EXA project [18].
- An R&I call for HPC Energy efficiency to develop system software technologies that will drastically reduce the energy consumption of future EuroHPC supercomputers through advanced monitoring, data analysis, and scheduling/resource management strategies [19].
- The DARE Framework Partnership Agreement (FPA) on RISC-V aims to establish long-term collaboration with industry, research, and institutions, followed by a call for the first Specific Grant Agreement (SGA) in 2024 [20]. Beginning in 2025, this initiative aims

to enhance European-developed Intellectual Propriety (IP), increase value chain potential, and mitigate embargo risks.

2.4.5 Applications

To date, EuroHPC's primary funding instrument for applications is the Centres of Excellence (CoEs), fostering collaboration between HPC users and application development experts. CoEs aim to make future EuroHPC exascale systems accessible to European researchers and industries while addressing scientific, industrial, and societal challenges. They deploy prominent codes (“Flagship codes”) across EuroHPC supercomputers.

In 2022, ten CoEs were launched in domains like climate, drug development, astrophysics, and plasma science [21]. To address gaps, a 2023 call selected additional CoEs in personalised medicine, digital twins, energy, neuroscience, and HPC application optimisation [22]. Another call initiated the development of Quantum CoEs [23]. CoEs have significantly influenced European application development, becoming a recognisable “brand”. In 2024, a new “Application Concept Paper” has proposed a structured funding framework for the application pillar, which should influence the 2025 calls, including new funding instruments for novel algorithm and library development. User support is also an important matter currently addressed by the EPICURE project [24].

The field of AI is seeing enormous technical progress, impact, and has become strategic for Europe. More AI applications are coming to HPC and HPC applications are increasingly integrating AI components into their workflows. CoEs focused in HPC/AI like RAISE [25] and specialised support projects like MINERVA [26] are helping the European application communities to embrace AI practices.

2.4.6 Skills & Usage

EuroHPC aims at increasing the expertise through several initiatives, launched since 2022:

- The EuroHPC Master’s programme [27] (2021), supports a pan-European MSc in HPC, with first cohort graduated in 2024. The 2nd phase in 2025 will expand coverage to AI and QC.
- The EuroCC2 grant [28] established a pan-European network of National Competence Centres (NCCs) in 2023, with a renewal planned for 2025.
- The CASTIEL project [29] (2022) coordinates NCCs and CoE activities, focusing on best practices and training.

- The EuroHPC professional traineeship [30] (2022) and a EuroHPC virtual training academy [31] (2024) federate existing training activities and create a structure training program with high quality material on HPC/AI/QC.

2.4.7 International Cooperation

An International Cooperation call with Japan was launched in 2022 and the selected HANAMI project [32] started in 2024. In 2024 EuroHPC launched a call for International Cooperation with India [33], and the GANANA proposal was selected, which is planned to start in 2025. New initiatives for other regions, including Latin America are under discussion.

3 Sovereignty

One of the most important mandates of EuroHPC is to support European sovereignty in HPC. This explains why the term “sovereignty” is referenced over 15 times in this document, and the term therefore deserves to be properly introduced here. In our context**,** sovereignty refers to avoiding control from outside of the EU, achieving freedom from external control [34]�.

Sovereignty in our domain does not require that the totality of a supply chain is resident to the EU, but rather to protect access to technology and the freedom to use it as the EU sees fit. The following are the associated **objectives of sovereignty**:

1. **Protect against embargo and be able to determine export control rules**: Protection against embargo is the guaranteed availability of technology and the freedom to use it, which requires to establish/strengthen key elements of the supply chain in Europe. The focus is not on owning the entire supply chain but having sufficient awareness and leverage to assure an adequate flow of supplies. Determination of export control is the power to decide where and under which conditions products can be shipped. Today the export control agenda and rules are managed by the US. Ideally the EU should have its own process (which might or might not align with the US government processes).
2. **Ensure that funding for EU research predominantly remains in Europe, and that research results benefit Europe**: this is not about restricting access to EU R&D results from outside or limiting international cooperation, but all about preventing transfer of control of IP to entities outside of Europe and ensuring that such results are available for use in the EU. This includes access to research data created within the EU that may be applied for commercial applications.

3. **Protect and promote European Union values and security standards**: the EU is a leader in world politics, with its own values. Examples include data protection and privacy, fair and trustworthy AI, use of open-source licenses and open standards, and digital rights and principles [35]. Protecting and promoting such European values is a key governmental obligation and an important reason for desiring sovereignty. In order to protect the EU values, one prerequisite is preventing the introduction of "backdoors" in IT HW/SW products which could compromise the security of EU governments, industry and end-users. European cybersecurity standards and established security processes must be implemented in full to guard against such risks. Furthermore, the EU has a different concept of data protection and privacy than other regions, such as the USA. Instituted data protection and privacy regulations and processes must be followed.
4. **Develop and keep high-tech expertise in the EU** (develop ecosystem for increased expertise and high-quality jobs). This refers to fostering education in key fields of science and technology and to creating career opportunities in Europe. The way to achieve this is through economic and career incentives for sought-after experts in conjunction with targeted training & education programs.

In this context, EuroHPC shall invest in the development of European hardware, software and application products, to guarantee access to the necessary source components and maintain control over European supply chain of technology and data. Attempting to reach a target of 100% European solutions is not realistic in the timeframe of this MASP, but EuroHPC shall support established European HPC suppliers and foster the emergence of new ones, by establishing strong partnerships with them and offer long-term commitments to support their home-grown developments. In particular, adoption and use of European technologies in the deployment of EuroHPC HPC and AI infrastructures should be more strongly supported including from a legal point of view, so that the European suppliers can commit to long-term developments with some guarantee of adoption. That being said, Europe shall remain open to international collaborations and contribute to the overall effort jointly with other areas of the world as to avoid falling into isolation.

4 Strategy recommendations on Pillars

EuroHPC shall support the development of competitive and sovereign HPC and AI **solutions** that fulfil user needs and requirements, with training and user support to deliver impact for science and society. **Applications** in HPC, QC, AI and High Performance Data Analytics (HPDA) must be exploited on appropriate **infrastructures**, relying on best-breed **technology**. HPC/AI/QC Infrastructure investments should both promote the uptake of research and innovation results generated in Europe, and influence or steer the R&I on missing or critical technology. A recurring R&I cycle should be reflected in EuroHPC's approach: users and market needs steer architecture and technology targets, then demonstrators and pilot projects allow integration and validation efforts towards solutions.

The activities of EuroHPC are structured in seven pillars (see Figure 1 in Section 2.2). Following subsections describe the recommended strategy per pillar, with special focus in the time frame 2025-2027. It must be stressed that the pillars are not separated entities, but that a very tight interrelation between them is necessary to achieve EuroHPC's goals (see Figure 4 in Section 5). Therefore, Section 5 describes the cross-sectional activities that emphasise the links between the pillars.

4.1 Infrastructure

Main Strategy Recommendations for 2025-2027 period:

- Support the HPC community by extending the HPC infrastructure with upgrades of the older mid-range and petascale systems and deploy two exascale systems.
- Deploy the selected QC systems and plan by 2027 for the upgrade/procurement of the next generation of quantum systems, to access the latest QC technologies including those implementing error correction and fault tolerance.
- Tighten the connection between HPC, AI, and QC infrastructures, via federation and middleware solutions. In particular, for the HPC-QC coupling this requires investments on middleware.
- Invest in standardisation, benchmarking, certification, and validation activities for QC, linking to the other digital infrastructure or EU technology developments.
- Prepare the rise of post exascale architectures and services within the next regulation by contributing to a Scientific and Industrial Case with all pertinent stakeholders.

Looking beyond 2027, define and apply metrics reflecting the real-world impact of EuroHPC activities (e.g. via application-based benchmarks, scientific publications, or patents), ensuring that the position of EuroHPC systems on the Top500 is not the main goal in infrastructure procurements.

In line with the Regulation, EuroHPC shall organise activities for the acquisition, deployment, upgrading and operation of the secure, hyper-connected world-class HPC, QC, AI, and data infrastructure, including the promotion of the uptake and systematic use of research and innovation results generated in Europe. Access to the EuroHPC infrastructure is provided for free to the European user community and is governed by the EuroHPC Access policy [36].

Table 1 is indicative and summarises the acquisition strategy for the 2021-2027. Based on the experience to date, the process of acquiring a EuroHPC supercomputer takes over two years.

	HPC/AI Infrastructure						Quantum Infrastructure	
Year	**Midrange**	**Industrial**	**Petascale**	**Pre-exascale**	**Exascale**	**AIFs**	**Digital QPU**	**Quantum Simulator**
2020			5 **procured**	2 procur.				
2021			4 **deployed**	1 procur.				
2022	4 HEs **selected**			1 deploy.	1 HE select.			
2023				1 deploy.			6 HE select.	
2024	1 HE select.	1 HE select.	1 deploy.	1 deploy.	1 HE select.	7+ HE for AIFs select.	2 HE select.	1st deploy. (HPCQS)
2025	2 deploy.	*1 deploy.*			*1 deploy.*	*additional AIF select. with first deploy.*	*6 first NISQ systems deploy.*	*2nd deploy. (HPCQS)*
2026						*More AIFs deploy.*	*+2 systems deploy.*	
2027					*1 deploy.*	*Last AIFs deploy.*	*New HE select.*	
Total deploy	2	*1*	*5*	*3*	*2*	*10+*	*8*	*1*

Table 1: Indicative overview of HPC and QC system acquisitions (2021-2027). Entries in standard font have been already implemented; entries in italics refer to systems to be deployed before end of the regulation.

4.1.1 HPC infrastructure

Mid-range systems: Since 2022, EuroHPC has acquired and deployed mid-range supercomputers complementing the top-ranked systems. These supercomputers are co-owned by EuroHPC and Member States, and the Hosting Entities (HE) can choose short running innovation partnerships to acquire systems that are tailored to their needs. EuroHPC should finalise the deployment of the last announced mid-range systems while thinking before the end of the regulation to upgrade/renew the first wave of mid-range systems installed to keep providing leading edge HPC services to communities across Europe.

Exascale: Starting 2023, EuroHPC has acquired and starting to deploy in 2025 two leadership class exascale supercomputing systems. At least one exascale supercomputer will be built with a significant amount of technology based on HPC technology development in Horizon 2020, Horizon Europe, and EuroHPC emerging processor and accelerator technologies. While the perimeter of such exascale system could also encompass also strongly AI, EuroHPC could use such exascale systems to shape and integrate new services that could pave the path to post-exascale.

AI-Factories: From 2025, EuroHPC shall acquire and own several new AI-optimised supercomputers within the deployment of AIFs (see Section 4.2), while the acquisition of an additional high-end supercomputer (post exascale) has been postponed. Purchase criteria for the AI-optimised supercomputers will include fitness for the intended set of HPC and AI applications, variety of solutions, phased installation in order to take benefit of yearly improvement of the GPU on the side of AI features, delivered performance for these, and energy/carbon efficiency.

Industrial HPC systems: Subject to support industries and SMEs, EuroHPC is also supporting the acquisition and deployment of industrial supercomputing systems for industrial users in cooperation with and co-funded by private members of EuroHPC, adhering to industry specific requirements for increased security, data protection and availability. This initiative is aimed to foster collaboration between research and industry in both open and confidential research. In 2024 EuroHPC selected a consortium led by CINECA for deploying a first industrial grade mid-range supercomputer.

The Top500 list should not be the only benchmark and motivation for deploying compute infrastructures. Together with the User Forum EuroHPC could also work on a **new set of KPI for highlighting the scientific and industrial impact** provided using its facilities and services on Europe Science and Innovation.

4.1.2 Quantum Computing Infrastructure

Potential: Quantum Computing (QC) has a high potential for technological sovereignty of the EuroHPC Member States. The importance of joint investment, approaches and acceleration for QC within Europe was recently prioritised by the launch of the Quantum Declaration / Quantum Pact by the European Commission (EC) and the different EU member-states [37], which requires strong alignment of EuroHPC strategy and work programmes.

Quantum computers vs. simulators: In digital quantum computers, applications are described by a sequence of discrete operations while in analogue quantum simulators applications are characterised by the continuous evolution of the system's state. These computer systems, including analogue-digital hybrid systems, have recently evolved significantly and shown large potential (in terms of performance and energy) to compete with the best classical supercomputers on specific tasks. While first systems are commercially available, definite multifunctional advantage is not expected to be achieved in the next few years.

HPC-QC integration: Integrating quantum systems into HPC environments brings new opportunities but still requires strong efforts on hardware as well as on enabling software and associated interfaces. It is necessary to further co-design and develop new algorithms, applications, and software practices, which requires the HPC and QC communities to work together and share knowledge and experience (see Sections 4.4.2.1 and 4.5.3). To achieve this, researchers and industry must have access to quantum systems by equipping EuroHPC HEs with among the best available quantum computers and simulators together with enabling technologies, as well as fostering training and developing use-cases.

Recommendations: QC technologies have mostly been developed independently from the HPC community. It is therefore recommended to reduce gaps in the HPC-QC ecosystem via:

- **Use cases** involving industry, start-ups/scale-ups, academia, Research and Technology Organisations (RTOs) and government – as successfully done in different national initiatives [38].
- **Testbeds**: Set up QC testbeds and field labs as part of the EuroHPC infrastructure.
- **Integration and use**: Stimulate the development of Quantum SW, Algorithms, Applications and integration layers like middleware on top of the HPC-QC Operational Infrastructure.

Fault tolerance: The development towards scalable fault-tolerant QC (including quantum memories and interlinked Quantum Processing Units (QPUs)) has been intense over the past years, with the European and global industry aiming to have such systems available before the end of the decade. Several Member States recognised this and included concrete goals in the national initiatives[3]. Following the installation of the first quantum computers and simulators, EuroHPC should plan for the procurement of the next generation of quantum systems. This should be defined by the improved capacity to develop more complex use-cases and by new capability to explore and implement quantum error corrected algorithms.

Coordination: Some coordination between EuroHPC and the first 6 QC, the 2 recently awarded Quantum HEs, and the 2 HE from the HPQCS project (toward quantum simulators) has been initiated with the EUROQHPC-I project starting early 2025. This coordination should be

[3] Like the PROQCIMA LSQ programme in France with 500M€ over 8 years for developing two 128 qubits universal quantum computers using European technologies

strengthened and further synchronised with the HPC and QC CoEs, while continuing the build-up of a federated HPC/AI/QC Infrastructure.

Standardisation: Additionally, standardisation, benchmarking, certification, and validation activities, and linking to the other digital infrastructure or EU technology developments appear mandatory such as EuroQCI [39], the Quantum Internet Alliance (QIA) [40]. In that aim, EuroHPC will launch a call toward the establishment of (hybrid) QC benchmarks in 2025 and several members states are already involved into standardisation activities within European bodies like CEN/CENELEC [41].

4.2 AI Factories

Main Recommendations for 2025-2027 period:

- Implement all selected AIFs, deploying the AIFs infrastructures and services in a coherent way that ensures diversity of solutions and phased deployments of AI-optimised facilities across Europe.
- Develop specific access policies addressing the needs of AIFs users, especially industry and SMEs, allowing differentiated access policies per AIF.
- Enable mentoring and benchmarking in this first round of AIF.
- Support the development and implementation of novel AI-optimised architectures and services that are adapted to the needs of AI communities and applications.
- Establish and reinforce technology watch, to monitor the rapid changes in AI applications and technologies to catch up and keep at the forefront of AI developments.

Looking beyond 2027, in view of the transformative AI potential, and based on the experiences learned from the first-generation AI Factories, as well as the upcoming deployment of the *Gigafactories* [1], consider an evolution of the AI Factories into the next EuroHPC phase, with high focus on applications and skills.

In response to the global focus and enormous recent progress on AI, the EU and EuroHPC have prioritised activities aiming to position Europe at the forefront of responsible research and innovation in trustworthy and ethical AI. In 2024 EuroHPC launched the call for AI Factories (AIFs) that will provide the required AI-optimised computing platforms, support the implementation of AI, increase skills, retain the needed talent, and enable adoption of AI across industries and science (see Figure 2). The AIFs will address the urgent compute and service needs from Generative AI (GenAI)[4] and other AI methods like machine learning where Europe has a strong position.

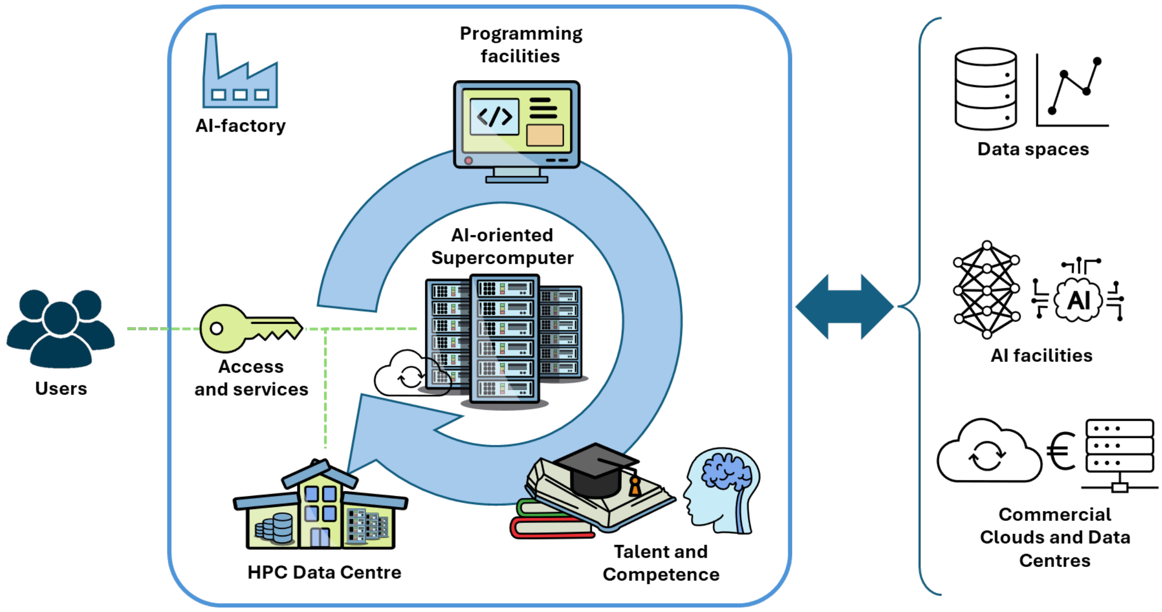

Figure 2: Schematic of the elements in an AI Factory and their relationship with each other and the surrounding ecosystem.

Integration of computing and data: Data and AI communities in Europe need to be onboarded quickly in the HPC ecosystem to respond to the exponentially growing interest in AI, and to find solutions for integrated HPC-AI approaches. Actions dedicated to integrating the HPC and data-driven communities (e.g., Common European Data Spaces [42]) ecosystem should be considered addressing industrial, governmental, and scientific use cases, including HPDA and AI, as well as training and scaling AI models. Data stewardship policies, procedures and software services will need to be implemented in order to ensure a safe use of data for AI model development.

Use cases: EuroHPC will work with its Advisory Committees to establish the areas of actions that could be considered. It is clear that HPC systems are needed by cutting-edge Machine Learning (ML), Deep Learning (DL), and more specifically the training, development, and use of large language models (LLMs), large-scale multimodal foundation models, and other GenAI approaches. Additionally, new requirements for efficiently running AI on HPC systems are not to be underestimated, especially given the variety of software components needed for modern AI. Technologies will need to be developed to reduce or limit the energy and carbon footprint, in particular for large AI training workloads.

[4] Generative AI refers to models that are trained to create new data, rather than making a prediction or a decision based on a specific dataset.

The following **key actions** are needed **to ensure a broader uptake of HPC/AI methods** across a wide range of communities alongside the AI Factory initiative:

- **Optimise EuroHPC access tracks:** Until AIF new AI-optimised supercomputers become available, prioritise large-scale GenAI training/fine-tuning on pre-exascale and exascale systems while development-oriented projects on mid-range supercomputers, defining evaluation criteria for the selection of flagship projects[5]. Define rules for the flagship projects to access resources in order to guarantee availability when needed for time-constrained production and operational workloads. Implement fast track mechanism allowing new AI communities to access rapidly (in few days) to a small amount of HPC resources and user support. Once new AI-optimised supercomputers become operational, gradually transition AI workloads to the new systems.
- **Large-scale foundation models**: Implement programmes for the development of and making available European large-scale foundation models for GenAI, building upon and expanding ongoing initiatives. At the same time, EuroHPC should encourage (or require) users to adopt open science practices, such as releasing open models, open data, open source, and release intermediate checkpoints, which can benefit the whole community and increase Europe's competitiveness in AI.
- **End-to-end capabilities for AI projects**: beyond development (training/fine-tuning) of models, enable inference, integration of AI in production services, with use of sovereign Cloud platforms. Support the integration/federation of EuroHPC systems (HPC/AIFs) with EU commercial Cloud providers for a seamless experience for AI developers and end-users.
- **Security**: Evaluate and deploy mechanisms enabling better data security and privacy in AI-optimised supercomputers: secure processing environments and sandboxes, software-defined data pools for AI with privacy guarantees, end-to-end encryption with user-managed keys.
- **AI software stack and deployment on HPC systems**: Support the deployment on EuroHPC systems of specific HPC/AI tooling, from middleware (e.g. Kubernetes platforms) to AI frameworks. Support the deployment and development of HPC workflow tools for AI and HPDA, in particular Machine Learning based System Operations (MLOps) for facilitating development and deployment for inference.

[5] Aim of these flagship projects is developing European reference AI models in critical and differentiating domains such as health, weather, climate, manufacturing, robotics, pharmaceuticals and other scientific applications.

- **Diversification**: Select diverse technologies (HW and SW) in future procured systems (as done in QC) to ensure robust and resilient AI-optimised supercomputing environments.
- **Phased deployments**: Support a multi-stage implementation of AIF AI-optimised supercomputers, enabling the rapidly evolving technologies to be integrated gradually instead of purchasing monolithic systems that remain unchanged over long periods.
- **Performance and efficiency**: Develop methods and tools for deep analysis and optimisation of AI application performance with energy use and carbon footprint considerations. Such tools could be adapted from existing HPC-focused developments and should enable AI-code developers to optimise the AI applications or their use.
- **AI-enhanced application development**: Support the integration of AI into HPC simulation codes to the widest extent. Establish programmes for modernising old codebases and legacy HPC applications. Find and establish datasets enabling the training of AI models suitable for transitioning HPC codes into HPC/AI coupled applications.

Hardware requirements: GenAI is currently driven by transformer-based models with strong infrastructure requirements in terms of scale up (number of GPUs and amount of memory per compute node) and network connectivity (at least one high speed interconnect link per GPU), either for initial training and inference, and largely beyond the requirements of HPC workloads. For HPC centres addressing both HPC and AI workloads this has strong consequences in terms of capital expenditure (CAPEX) as well as power consumption.

Future AI models: While exascale and the AIFs' AI-optimised supercomputers will address needs for large AI model training and/or fine-tuning, it is important to assess and understand the evolution of AI communities in developing/using alternatives to transformer-based models (e.g. Mamba, xLSTM, RWKV, Liquid Neural Networks, KAN, to name a few) that could exhibit different infrastructure requirements. This could be part of a wider initiative consisting of a Scientific and Industrial Case toward post-exascale that EuroHPC could launch concurrently with specific RIA actions.

4.3 Federation and Hyperconnectivity

Main Recommendations for 2025-2027 period:

- Starting with federation of HPC systems, extend this to cover rapidly also the AIFs and QC systems.
- Connect the EuroHPC federated infrastructure with national HPC/AI/QC infrastructures, and private cloud providers.
- Deploy hyperconnectivity solutions.
- Connect EuroHPC's infrastructures with the European data spaces, repositories and data lakes in coordination with EOSC, ESFRIs, and scientific institutions (e.g. SKA, CERN, DestinE, etc.) and available edge data sources.
- Create a security task force to develop and implement security mechanisms on the federated EuroHPC infrastructure in relation with the European Unit Agency for Cybersecurity (ENSIA [43]) and national security agencies.

Looking beyond 2027, in view of the critical importance of data access and management for European HPC/AI/QC infrastructures, consider including data management and storage topics into the next regulation of EuroHPC.

EuroHPC aims to build a fully federated, hyperconnected, and secure HPC ecosystem, providing end-to-end connectivity, performance, and resilience. This federated infrastructure will support academia, industry (including SMEs), and the public sector, offering tailored configurations for diverse applications and user needs. It ensures coordinated access to EuroHPC supercomputers, quantum systems, simulators, and data repositories, fostering innovation through access to cutting-edge technologies and solutions. Early feedback loops with user communities will align infrastructure development with user requirements and enable swift adoption of new technologies. Furthermore, EuroHPC shall extend its hyperconnected, federated HPC infrastructures to lower-tier national and institutional operators. This will enhance understanding of application performance, energy use, and security, exploring confidential computing to protect data while maintaining efficiency. EuroHPC could also consider the link with data spaces, as the right environments to enable data sharing in a scalable, governed, trusted and reliable way.

4.3.1 Federation of supercomputing resources

Extend federation to cover HPC, AIF, and QC infrastructures: EuroHPC's Federation Platform [44] shall start in 2025 connecting existing HPC facilities. In the future, the priority should be to extend the federation as soon as possible to the AIFs and then to the QC infrastructure and resources, providing Europe-wide, secure services for a wide range of public and private users.

Some extensions to the federation platform might be needed to best support emerging AI use cases, in particular by industrial users. To reach the latter, engaging users early in design and implementation is key. By federating the EuroHPC ecosystem, all users, including SMEs, will get appropriate support to access secure services and European HPC expertise, knowledge, and tailored training services from CoEs and NCCs.

Reduce Carbon footprint: Considering the current exponential increase of HPC use for AI, ML and Natural Language Processing (NLP), there is an essential requirement to satisfy the needs of new and emerging users whilst also measuring and controlling the carbon footprint. Federated HPC/AI/QC infrastructures enable dynamic load shifts, fault tolerance, and energy-efficient operations. In this context, EuroHPC shall investigate carbon footprint reduction by shifting, when possible, workloads to energy-efficient sites.

Connect to European Clouds: Integration with European initiatives like European Open Science Cloud (EOSC) [45], European Strategy Forum on Research Infrastructures (ESFRI [46]), GAIA-X [47] and European Cloud providers will strengthen links with science and industrial services, supporting AIFs, large-scale instruments, and digital twins in data processing and AI applications. In this manner, a federated AI-oriented platform linking the AIFs with the HPC infrastructure and European Cloud providers shall create a seamless, sovereign continuum for AI applications, including training, fine-tuning, and inference. EuroHPC should also investigate the link to edge and cloud infrastructures (computing continuum) to enable seamless access and storage of data. Special focus shall ensure industry-friendly services that encourage private sector and SME engagement with EuroHPC infrastructures.

4.3.2 Hyperconnectivity

In 2023 and 2024 EuroHPC with the EuroHyPerCon [48] external study conducted a wide analysis of current usages, needs and expectations of HPC centres, end users' communities, and NRENs (including GEANT) across Europe. Based on these elements a set of recommendations for increasing progressively the bandwidth of national and transnational networks links to beyond 1.6 Tb/s has been formulated with associated costs and procurement options for EuroHPC. These elements were presented in October 2024 to the GB, and at the end of 2024 an open procedure for selecting a provider for hyperconnectivity capabilities and services in a phased approach (from Tier0 to Tier2 sites) was launched. Again, for a swift uptake by the users, there is need to include the user communities at an early stage.

4.3.3 Data Management Services

Data and storage have not been until now part of EuroHPC’s scope, but it is considered critical for the success of EuroHPC that highly efficient data management technologies for controlling and moving large volumes of data within the HPC/AI/QC environments are established. As data-intensive applications, such as climate modelling, genomics, and AI generate massive datasets, EuroHPC HEs must efficiently transfer data both into and out of the HPC system and between various storage layers within their clusters. This can be achieved currently by EuroHPC tightly collaborating with the responsible EC units or data-focused Joint Undertaking (JU). In the future, it is recommended to integrate data management into next EuroHPC periods, considering it a key element of the HPC/AI/QC workflows and infrastructure.

Key Challenges and Solutions in the area of data management that EuroHPC shall address:

- **Access to European Data Spaces**: EuroHPC systems should develop access to Common European Data Spaces [49] and other EU initiatives, including the Data Spaces Support Centre [50], SIMPL [51], and domain-specific data lakes and repositories (e.g., SKA [52], EMBL [53], CERN [54], ESFRIs). This ensures access to vast, structured datasets essential for AI and HPC applications.

- **Data Movement and Bandwidth**: Efficiently transferring vast datasets across HPC systems, AI Factories, clouds, and repositories is critical. Technologies like Globus [55] and Nodeum [56], alongside high-bandwidth networks like the ones to be procured by EuroHPC, are potential solutions. A common approach among EuroHPC sites and Federation services could improve efficiency.

- **Data Formats and Interoperability**: Differences in file systems between HPC (e.g., Lustre [57], IBM Storage Scale [58]) and cloud (e.g., S3 [59]) systems complicate data handling. Standardizing formats like Zarr [60] or HDF5 [61] could reduce overhead. FAIR principles: ensuring data is Findable, Accessible, Interoperable, and Reusable—should also be fostered to enhance compatibility and usability across platforms.

- **Orchestration and Workflow Scheduling**: Workflow management across HPC and cloud platforms faces challenges in task prioritisation and resource utilisation. Hybrid schedulers like PyCOMPSs [62], Dask [63], and Nextflow [64] could provide seamless integration.

- **Automation and Storage**: Enhancing automation and software-defined storage linked to compute workloads would improve system performance.

- **Cloud Integration**: To support cloud-based operations, connector services like S3 should be implemented for collaboration with EU and global cloud providers.

- **Regulatory Compliance**: To serve sensitive sectors like public services and healthcare, EuroHPC could establish a working group to ensure secure data storage, processing, and transmission in compliance with EU and national regulations.

4.3.4 Security

EuroHPC's evolving HPC/AI/QC infrastructure and the services for new communities like AI, scientific instruments streaming data, public services, and SMEs, face increasing cybersecurity challenges. The NIS2 directive [65] underscores the need for a unified and high level of cybersecurity across HEs. However, physical and logical security is currently managed individually by HEs under national laws, leading to inconsistent levels across the infrastructure.

A **security task force** as already initiated by EuroHPC is essential to reinforce it with a minimum security and common standards. This task force should coordinate with national and European cyber agencies, such as the Cybersecurity Competence Centre [66], to address incidents, adopt European security technologies like Post-Quantum Cryptography (PQC) and Quantum Key Distribution (QKD), and advise on best practices. AI workloads, often requiring frequent access to external datasets (e.g., RedPajama [67], The Pile [68]), face unique security risks. Opening nodes to external sources without controls can lead to misuse, such as Denial of Service (DoS) attacks [69] or reverse shell exploitation. The task force should define rules for secure external dataset handling, clarify dataset responsibilities, and align practices with the EU AI Act [70].

Key Challenges and Recommendations to be addressed by the security task force:

- **Data Integration and Ingestion**: Distributed data lakes and machine-to-machine workflows for scientific instruments require secure connections. Common protocols and encryption standards should be enforced, ensuring safe data ingestion and management.
- **Support for Sensitive Data**: Addressing public services and health sectors' needs requires compliance with national and EU regulations for sensitive data. The task force should explore confidential computing solutions and, in the long term, homomorphic encryption for data protection during computation.
- **Post-Quantum Security Preparations**: With the anticipated threat of quantum computers breaking Rivest-Shamir-Adleman (RSA) encryption [71], the task force should evaluate post-quantum Authentication, Authorisation, and Identification (AAI) services based on European technologies to future-proof the infrastructure.

- **Collaborative Cybersecurity Projects**: A proposed cybersecurity/AI project in WP2025 should integrate efforts across federated HPC/AI/QC services. This project would reinforce EuroHPC's security framework, ensuring compliance and innovation.

4.4 Technology

Main Recommendations for 2025-2027 period:

- Support European HW/SW technology developments to build up a European supply chain for HPC, AI, QC products and demand their use in EuroHPC system deployments.
- Continue investment on European processors, particularly on: Arm server processors, RISC-V hardware and software ecosystem, special purpose accelerators (e.g. for AI), advanced semiconductor packaging and chiplet integration.
- Build demonstrators for disruptive technologies (QC, neuromorphic, cryogenic computing, etc.) to raise the TRL of European IP and keep it ahead of international competition.
- Provide continuous investment on the varied European SW components, from system SW up to programming models. Particularly support adaptations to European processors and to implement and contribute to software standards.
- Support research software engineers and foster the application of professional SW development techniques, including CI/CD, automated testing, software documentation, product releases, etc.

Looking beyond 2027, increase funding on and adoption of European technology, particularly around processors and accelerators based on, e.g., RISC-V and Arm architectures, with special emphasis in software support, and to the integration of traditional HPC with QC and AI.

The Technology pillar develops Hardware (HW) and Software (SW) for EuroHPC's future HPC, AI, and QC infrastructures, delivering world-class performance while prioritizing energy and carbon efficiency. Access to cutting-edge, energy-efficient technologies, and stable, interoperable components is vital for EuroHPC's success, making it mandatory to achieve some level of technology sovereignty to guarantee access to the necessary source components[6] and maintain control over European data. As attempting to reach a target of 100% European solutions is not realistic in the timeframe of this MASP, European added value resides in the design and integration know-how of the subsystems, and on the control over

[6] The HPC supply chain ranges from core digital technologies and components (processors, memory, interconnect, disks, tapes,…) to racks or any larger scale integration unit (e.g. containers, thermal, electrical, and mechanical equipment for energy supply and cooling), plus software stack (from operating systems to middleware and programming environments tools and applications).

the generated IP. Currently the European HPC supply chain consists of one large integrator, plus SME integrators or technology developers. They rely on components developed and manufactured outside of Europe, adding European components and IP where possible, such as advanced cooling technologies. Europe is also the home of a number of ISVs developing critical system and application-level software for HPC. EuroHPC shall support established European HPC suppliers and foster the emergence of new ones.

A representation of the technology stack is shown in Figure 3, pushing out both up and down from technology components at the centre. Going down, we grow out to racks, systems, Data centre Infrastructure, and Federation of systems. Going up from system components, we grow the SW stack from firmware and BIOS to low level SW, Toolchains, languages, System SW... up to application SW.

Pillar	Area	Component	Area	Component
Applications	**Applications**	Application codes, libraries		
Technology (Software)	**Programming Environment**	Programming Language and Frameworks	**System Management**	Runtime System
		Parallel Programming Models		Workflow manager, Resource management/ Job scheduling
	Tools	Compilers		Software deployment tools, SDKs
		Debuggers		File system
		Performance analysis tools		Operating system
Technology (Hardware)	**System Components**	Processors (CPU, GPUs, other accelerators)		
		Memory and Storage		
		Network		
	Rack integration	Mechanics, Electric, Cooling		
	System deployment	Site preparation, Containers		
Infrastructure	**Operations**	System management, User access		
	Data Centre	Cooling, Heat reuse		
Federation	**Connectivity**	System connectivity, Uniform user access,		

Figure 3: HPC technology stack

Sovereign supply chain: Supply chain management and make-or-buy policies in deploying future EuroHPC infrastructures will be a primary determinant of Europe's digital sovereignty. EuroHPC shall contribute to strengthen both the supply and the demand side of HPC/AI/QC technologies, collaborating and in alignment with other initiatives like the Chips JU [72] and the Quantum Declaration / Quantum Pact [37]. On the processing technology side, high-end HPC/AI processor development requires a large amount of initial capital investment, continued for a period of 5-10 years, before becoming commercially self-sustained. To be successful, it also requires a mature SW stack that is accepted by the market (discussed more in the SW section). For QC it is critical to secure ownership of technology developed in the region and develop a full (and to the extent possible hardware agnostic) software stack[7] based on European solutions that enable the operation of heterogeneous systems including execution and management of jobs. On the SW side, both commercial and open-source pieces are combined, and European added value lies in specific middleware optimisations and integration know-how. To strengthen the supply chain, EuroHPC shall address the recommendations issued in this technology pillar, and consider additional pilot technology demonstrators for HPC solutions, identifying and prioritising critical elements. To benefit from these investments, it is also paramount to prepare the EU workforce for the developed HPC/AI/QC technologies (see Section 4.6).

Co-design: Linking technology development to significant scientific and industrial use cases will ensure broad market relevance and develop digital sovereignty beyond the scientific use cases. Close co-design collaboration between suppliers, customers, HPC centres, and users is crucial to align R&I with end-user needs and would benefit from energy/carbon efficiency targets integrated across all Technology Readiness Levels (TRLs).

Roadmap: A strategic R&I roadmap with clear goals, targets, and Key Performance Indicators (KPIs) will enhance European technology capabilities. Partnerships with industry and research organisations can be married with the use of European R&I results in infrastructure procurements. Technology R&I must strengthen EU sovereignty and leadership [73] by fostering European IP, ensuring supply chain readiness, and meeting Green Deal [74] sustainability goals. Robust networks, storage, and cybersecurity are essential for safeguarding valuable digital data, ensuring secure access, and optimizing system use. Emerging models, such as HPC/AI/QC hybrid computing and European Digital Twin initiatives, must inform technology development, by leveraging complementary R&I activities in big data analytics, AI, neuromorphic computing, and QC. Structured and coherent co-design between technology projects and projects from the application pillar should be established to ensure the suitability and acceptance of the HW solutions.

4.4.1 Hardware Technologies

The competitiveness of the European HPC/AI/QC infrastructure depends on the performance, energy/carbon efficiency and availability of competitive HW technologies. Component require advanced silicon technology nodes to achieve high performance and energy efficiency, with large-scale packaging and highly efficient cooling solutions. Mission critical subsystems or

[7] Including frameworks for the implementation of error mitigation and error correction schemes, data, workflow and resource management, I/O protocols, signalling, SW engineering methods and practices tailored for quantum and hybrid computing, and more.

components include memory and storage hierarchies as well as high-speed interconnect networks. At the system level, rack-to-container integration and disaggregated architectures must also be considered. HPC technologies, including General Purpose Processors (GPP), accelerators, and networks/interconnects as well as the requisite system software[8], which are developed through EuroHPC calls must pursue energy/carbon efficiency goals, be innovative, be able to perform and compete globally, be production ready and, whenever feasible, be deployed in industrial settings.

As HPC systems become increasingly heterogenous, larger and eventually modular, performance depends on reliability, availability, serviceability, performance, energy/carbon efficiency, adaptability and security of the underlying technologies, from individual components up to board, modules and the entire system. With growing volumes of digital data and federation of their sources, high performance interconnect hardware, storage and AI engines are becoming increasingly valuable, in many cases eclipsing raw compute power. It is essential to establish software compatibility and integration, and in addition state-of-the-art hardware enabled cyber security technologies that protect data at all layers and provide secure access and use of the systems. EuroHPC will, via its Advisory Groups, monitor the developments in critical hardware areas where European Leadership is currently lacking. This may include asking its Advisory Groups to undertake a full analysis of the situation.

4.4.1.1 HPC/AI processor ecosystem

EuroHPC supports the development of HW technologies such as high performance, energy efficient processors, accelerators, and interconnects. In particular, EuroHPC, in a joint effort with the Chips JU [72], supports the development of low power General Purpose Processor (GPP) and accelerator technologies designed in Europe. The targeted ecosystem for European HPC processors/accelerators will contribute significantly towards European technological sovereignty through a strategic R&I roadmap that strengthens the European capabilities to design, develop and produce the IP related to high-end processors and/or accelerators. This must be driven by relevant key performance indicators, including energy/carbon footprint and efficiency. The development of European processors and/or accelerators should include preparation for future integration in European supercomputers and should be privileged as European technology (as is done in other regions).

General Purpose Processors (GPP): Sometimes referred to as Central Processing Units (CPUs), a range of GPPs supporting server applications including is becoming viable in HPC and

[8] Including domain-specific libraries, runtime systems, frameworks and programming environments

beyond. Classical HPC CPUs must adjust their role as accelerators (Graphic Processing Units (GPUs), neuromorphic engines, Field Programmable Gate Arrays (FPGAs), etc.) are being integrated with production systems. In modern HPC systems, the role of the CPU is migrating from the central compute engine to a dual role: orchestrating accelerators and processing workloads that are not amenable or very difficult to adapt to accelerators. The key requirements are acceptable CPU performance (based on measurable KPIs) and a viable SW stack supporting customer production environments.

AI-accelerators: specialised AI accelerators have evolved rapidly and are increasingly used in HPC systems. However, ensuring joint support and optimisation of both HPC and AI workloads on the same system is difficult because performance does not always rely on the same features and configuration or sizing parameters - at processor, memory, and network levels - and because the HPC and AI software stacks notably differ. EuroHPC must invest in appropriate accelerators and interconnect subsystems for AI (training or inference workloads), ideally serving also the needs of HPC workloads. All processing components in today's HPC infrastructure are non-European; EuroHPC needs to seek alternatives by developing solutions based on ARM, RISC-V, European GPUs or other accelerators, or disruptive solutions (optical accelerators, neuromorphic, dedicated inference engines...).

RISC-V: The RISC-V Instruction Set Architecture (ISA) is an open-standard abstract model for the design and implementation of modern CPUs.

Recommendations on RISC-V: For the RISC-V ISA to succeed in the HPC space three concerns must be addressed:

- **SW ecosystem development and proliferation**: important for accelerators but decisive for server CPUs.
- **Indemnity**: as soon as a company achieves financial success, patent trolls arrive. With professional IP companies, management of this risk is included in the purchase price. For open standards, the end user is responsible. This may be addressable by a cooperative action with a central fund but needs to be well thought out.
- **Fragmentation** (split in SW trees, often due to variations in HW developments) is managed in single companies by limiting the supported features and testing the choices made. Fragmentation is exacerbated by geopolitics and by the variability in designs, in particular for open, extendable instruction sets. Risk is that Independent Software Vendors (ISVs) will not port and support the ISA with all its diverse features due to the limited ROI for each fragment. It is recommended that Europe Align and help to drive existing standards, and where possible involve ISVs, in lieu of developing an independent SW and trying to convince ISVs to adapt to it after the fact.

Disruptive processing technologies: with the cadence of performance and energy efficiency improvements driven by the slowing of Moore's law, and with the emergence of novel applications scenarios (like the integration of HPC and AI), disruptive processing technologies can be attractive approaches to significantly improve compute performance and energy efficiency. Areas in which Europe is well positioned and should continue strongly investing in research and development are quantum, neuromorphic, and cryogenic computing, to name just a few. Such disruptive developments offer a unique opportunity for Europe to leapfrog international competition, steer future roadmaps and control IP and commercialisation. For this to succeed, a sustained effort is needed to increase the maturity of the solutions to higher TRLs and readiness for production. Therefore, EuroHPC should invest in facilitating their path to commercialisation by increasing maturity, integrating them into pilot systems, and exploring applicability for HPC/AI/QC use cases and applications. Close involvement of users in a co-design effort will be important to align technology development to user needs and grow a market that is able to sustain further technology evolution. To capitalise across EU investments, closer integration between calls from Chips JU and calls from EuroHPC is advised for a full view/continuum of co design actions.

Chiplet solutions and packaging: high-end processors are reaching reticule limits, becoming too large and expensive[9] to produce as one single block of silicon. Instead, processors are manufactured aggregating various smaller chiplets (e.g. [75]) with different functionalities (e.g. core processing, memory, I/O). This trend goes towards higher package heterogeneity, mixing already CPU with acceleration chiplets (e.g. [76]) and opening the opportunity to tailored processor designs for specific markets and needs (e.g. AI-oriented applications, inference, tensor operations, etc.) Europe is supporting chiplet based development through the EPI, DARE and Automotive initiatives. To facilitate the success of those and further European processor IP, EuroHPC should put dedicated effort in developing a European packaging technology supporting standard interfaces, in particular Universal Chiplet Interconnect Express (UCIe), to allow the integration of various chiplets (e.g. ARM, RISC-V, or accelerators for tensors/stencils).

4.4.1.2 Network and interconnect technologies

High-speed interconnect networks are critical for both monolithic architectures and the fastest possible integration of disaggregated HPC/AI/QC/Neuromorphic resources and storage/memory systems. Furthermore, high-speed interconnect components represent a significant part of the acquisition cost of state-of-the-art supercomputers and are essential for

[9] The production yield is quadratically inversely proportional to the size of the chip.

strategic supremacy in HPC/AI/QC,and are growing in importance as current transformer-based AI systems benefit from heavily provisioned interconnect (1 link/GPU). On a more mid-term view, EuroHPC should invest into R&I on photonics used from intra-chip communication (photonics-based chip-to-chip optical connectivity) to rack-to-rack interconnect. The global market for high performance interconnect is currently dominated by a single non-European player. There is therefore a real opportunity for European industry to gain market share outside Europe if a competitive solution can be developed. For these reasons, EuroHPC has implemented several projects funding significant European research in this important area and should continue to support and develop it. In particular, EuroHPC should connect with and support the activities of the Ultra Ethernet Consortium [77], with the aim of implementing new interconnects that are both feature-rich and high-performance in future EuroHPC infrastructure.

Separately, EuroHPC and projects such as EuroQCI [78] and the Quantum Internet Alliance (QIA) [40] should continue development of Wide Area Networks for the benefit of the future HPC+QC infrastructure.

4.4.1.3 Supercomputer and data centre integration

Supercomputers and the data centres operating them rely on the interplay of many different components, including compute nodes, interconnects, storage subsystems, electrical power supplies and distribution, monitoring systems and cooling systems. Robust integration approaches across the full range of components are required to assure reliability, performance and energy efficiency of supercomputers and data centres.

Use of containerised systems (modular physical units of HPC systems) is becoming an option for modular construction of even the largest HPC systems. Containerised data centres should be considered for EuroHPC systems.

4.4.1.4 Memory Technology

Memory Technology is principally controlled by 3 major WW vendors: Samsung (South Korea), SK Hynix (South Korea), and Micron (USA). Memory standards are developed and managed in JEDEC (Joint Electron Device Engineering Council). Datasets are continuing to grow, and data storage and movement are increasing in importance to compute. As such, Europe should invest both in memory technology and in research in Processing In memory (PIM) and Processing Near Memory.

4.4.2 Software Technologies

The development of software technologies for HPC, AI and QC will address a system SW stack which connects low-level interfaces at the operating system level with user and application programming interfaces. While the important role of open source and public domain software is acknowledged, the impact of open source software on a sovereign European value chain is often limited due to the lack of specific knowledge, capacity and control of the development. The competences for the independent development, build and deployment, maintenance, and support of many critical software components for the operation of supercomputing environments are currently not usually available in Europe.

European Software Stack (ESS): EuroHPC will work with stakeholders to coordinate co-design in the R&I of hardware and software activities and ensure those activities meet user requirements and that developed technologies are deployed. Calls shall be launched, which will take each building block in HPC, AI and QC from innovation to deployment, targeting different TRLs as required by the status of HW developments. This activity shall be closely coordinated with ongoing development of software integration layers (middleware) and applications that are targeting current and upcoming European supercomputing technology. Admittedly, not every single SW component of a European supercomputer shall be developed in Europe (see Section 3 on European Sovereignty); instead, EuroHPC shall support European scientific institutions joining international bodies (e.g., OpenMP, MPI, PCIe, CXL, to name only a few), to influence their evolutions toward EuroHPC's interests, hence minimizing the effort of adaptations in the rest of the involved software components. Instead, API-level compatibility and development of specific back-ends shall be favoured where possible. To eventually attain high TRLs, the ESS must adhere to well-established SW development procedures for production software, including requirements for measures to assess and secure the quality, reliability, and security of the developed software as an integral part of the development cycle.

Challenges: A number of challenges arise when it comes to HPC/AI/QC software stacks and the related applications. System software and programming environment solutions are needed to support the following end-user application challenges:

- **Performance**: software supporting the optimisation of applications, their dependencies with respect to parallel systems and network design for data-intensive and compute-heavy workloads.

- **Scalability and flexibility**: applications need a software environment to enable easily scalability in order to use resources efficiently, and where feasible adapt to changes in available resources.
- **Portability**: software components and applications should work across heterogeneous and diverse architectures (HW and SW environment), which is a particularly difficult challenge for older codes.
- **Performance and efficiency portability**: in addition to the above, one should achieve comparable levels of (relative) performance and energy efficiency across different architectures.
- **Programming productivity**: programming environments should help reducing the time needed to develop applications that exploit the underlying hardware efficiently in terms of delivered performance and energy.
- **Data management**: SW needs to adapt to ever-increasing variety and complexity of underlying memory and storage subsystems, including accelerators/co-processors equipped with self-hosted memory and multi-tiered memory/storage systems. It shall also address challenges of data distribution and processing across networks.
- **Availability**: how to deploy the software so that it is available on all EuroHPC systems and fully integrated with the SW stacks deployed there.
- **Usability**: it is difficult for new (and sometimes even for reasonably experienced) end-users to find the optimal setup for their use cases; SW tools should help with analysing performance achieved and energy used and provide actionable feedback (potentially relying on AI techniques).
- **Resilience**: hardware failures, network overloads, and other system failures lead to data loss, delays, or system downtime, resulting in financial losses, productivity losses, security risks, etc. Due to the increasing role of renewable energy, adapting to changes in renewable energy supply is a new challenge here.
- **Security:** software solutions are needed to protect applications against system errors, bugs, or vulnerabilities, such as data poisoning, model stealing, or adversarial input.
- **AI-SW integration**: AI applications often use different frameworks, libraries, and tools, which can create compatibility, integration, orchestration and usability issues, particularly for HPC/AI hybrid environments.
- **Energy consumption**: energy efficiency, eventually, is becoming an overarching concern and priority at the same level as raw performance; this efficiency can benefit from many improvements in the software stack and is eventually an important metric for an application and the global use of an HPC system. In addition, providing flexibility

to maximally leverage time-varying supplies of clean, renewable energy would be valuable in further reducing the carbon footprint.

- **Lack of expertise and support resources**: high level support, and SW developer and user training must be recurring, and tailored to address actual user community issues. However, more resources should be dedicated to promote and provide user support for the various software elements installed on EuroHPC supercomputers, in connection with CoE and projects like EPICURE.
- **Lack of a continuous source of base funding** that enables keeping the software up to date, but also securing the expertise of the involved researchers and research engineers for the long term.
- **Wider adoption** of the developed software solutions in production environments, given the strong operational and security constraints.
- **Lack of mature operational software for QC**, which results into a very limited set of quantum integration with HPC, software methodologies, environments, tools and applications.

SW Modularity: The promotion of common interfaces on the basis of open community standards is critical to develop an innovative, competitive, resilient and more autonomous HPC ecosystem. It will enable developers to select and implement potentially competing alternative solutions, the seamless substitution of software components and the rapid composition of new solutions. This shall not preclude, however, the existence of non-standard(-isable) Application Programming Interfaces (APIs) for reasons such as providing high-level abstractions, intermediate or domain-specific libraries, or forerunners of standardisation attempts. In addition, *de facto* and community standards have demonstrated to play a very important role in the world of HPC and should be actively sponsored.

SW Diversity: Activities to support the development of a system software stack shall account for the diversity of the European software ecosystem, which involves many contributors from multiple institutions. By pursuing a modular approach with focused grants for specific software developments with limited scope, EuroHPC shall address the challenges of the evolving European HPC ecosystem, while maintaining inclusive and balanced support and funding. Given the relatively low cost of these SW components with respect to HW efforts, EuroHPC shall favour healthy and collaborative competitivity and diversity. Allowing more than one SW component to implement the same functionality following different approaches will bring the benefits of competitivity plus increase the chances of success and long-term sustainability. Using Open Source licenses shall ensure cross-pollination and wide acceptance of the most successful approaches. Enforcing interoperability and promoting the creation, adoption and contribution to open standards are key elements for the implementation by EuroHPC.

Priority domains for SW technologies that address the aforementioned challenges include:

- **Strategy for adoption**: develop a structured strategy for high TRL software solutions to be adopted in the EuroHPC production environments. This shall start with a direct dialogue between software developers, system vendors, and operational teams to address the strict requirements (e.g., security, performance, reliability) and SLAs of the EuroHPC infrastructures. This may also require a new level of balance between requirements for hardware and software investment within the future EuroHPC system procurements.
- **Generative AI**: Leveraging generative AI within the life cycle of European software components and applications as a new methodology for developing, deploying, optimizing and maintaining software components.
- **CI/CD**: An effective common development and deployment mechanism for end-user software such as a Continuous Integration/Continuous Deployment (CI/CD) platform and software container technologies; optimised container images can underpin the open science approach (e.g. interoperability, portability, and reproducibility) and are an option for the support for legacy code. The container mechanisms used must allow highly efficient use of the hardware capabilities across all relevant platforms (in terms of performance and energy).
- **Workflow managers** supporting scientific and AI pipelines across modular HPC supercomputers, federated HPC, cloud-HPC, and QC-HPC. The focus should be on workflow managers that support the integration of HPC, AI and data analytics in the same application workflow within a supercomputer. In addition, since many workflow solutions are available, efforts towards their integration should be sought.
- **Scheduling and resource management software** (including dynamic elastic resource allocation and management mechanisms) for highly heterogeneous supercomputers, and mixed HPC/AI/QC environments. Note that the heterogeneity mentioned here refers to the hardware heterogeneity within one system, and is not addressed by the federation platform. This includes not only global resource management systems but also runtime systems and system software handling resource heterogeneity, which shall evolve to efficiently handle upcoming hardware and system configurations. Where applicable, such SW shall optimise the global energy use of HPC/AI/QC systems and sites, be able to match resources with the evolving needs of malleable applications

and adapt to varying availability of green energy. The overarching objective is to co-optimise achieved throughput and energy/carbon footprint.

- **Cloud-accesses**: Middleware for Cloud-HPC and Cloud-QC integration to make supercomputers easy to use for non-traditional HPC users, e.g. SMEs working with data analysis, generative AI, or data streams from the compute continuum.
- **Monitoring**: Fine-grain, non-intrusive and holistic monitoring and analysing of performance and energy data down to the application/job/workflow level, and advanced data analysis to determine performance, energy, and resource consumption patterns and create actionable recommendations for application developers, end-users and system operators.
- **Security:** Software monitoring and protecting the security of systems, and detecting and responding to incidents and intrusions related to the EuroHPC infrastructure.
- **Support European processors**: Complete and highly optimised (in terms of performance and energy use) software stack for European processors, including compilers and libraries, application and system runtimes, application frameworks and programming environments.
- **Standards**: Activities to achieve and maintain a leading influence in standards for frameworks and programming models and their implementations for HPC, AI and QC.

4.4.2.1 Quantum Computing Software Technologies

As quantum computers are added to the EuroHPC infrastructure, a comprehensive SW stack must come with them to enable non-expert application developers. User interfaces, libraries, debuggers and validation tools, high-level programming models and languages are needed, as well as compilers to translate high level languages to QC circuits, and transpilers[10] that adapt already compiled circuits to a dedicated technology. Although some of these tools already exist, their maturity level (TRL) is relatively low, and additional developments will be needed when the sizes of quantum computers increase.

Hardware abstraction: The plethora of QC solutions requires many of the SW tools to be designed targeting specific modalities. However, it is important to abstract HW-specific parts of the SW away from the end user. These abstractions are fundamental for the uptake of the QC technology. The complete toolchain described above, with clear interfaces, paired with the appropriate level of abstraction, will also allow experts to develop SW components for where their expertise lies, be it in the quantum, or computer science domain.

[10] Transpiler is another name to refer to source-to-source compilers.

Scheduling software: The system-related SW is closely related to the QC hardware and to the fine management of the compute resource provided by the QPUs. This leads to a classical schema where a computational task must be submitted to a limited and expensive computing resource. The HPC world addresses this kind of situation with efficient scheduling mechanisms, which handle waiting queues fairly and optimise the usage of resources. In hybrid HPC/QC environments, multi-level schedulers need to take care of the different time restrictions that occur in a hybrid Quantum Computer Science (QCS) program (e.g. between shots, iterations, offloaded tasks). To this end, the definition of a standardised approach, which considers the different characteristics of each type of QC hardware, such as the sampling rate, qubit connectivity and qubit number, among others, is required.

Quantum emulators: in recent years different emulators have emerged: SW-based, GPU-based, and FPGA-based. SW-based emulators use methods like decision diagram-based simulators to reduce memory needs by finding patterns in state vectors and quantum gates. GPU-based emulators use Single-Instruction-Multiple-Data (SIMD) to increase parallel processing in matrix operations necessary for quantum circuit simulation. FPGA-based emulators also use SIMD techniques and special designs to make the most of the sparse nature of gate matrices, cutting down on unnecessary operations and processing time. Even with these improvements, scalability is still limited by memory and execution time, leading to the use of modern HPC systems to simulate large quantum systems to mitigate the exponential cost of these simulations[11]. In the future, emulators will remain important for refining quantum computing models. Unlike real QCs, emulators allow step-by-step analysis of quantum algorithms with high accuracy, including phase information. Emulators with noise models are also valuable for engineering new quantum technologies, as they provide performance insights by varying physical parameters. Moreover, emulators enable tracing the state of the circuit at any point for debugging, which is not possible on actual QPUs. Most available emulators, although being open source, are developed by QC manufacturers and often lack support for HPC implementations like distributed computing and GPU acceleration. EuroHPC should support the development of a fully parallel, accelerated (open source) emulator, needed for the rapid adoption of quantum technologies.

Middleware: QC middleware should leverage the experience that already exists in HPC and should make sure that it can be easily integrated in this previously existing framework. The dichotomy between user-related and system-related middleware makes it necessary to explicitly define the interface. De-facto standards are currently emerging, such as OpenQASM

[11] The largest simulation of a quantum circuit used 0.5 PB of memory to simulate 45 Qbits, see [85]

[79] and QIR [80], but there is no consensus at the time of writing. QC middleware should also expose solutions to emulate on HPC systems the behaviour of quantum applications running on various QPUs. This use of emulators is helpful for: 1) application development, 2) validation of applications before running on QC HW, 3) debug and profile a quantum job, and 4) validate the correct execution of a quantum program by comparing emulated and HW results.

Quantum Computing and AI: While current quantum computers still have a limited capability for accelerating machine learning workloads due to slow load and store of data, lack of quantum memory, and limited coherence times, Quantum Machine Learning (QML) is nevertheless quickly becoming worldwide a very active research topic. Moreover, several leading QC system vendors, e.g., Quantinuum, define AI applications as a priority. To keep alignment with this development, it would be important to launch R&I calls for developing QML applications, also with the prospect of running on fault tolerant QC that could arrive at the end of the decade. It should also be noted that AI is very useful for designing QC hardware and processes (qubit frequencies allocations, optimising qubit control, etc.). AI techniques are also used on the software side, supporting the initial preparation of variational quantum algorithm ansatz, quantum gates synthesis, code transpilation, and optimization prior to computation**.** Moreover, after the QC computation AI can be used to perform quantum error mitigation and detection, variational algorithm ansatz tuning, or quantum sampling. A call addressing AI for QC and QC for AI should allow to explore different couplings of these two groundbreaking technologies.

Error mitigation and correction: EuroHPC shall consider providing holistic integration calls with the mission to build generic as well as HW-specific SW stacks, including state-of-the-art Quantum Error Mitigation (QEM) and Quantum Error Correction (QEC). The goal is to establish efficient co-design of applications within the framework of a co-evolving HPC/AI/QC community, and requires tight collaboration between European HPC centres, academia, institutes, QC HW and SW startups, and SMEs. The overall aim is to build European HW/SW-collaborations that can compete at the forefront of the global state of the art of large-scale demonstrators and make deeply educated decisions regarding future quantum-system procurements.

Standards: International standard bodies are currently working to define standards for quantum technologies. In order to safeguard European developments, EuroHPC should engage and/or support European QC communities and private bodies (QuiC) with these efforts to ensure proper representation in these discussions alongside with several members states that are already involved into standardisation activities within European bodies like

CEN/CENELEC It should be noted that eventual standards will also play a role in the technical definitions of export controls, which already significantly affect the QC market.

4.5 Applications

Main Recommendations for 2025-2027 period:

- Support the communities in their effort for developing, porting and optimizing their applications to the currently predominant HPC system architectures with tools and methods that will ease further adaptations in the future.
- Support the integration of HPC experts into the scientific application communities, allowing thus for a strong interaction with the domain experts, which is crucial for the development of exa-scale ready applications.
- Strengthen the funding of the application pillar by rebalancing the funds with respect to the infrastructure procurements as to make best use of the procured infrastructures.
- Support the optimisation of foundational models on HPC platforms and support the integration of AI approaches in HPC applications (e.g. AI-hybridization, fine-tuned the generated foundational models, ...).
- Support the growth on QC applications, both in stand-alone and hybrid HPC/AI/QC contexts.

Looking beyond 2027, develop and promote frameworks based on separation of concerns between scientific coding and technical computing implementation, to facilitate automated porting of domain applications on EuroHPC platforms and their efficient exploitation.

The success of any technological infrastructure is determined by its impact on science, industry, and society. To date, Europe has a strong record in application development and is world-leading in many academic and industrial domains. To maintain this position constant efforts are needed as applications have to adapt to new HW technologies, incorporate new algorithms, methods and scientific methods, and improve their efficiency and scaling on existing and future systems. Therefore, supporting the scientific and industrial communities to ensure that they develop and optimise their applications on EuroHPC platforms is crucial.

Community heterogeneity: However, the European HPC user community is not a homogeneous body**;** it spans a broad spectrum of skills, knowledge, and experience in developing and using HPC, AI and QC applications. The scientific communities work with legacy codes, which brings challenges and limitations – many codes cannot be easily fully rewritten; HPC for numerical simulation, unlike the younger AI area, has a strong and complex application and software basis. The challenges to be addressed now are preparing existing codes and applications (academic and commercial) for the current and future HPC/AI/QC architectures deployed by EuroHPC, and designing new algorithms and methods that run and scale to match future HW/SW and that are fit to tackle upcoming scientific challenges. This effort should be based on scientific and industrial cases giving a prospective on the scientific and industrial questions targeted by the user communities. The goal is to have a rich set of commonly used applications in key scientific and industrial domains, supporting existing users as well as emerging ones, readily available on EuroHPC systems and using these efficiently.

Continuous dialogue with application communities: In this respect, EuroHPC shall seek for a stronger and continuous dialogue with the application communities to ensure adequate support for Europe's evolving and rich application ecosystem. This dialogue should also include the upcoming federated services and improved interconnect between EuroHPC sites. The conception of these services shall involve the users by design to make sure that user requirements are met and to ensure a quick adoption by the community. The User Forum and its Coordination Group represent a key player in this dialogue. The independence of the User Forum is crucial for their integrity and for being able to fully serve this purpose. It is also important to connect and better coordinate the different initiatives and communication channels (e.g., NCCs, CoEs, User Forum, user support projects etc.) towards the application communities. The different needs of various parts of the communities (e.g. users vs. application developers, HPC vs. AI focus, etc.) should also be considered in this context.

Funding instruments: Today, the main funding instrument of the application pillar are the Centres of Excellence (CoEs). A new concept is under discussion, accounting for the fact that the variety of needs of the application community requires different funding instruments and tools. In addition to the Centres of Excellence, the new concept foresees additional funding instruments, for example specific calls for innovative algorithms and for transversal libraries. In all cases, it is key here to rebalance the funding toward applications to ensure an effective use of the EuroHPC platforms by the real applications and therefore a positive significant impact on society.

4.5.1 HPC Applications

The lifetime of applications can easily span decades. Therefore, all development activities require long-term planning and a sustained effort beyond the typical duration of 3-4 years for a EuroHPC project. This is even more important now, as acceleration, improved performance and energy efficiency depend more on optimised applications than on better and faster systems. Funding must be provided to ensure that applications reap the full benefit of new computing platforms but also to retain personnel qualified to deploy these applications on these platforms on the long-term.

Recommendations: To address the challenges associated with the increasing complexity of SW development on heterogeneous HPC architectures, the general shortage of skilled developers and the general objective of achieving more modular, sustainable, reusable, reliable, secure, and higher quality software, EuroHPC shall:

- **Portability and scaling:** Support for HPC and HPC/AI-powered codes, applications, and tools in all phases (such as in co-design, development, incorporation of new methods, exploiting low/mixed precision, porting, re-structuring, optimisation, upscaling, interoperability, re-engineering, etc.) for achieving highest compute and data processing performance and energy efficiency up to extreme scales, when possible, given the constraints of the communities' legacy codes.
- **Software engineering:** Support the user communities in their effort to apply common software engineering standards and best practices with respect to code development, code integration and code deployment. Such standards must emphasise SW quality in terms of delivered performance and energy use and build upon the tools and procedures that have already proven useful in the different communities. Best practices include modularisation of applications by identifying common SW building blocks and supporting their redesign using highly optimised libraries, when possible. This requires more integration of HPC experts into the scientific application communities, allowing thus for a strong interaction with the domain experts.
- **Novel algorithms and applications:** support the development of novel algorithms and applications, especially in areas where HPC has not been yet exploited and where there is an opportunity to enlarge the portfolio of European applications and algorithms. A sample area is electric power systems (EPS) where (HPC) is not a standard part of the toolboxes employed.
- **Workflows:** promote new frameworks for the development of complex workflows that combine different application components, possibly of different nature (HPC, AI, HPDA) to be executed inside large allocations in a single supercomputer. Those frameworks should address challenges related to the efficient use of the new heterogeneous and complex HPC systems, with malleable, elastic execution and dynamic allocation that take into account performance as well as energy. Support new usage methodologies for interactive execution based on workloads, especially for AI workloads or converged HPC+AI ones.
- **Benchmarking**: consider new methods of benchmarking which are relevant for the actual use cases (HPC, AI, based on performance/energy for systems on production). Today, the evaluation of the performance of our HPC systems is mainly based on indicators such as the theoretical floating point operation performance, synthetic

benchmarks (e.g. HPL) or scaling behaviour of individual jobs to an entire HPC system. These values may help to guide developments but do not reflect the value to science or society as such. New benchmarking criteria, capturing the aforementioned impact could include (but not be limited to):

1. **measuring** the **outputs and results** of innovative and efficient **applications** that fully exploit available HPC technology for real use cases.
2. **measuring entire workloads** (for instance including I/O), which would account for the fact that optimisation requires a system-wide and holistic approach.
3. **taking into account both energy/carbon footprint and performance** (in terms of results and/or impact per Joule or gram of CO_2) of the applications and workflows.

Such benchmarks would then establish the efficiency of a system for a specific application domain or even use case. Looking towards the future EuroHPC regulation, the position of a system on the Top500 list should not be the main goal in procurements, but rather how it performs on real-world applications, and how large it is its scientific and industrial impact (e.g. number of publications or patents achieved with the system).

- **Libraries:** Promote the development and porting of transversal libraries for applications to accelerate readiness for new architectures and address horizonal and cross-cutting elements, such as AI and energy efficiency. Mechanism for supporting the uptake of these transversal libraries by the user communities are to be considered too.
- **Energy efficiency**: Support application developers and end-users in achieving meaningful reduction of energy use through new methods and tools applicable by the targeted users, and not just a top cadre of specialists. Effective training will play a large role here, too.
- **Security:** Support the user communities in improving application security and preventing misuse and cyberattacks. This can be achieved for example by stronger access control, isolation of workloads, code signature, encrypted containerisation, or safe distribution of certified software and applications. Paradigms such as “confidential computing” shall be more widely supported.
- **Embrace novel computing hardware:** Stimulate the usage of novel (and possibly disruptive) computing hardware, such as quantum devices, neuromorphic computing or other accelerators for specific AI tasks, as well as their integration into the HPC software and application stack.

In addition to these recommendations, we see some specific challenges related to the increased importance of AI and of Quantum Computing in HPC.

4.5.2 AI Applications

EuroHPC aims to achieve excellence and maintain European world-leadership in HPC/AI/QC applications that are key for European science, industry, and the public sector. In particular, these applications need to integrate the worlds of simulation and AI to facilitate hybrid workloads, such as AI-complemented simulations or larger workflows consisting of alternating AI/ML and HPC steps.

Recommendations: The following objectives need to be pursued:

- **Foundation models:** Support the development of European Foundation multimodal model(s) for science in HPC systems either through a universal single model (à la the Trillion Parameter Consortium, TPC) or via several models depending on relevant domains and underlying scientific principles. These models are the cornerstone of specific AI applications and will thus provide a solid, trustworthy and sovereign basis for a wide variety of European AI tools at large.
- **Specialisation of models**: once several (and not hundreds) multimodal foundation models in Europe are trained, maintain them and strongly support the specialisation of such models in science and industry (fine tuning) for increasing diffusion of AI models.
- **New domains**: Identification of applications areas in HPC that need additional AI-support to meet the diverse European user community needs.
- **Interoperability**: Development of common APIs that allow interoperability of Big Data and AI workloads, which are typically deployed in public clouds and European Data Spaces [49], with HPC infrastructures.
- **Code generation**: Development of AI tools to accelerate application development.

4.5.3 QC Applications

More and better quantum applications and use cases are needed for a wider adoption of the deployed EuroHPC quantum computers. European Quantum Excellence Centres (QCoEs) [81] shall bring users of quantum technologies together and train a growing skilled workforce able to develop new applications for QC, applying SW engineering principles, and foster knowledge and uptake of QC. These QCoEs should develop quantum applications that can solve real-world problems. This could involve collaboration between QCoEs, HEs, and industry partners to identify challenges that can be addressed using QC and then developing applications that can solve those challenges. Quantum programming facilities and application libraries, especially if released open source, help developers to create new quantum applications. The EuroHPC QC platforms acts as testbeds for quantum technologies and serve as software development platforms for both middleware and applications.

Application development should focus on use cases providing the most foreseeable advantage in a relatively short term, as well as studies of new qubit technologies.

Recommendations:

- **Hybrid HPC/AI/QC**: EuroHPC should support experts from HPC/AI/QC startups, academia, and end users (including SMEs and large companies) in developing proofs of concept for novel hybrid HPC/QC algorithms. Quantum-inspired algorithms enable using powerful quantum information processing techniques on classical HPC hardware. Therefore, quantum-inspired approaches for HPC and AI must also be supported, as they lead to improved solutions for classical problems and to more efficient classical simulation of QC.
- **QC benchmarks**: Progress in application development and experimentation should be the basis for defining a broad set of application-centric benchmarks in close cooperation with the application communities, avoiding to prematurely lock into a particular technology or algorithm. Benchmarks are used in HW-SW co-design, essential for the success of both QC devices and applications. They are also needed to establish a widely acknowledged ranking system, mature and flexible enough to accommodate future technological developments.

4.6 Usage and Skills

Main Recommendations for 2025-2027 period:

- Provide specific training and education to grow the pool of hardware, system-SW developers, and HPC/AI/QC system administrators, building upon IT and STEM curricula. Federate European and national training and education for HPC/AI/QC to exploit synergies between different initiatives.
- In order to prepare the post exascale era EuroHPC should launch in 2025 a bottom up consultation effort to identify key use cases among scientific, industrial and public services user communities, in order to gather applications and services requirements in HPC, HPDA, AI and QC.
- Support the hybrid HPC/AI/QC environment via projects that pull together QC Hosting Entities and NCCs to foster collaboration between HPC/AI and QC, extend European HPC

masters with QC and AI topics, and provide training and education instruments for HPC and AI specialists to learn how to use QC systems.

- Provide specific training and education instruments for AI specialists to learn how to efficiently use HPC resources extracting maximum performance to lowest energy consumption and carbon footprint.
- Continuous investment in support structures for HPC/AI/QC users, making it clearer which projects/initiatives exist, and which are their respective responsibilities.

Looking beyond 2027, intensify the investment in a growing and diverse pool of HPC/AI/QC experts, particularly by developing attractive career paths and long term-perspectives that motivate young talents to enter and stay in the field.

To enhance Europe’s competitiveness, boost its technological and data sovereignty, and strengthen European innovation, the European HPC ecosystem made up of EuroHPC, Member States, HPC research institutes, HPC users, CoEs and NCCs must work together to a generate a highly knowledgeable, world-leading scientific and industrial community capable of advancing HW, SW and applications, and provide training and support at different maturity levels. In particular, EuroHPC shall support the development of digital skills, professional training, and education, attracting engineering knowledge and human resources to HPC in Europe and increasing Europe’s workforce skills.

Consultative groups: To increase involvement of existing and new users, EuroHPC established in 2024 a new consultative group consisting on a User Forum This group shall support RIAG and INFRAG and provide reliable, sustainable feedback to the governance bodies of EuroHPC on current and future infrastructure and software requirements, and give strategic advice for the development of targeted use cases and a renewed scientific and industrial case. They will also serve to disseminate the range and availability of EuroHPC infrastructure, training, and skills to new and existing user communities.

Key use Cases: As EuroHPC will end its second period with the deployment of 2 exascale systems, several first quantum computers and a set of AI-optimised supercomputers in the field of AI Factories, the next regulation will aim to deploy so-called post-exascale systems across Europe. While post exascale concept is not fully defined yet it could be important for EuroHPC alongside with R&I projects on new technologies to launch a wide consultation, for gathering key use cases among scientific, industrial and public services end users communities in order to gather their needs and expectations in terms of HW/SW technologies and services. This could lead to a European definition of the post-exascale concept consisting not only of more powerful or more architectural-diverse/tailored systems but also on a new generation of services provided to end user communities.

4.6.1 National Competence Centres (NCCs)

Motivation: It is essential to extend the use of supercomputing to a wider range of scientific and industrial users, for instance by helping SMEs develop innovative business cases using supercomputers and providing them with training opportunities and critical HPC/AI/QC skills they need. Investment in HPC NCCs is promoting a wide coverage of HPC/AI/QC activities and expertise in the EU and is providing specific services and resources for industrial innovation (including SMEs).

History and role: The NCCs were created by the EC in 2020 and were strengthened in 2022 to prioritise and support exchange of best practices, to foster the uptake of HPC solutions by startups, SMEs and large companies, the sharing of existing libraries of HPC codes, and access to upgraded HPC application codes. They facilitate access to the best HPC/AI/QC codes and tools and innovative scientific and industrial applications in collaboration with CoEs and the European Digital Innovation Hubs (EDIHs) [82]. This includes federating capabilities, exploiting available competences, providing user input into the development of HPC technologies and applications, and ensuring that application knowledge and expertise has the widest geographical coverage in Europe. HPC Competence Centres and HPC Hosting Entities work together to facilitate access to large-scale HPC enabled pilot demonstrators and testbeds for big data applications and services in a wide range of scientific and industrial sectors.

Recommendation: Furthermore, in order to strengthen the ongoing deployment of first QC infrastructures, EuroHPC could setup projects that pull together QC Hosting Entities and NCCs to foster collaboration between HPC/AI and QC communities toward hybrid HPC/AI/QC[12].

4.6.2 HPC skills

Motivation: The development of a skilled workforce is one of the most sustainable investments in HPC/AI/QC with the potential for long lasting impact in a rapidly changing environment. Europe needs skills in highly specialised HW and SW development in order to support HPC/AI/QC infrastructures, federated resources and services, technologies, and applications. Europe needs an increase in HPC skilled workforce that is diverse, and gender balanced. This workforce is critical to support the design of emerging European HPC technologies and applications, the running of existing HPC/AI/QC systems and the provision of support to users.

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[12] Already started by ENCCS (Sweden) in collaboration with LUMI and NordIQuEst through the Quantum Autumn Schools [82]

Build upon IT and STEM: Training, skills, and support is a cross-cutting topic relevant to HW and SW technologies, applications, including areas such as AI, data, cybersecurity, or QC, and not forgetting large system administration and computing centres operations. Proximity with more general Information Technology (IT) or Science, Technology, Engineering and Mathematics (STEM) areas should be leveraged, e.g. by connecting with existing curricula in broader IT or STEM areas that could offer HPC extra specialisations to complement EuroHPC efforts. Lifelong perspectives must also be considered, facilitating periodic re-training or on the job training, and circulation between academic and industrial sectors.

Status Quo: EuroHPC has launched three calls in support of these objectives: the EuroHPC Professional Traineeships and EuroHPC Training Platform and Summer School [30], and the EuroHPC Virtual Training Academy [31]. On top of these, the CoEs offer specialised training for HPC specialists as well as IT and data professionals, application developers, and advanced users of HPC applications. At this stage as these initiatives have been launched recently INFRAG and RIAG do not have additional recommendation to provide.

Training material repository: In order to exploit all the above sources and leverage the HPC training materials developed in the European projects (e.g. R&I project, CoEs, and NCCs), a portfolio of common European HPC training material should be established. EuroHPC shall create, implement, and maintain a reliable and long-term repository to safely store all the existing and future training materials and make them available to the European citizens. This facility could also accommodate HPC training material provided by the Participating States.

Master Program: The **EUMaster4HPC** [27] is educating the next generation of HPC experts and already celebrated the graduation of its inaugural cohort in 2024. EuroHPC launched a new call for the following phase of its Master Program, for which INFRAG and RIAG consider important to extend its scope beyond HPC to cover now AI and QC, and to be more ambitious on the number of students trained per year (targeting ideally 200+ students graduated per year). This is vital for ensuring that a regular flow of skills will feed the activities of the infrastructure, ensuring gender equality and inclusiveness of all countries. This ambition comes also with mandatory efforts of raising awareness about such a pan-European program and appropriate career plans among academia and industry.

Talent creation and retention: More actions shall be considered to develop and retain a European talent pool in HPC and develop viable and rewarding career paths for Research Software Engineers (RSE) and other key roles. In addition, appropriate support (on different maturity levels) in using the EuroHPC infrastructure and applications needs to be provided. Support to increase EuroHPC competences will also come with the NCCs and will support the European ecosystem of users and developers. These efforts need to be paired with pan-

European activities to coordinate user support, from a beginner to advanced levels, provided by HPC centres (both EuroHPC and national/institutional) and technology and application projects.

Recommendations: EuroHPC shall consider actions in the following domains:

- **Specialised training for HPC specialists** should be continuously offered, from technology developers to computing centres staff (HPC sysadmins, HPC engineers), to software and application developers, and to advanced users of HPC/AI/QC applications and related topics.
- **Performance and energy efficiency:** Skills to support development of performant, energy efficient and sustainable solutions in HPC technology and application design must be promoted, in the interest of reducing the energy and Carbon footprint of the HPC/AI/QC infrastructure. Actions should make developers of applications and workflows as well as end-users aware about the energy used by their applications or their use of these, educate them on methods to optimise these aspects through changes in application codes or application usage, and provide incentives for investing effort in reducing the energy/Carbon footprint of their HPC/AI/QC-related activities. Such training must emphasise the importance of efficiently using available infrastructure resources, in the interest of achieving high performance and at the same time reducing energy use.
- **Industry-specific training**: Short-term, industry-specific training schemes, for example combined with consultancy and trial use of HPC infrastructures through hosting entities and competence centres. SME-tailored courses and support offerings like staff exchange programmes with research and academia could be offered. For end-user SMEs, this could include hands-on training and solving real use cases, developed in cooperation with the competence centres and the European Digital Innovation Hubs.
- **Mobility**: Encourage mobility and supporting training projects that also include the opportunity to study/train in another European Participating State. Opening such programs internationally to talented people would be beneficial.
- **Skills for emerging and hybrid approaches**: Skills for emerging technologies such as quantum computing should be considered, as well as those combining HPC and other related technologies (AI, QC, data, cybersecurity, etc.). Such new tracks could include knowledge exchange programs, educational programs (e.g., [83]), knowledge databases (wikis) and other projects that bring these communities to work together. Create either a dedicated education program for SW engineers in quantum technology or extending the EUMaster programme with QC content.

- **Sustainable career paths** with reasonable and competitive conditions. The development of a European talent pool must be a permanent and overarching objective in HPC. The creation of a European job market for HPC professionals shall be considered, with rewarding career paths for research software engineers and other key roles.

4.6.3 HPC training for AI users

New cases relevant to the AI and data communities, and for which HPC resources and methods are relevant and will grow tremendously. This can include training of large language models, model development, cross-training of data sets and models, bias detection and quality assessment of trained models, monitoring and early detection in federated models, validation, and test of accuracy against simulations and complex digital twins. It is essential to provide broad diffusion of how HPC competences and approaches can augment and accelerate existing ambitions or provide new sources of revenue.

Regarding AI uptake the challenge of using HPC infrastructures by the AI community will rely on three key factors: 1) the availability of converged HPC/AI supercomputers, 2) revised access modes for the AI community, and 3) HPC experts able to support the AI research groups in optimising and scaling out their models. Of these three aspects, the third (support of AI research by HPC experts) can be the strength of EuroHPC.

Recommendations:

- **Upskilling programmes** for existing profiles from AI model developers, AI quality managers, Database engineers, Data Scientists, etc. AI model developers, AI governance and compliance professionals, and large dataset architects, in particular, should have access to HPC education and training. Different modalities from initial training to on-the-job training are to be considered, to match the different stakeholders needs, from deep technical specialisation to agile training for swift uptake by private companies. Support must come at national and European level for the full ecosystem of users and developers.
- **HPC material for academic AI curricula:** Develop off-the-shelf content and structures to include HPC teaching within existing academic programmes at undergraduate and post-graduate courses related to AI and Data for mass uptake across education establishments in all Member States.
- **Energy/Carbon efficiency:** Ensure that efficient use of resources and minimisation of energy/Carbon footprint is considered by HPC and AI professionals as an important factor. These AI-training activities should also teach application developers and end-

users how to select methods to tackle a given problem with efficient use of resources and energy in mind13. In a similar vein, energy used for ab-initio or recurring training must be amortised across many uses of a trained model, and such analysis should impact the selection of AI approaches and training schemes.

- EuroHPC shall also consider a **training certification scheme**, which could be adopted by all European actors and should be embedded with the digital identity of the user giving possibility to access the European HPC systems based on the level of knowledge the person obtained. In the case of AI and data arena, it is recommended to develop a certification alongside such upskilling programmes for AI and Data professionals as part of Continuous Professional Development.

All the above activities, while focused on European participation, need to implement the state-of-the-art in learning methodologies, including alternative forms of learning (e.g. student-centred instruction, participatory learning, hands-on learning, open learning) should be implemented.

4.6.4 Users

User support: Users of the EuroHPC infrastructure require support, tailored to their knowledge and problems at hand. This includes first and second level support to be provided by the infrastructure providers as well third level support, currently partially provided by the NCCs and projects like the CoEs. EuroHPC develops a structure covering all levels of user support and shall fill the existing gaps with appropriate actions. This has started with projects like EPICURE [24] and the MINERVA support centre for AI launched in 2024. Given the growing number of instruments for user support, EuroHPC should clarify the role of different support services provided locally by the HEs and AIFs, versus those provided at pan-European level, as well as to rationalise and pool certain actions between the NCCs, EPICURE, MINERVA, and CoEs.

Co-design and technology adoption: a fluent communication should exist between the application communities (both users and application developers), and the user support teams in HPC sites, as well as with hardware and software developers. This would help developers of European software and hardware solutions (see Technology Pillar in Section 4.4) to understand the end-user requirements, and vice-versa facilitate the adoption of the developed solutions by application communities. Currently this communication role is being

[13] Traditional ML techniques like regression or clustering can address certain data analysis problems with less energy use than more powerful, yet also power-hungry DL-based approaches.

played by, e.g., the CoEs, and it should be ensured that such communication channels continue existing in the future.

Energy efficiency: End-users play a significant role in limiting or even reducing the energy/Carbon footprint of the EuroHPC infrastructure. They must employ it in a responsible way, e.g. by avoiding jobs/workflows configurations that lead to inefficient use of resources and energy waste. To achieve this, training in best-known-methods for HPC/AI/QC system use, tools providing actionable feedback, and user incentives (e.g. [84]) are necessary.

User Forum: the EuroHPC User Forum was launched in 2024 to promote knowledge exchange, professional development and collaboration within the European HPC/AI/QC communities. It is constituted by users from academia, industry, and public sectors, as an open institution, inclusive, independent, transparent, and responsive to the needs of its members. The EuroHPC User Forum is led by a coordination group of 12 members representing various communities from academia and industry, numerical simulation and AI, traditional end user communities to new ones including humanities and social sciences. Activities started during EuroHPC User Days in October 2024, and several actions have been initiated (e.g. to encourage efficient use of HPC resources, and to gather HPC/AI user and application needs). Regular meetings with INFRAG+RIAG ensure a proper feedback loop with inputs and user surveys that are used for MASP updates or advice to EuroHPC Work Programs. **Special care must be taken in supporting User Forum activities and increasing representation of industry and new communities like public services or QC**, e.g. with support from ETP4HPC, BDVA, and QuiC.

4.7 International Cooperation

Main Recommendations for 2025-2027 period:

- Extend international cooperation to the regions of Latin America, South Korea, Singapore and Canada, covering HPC, AI and QC, and ensure not only strong scientific/technical collaborations but also political support.
- Support collaboration with international initiatives in a manner coordinated at European level, particularly in the area of AI (e.g. TPC) to secure positioning and ensure visibility of European developments and interest.

Looking beyond 2027, implement means to exchange compute cycles with international collaboration partners, allowing users from outside Europe accessing the EuroHPC infrastructure and, reciprocally, European HPC users to access infrastructures abroad.

In line with the external policy objectives and international commitments of the EU, EuroHPC should define, implement, and participate in international collaboration on supercomputing to foster research addressing global scientific and societal challenges, while promoting competitiveness of the European HPC supply of technologies and user ecosystem.

EuroHPC shall support international cooperation in supercomputing between European and Non-European partners in the following topics: scientific cooperation, EuroHPC R&I projects, reciprocal exchange of access time between European and non-European systems, exchange of young HPC professionals, and EuroHPC system procurements. It will also monitor closely activities related to the HPC sector as well as evolving user needs outside the EU.

Scientific cooperation: EuroHPC supports the continuation of the long-established tradition of full openness. This contributes to competence and technology building and addresses the European need for skilled staff at all levels from PhD students to senior engineers and scientists. Europe should strengthen its existing scientific partnerships (e.g., with Japan and India) and initiate broader scientific collaboration with aspiring HPC countries (e.g. Latin America, South Korea, Singapore, Canada). An important goal is to make the European HPC ecosystem as attractive as possible to talents world-wide. This includes to open parts of the infrastructure to qualified international users, exchange of students/staff, and offer European training and education programs to qualified people irrespective of their nationality (but possibly linked to affiliations within the member countries).

While first initiatives like Hanami with Japan established strong technical collaborations between partners it appears that on the political side where EuroHPC and the European Commission are supposed to engage discussions with their counterparts (MEXT, METI) about sustainability and cross access mode to HPC facilities, the situation is fully blocked. This need to be corrected and better addressed in future calls.

Hybrid HPC/AI/QC: Cooperation activities shall now encompass HPC, AI, and QC. Building upon existing cooperations with Japan and India, EuroHPC should also, in a moving geopolitical context, develop international cooperations with countries like Canada, Singapore or South Korea with strong national policies especially in AI and QC.

Technology development: While EuroHPC R&I projects should support the European digital sovereignty, it remains important to continue collaborating with international companies that actively contribute to the relevant fields of HPC/AI/QC, hence helping European HPC users and scientists to achieve the best results. Furthermore, one should keep the obligation for both European and international participants in European projects to disseminate the results and foster efforts to implement them into their products.

HPC infrastructure procurements: for mid-range systems and exascale supercomputers, one can observe an imbalance in that Europe is a fully open HPC market while the US, Japan and China remain firmly closed to non-domestic companies. While a reciprocal approach of EuroHPC in its procurements might at first seem natural, this is not deemed productive in the longer run. Instead, Europe should act in two ways: first, convince the international actors to open their closed markets, and second, oblige international participants to provide added value to the European HPC ecosystem by explicitly collaborating with European companies and research institutions, and especially European SMEs.

QC infrastructure procurements: For the procurement of quantum computers and simulators, it should be recognised that the EuroHPC region is leading the path to integrating these systems to HPC. As such, it is important to use this opportunity to benefit European businesses developing quantum technologies and procure these systems from companies based in the EuroHPC Participating States. A different approach is suggested for like-minded countries with a more nascent quantum industry, where quantum technology from EuroHPC states can provide strategic mutual benefit. In these cases, EuroHPC should consider working on activities with the objective of early adoption of cross-border technology by Participating States and partnering countries.

AI model development: EuroHPC should integrate international consortiums on the development of massive multimodal foundation models for science, not only by bringing data but also contributing to the development, training/fine tuning, and inference of our own European open-source models. EuroHPC should also engage in a coordinated effort into international collaborations like the TPC, while preserving the interests of Europe in terms of development of European models and protection of data.

Training: With a requirement of reciprocity and *juste-retour*, EuroHPC shall ensure that its infrastructure and activities are easily accessible for suitable international collaboration partners. Formal collaborations with foreign end-users should also include projects involving European HW and SW companies, thus fostering the development of European HW/SW solutions for HPC, AI, and QC (individually or as hybrid solutions), as well as their international uptake.

5 Topics cutting across pillars

Section 4 addressed each of the EuroHPC pillars separately, but these are tightly interconnected by a number of cross-sectional topics that run across several pillars (see Figure 4). This causes a level of repetition of terms and discussions in the text on these pillars. The following subsections shortly address the main cross cutting topics and should help to navigate the EuroHPC activities and pillars.

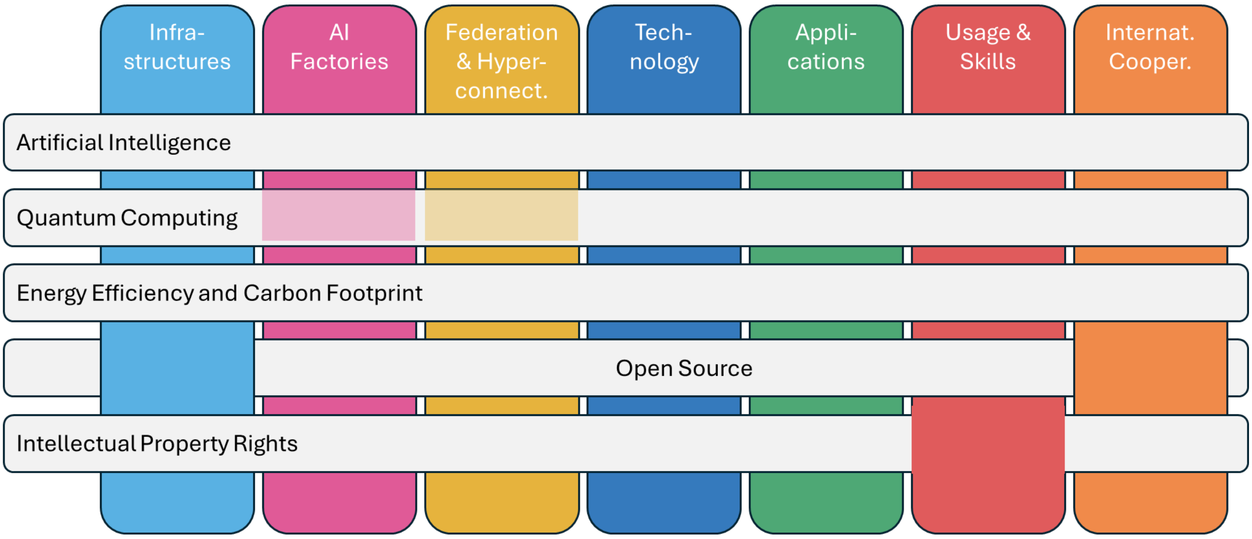

Figure 4: Pillars (vertical) and transversal topics cutting across them (horizontal). The pillars are discussed in Section 4, while the 'transversal topics' are summarized in Section 5. In this figure, a topic laying over a pillar (e.g. Artificial Intelligence over AI-Factories) is part of it. When the overlap is faded (e.g. Quantum Computing over the AI-Factories), it means that the overlap does not exist or is very weak right now, but that it should be intensified in the future. For topics laying behind the pillars (e.g. Open Source behind Infrastructures), the overlap is considered insignificant.

5.1 Artificial Intelligence

AI is strongly entangled with HPC at the infrastructure, technology, and application level, and for this reason is present and relevant to all pillars of EuroHPC:

- **Infrastructures**: both HPC systems and QC serve AI users, who come with strong requirements regarding access policies and software environment, which are challenging for traditional HPC operators.
- **AIFs**: specific computing infrastructure and services for the AI community, focusing on industrial and SME needs.
- **Federation and hyperconnectivity**: AI users need to run codes and have data on HPC, AIFs, private Cloud services, and even the edge. They require therefore unified user access and fast data transfers across platforms.
- **Technology development**: specific HW and SW solutions are developed for the AI-market.

- **Applications:** the AI application community is strong consumer of compute resources and comes to HPC with pure AI workloads and hybrid HPC/QC/AI applications, both having particular requirements that do not always overlap with those from simulation and modelling HPC users. Potential lies in using AI approaches for optimising QC applications (ML for QC).
- **Users & Skills**: as a relatively newcomer to HPC, the AI user community has strong needs for training on HPC skills, particularly in the use of HPC tools and the efficient use of energy and hardware resources.
- **International cooperation**: is mandatory to keep up with the extremely fast evolution of AI applications and methods.

5.2 Quantum Computing

QC is an emerging technology that shall become intrinsic parts of HPC infrastructures, both as QC-centric machines and as accelerators for parts of HPC/AI applications. For this reason, same as for AI, QC is present in all HPC pillars:

- **Infrastructures**: QC systems are deployed across Europe, aiming at creating efficient state-of-the-art hybrid HPC/QC infrastructures.
- **AIFs**: QC aims at becoming also a computing infrastructure for AI, which means that it would be part of future AIFs.
- **Federation and hyperconnectivity**: hybrid HPC/AI/QC infrastructures require unified user access and tight network connections to facilitate offloading code from HPC to QC devices.
- **Technology development**: specific HW and SW solutions are needed in QC, from prototyping of different quantum technologies up to developing middleware to facilitate their operation and the deployment of applications.
- **Applications**: as a technology in early development stages, strong investments are needed in the development of QC applications, as well as hybrid HPC/AI/QC codes. Potential lies in using QC algorithmic approaches for optimising HPC/AI applications (QC for ML). Moreover, already in the short term, great potential lies in using ML and generative AI for optimising quantum circuits and algorithms to approach fault tolerance and quantum advantage (ML for QC).
- **Users & Skills**: specific training for the use of QC and hybrid HPC/AI/QC solutions is needed, both for system operators, HW/SW engineers, and application developers.
- **International cooperation**: is needed to make European QC developments visible worldwide and increase their chances to succeed in the global market.

- **Quantum and AI:** is a next step. By harnessing the computational power of quantum systems, Quantum AI can achieve results beyond the capabilities of classical computers, enabling complex problems to be solved faster and more efficiently. A federated setup of HPC with QC will accelerate the possibilities with AI.

5.3 Energy Efficiency and Carbon footprint

Given the significant energy consumption and carbon footprint of HPC/AI/QC infrastructures, and their high environmental impact, efficient use of energy and minimisation of the CO_2 footprint are supremely important objectives. Moreover, it is critical to reduce total energy use and Carbon footprint of the complete infrastructures across their complete lifecycle and avoid the *rebound effect*[14]. For this reason, energy efficiency must be addressed by all pillars:

- **Infrastructures**: HPC/AI/QC systems should be purchased with energy/Carbon efficiency in mind and must be operated in the most energy/Carbon efficient manner, co-optimising use of resources, energy consumption and the workload throughput.
- **AI Factories**: HPC infrastructures for use with AI applications must be energy efficient, and AIF end-users must be trained to consider energy consumption and enabled to employ the compute resources responsibly.
- **Federation and hyperconnectivity**: unified user APIs providing energy consumption and resource usage metrics to the users should be provided. Also, a federate infrastructure could provide the opportunity to transparently move load to sites with an abundance of green energy to lower the overall energy costs and CO_2 footprint.
- **Technology development**: HW and SW solutions must target a near-optimal compromise of (high) performance and (low) energy consumption. Investments on low-power processing technologies, which might take the form of CPUs, accelerators, or disruptive technologies are needed. System software and programming models, on the other hand, should ensure that the hardware resources are optimally utilised, avoiding waste and optimising the combination of energy and throughput.
- **Applications** codes should be written so that they co-optimise performance and energy consumption and carbon footprint when solving a given numerical or AI-based problem. This can be driven by relevant efficiency metrics (which measure results over

[14] The rebound effect refers to a phenomena observed in many different contexts, namely, that an improvement on efficiency does not automatically lead to a lower energy consumption or carbon footprint, because the efficiency gains are overcompensated by performing more work. In the HPC context this means that efficiency improvements are often overcompensated by performing more application runs, or even installing larger HPC systems for the same costs, so that the overall environmental impact is not reduced.

energy used to create them), which might be domain or even use-case dependent and would have to be established.

- **Users & Skills**: HPC/AI/QC code developers and users both must be trained on specific strategies to minimise the energy and carbon footprint of their codes.
- **International cooperation**: best practices in energy efficient operation and use of HPC/AI/QC infrastructures should be shared widely to profit from the international experience and minimise the overall environmental impact of the growing set of HPC/AI infrastructures. Such best-practices should be disseminated towards commercial data centres in particular, which are nowadays deploying larger compute infrastructures that the public HPC and AI sites.

5.4 Open Source

There are many reasons why open source is important, including supporting wide-spread collaboration, improving accessibility, providing transparency and enabling use and improvements by third parties or user communities. Open-source licensing promises to enable widespread take-up of technology, to accelerate its further development and to lower the costs of using and maintaining such technology.

In the context of EuroHPC, open source relates to data, software and hardware. Since activities funded by the EuroHPC use public money, project results should be released as open source to the extent this is feasible. As previously mentioned, this is relevant also in areas such as AI, for example for making European large-scale foundation models for generative AI and data used to train them available, or in emerging areas such as tools for the development of quantum computing applications.

Although open source is in principle preferable, there are scenarios in which releasing technology under open-source licenses is not the best approach. For instance, industrial partners participating in EuroHPC projects should be able to protect their technology development under other license types that enable its commercialisation and support further development and maintenance. In these cases, dual-licensing approaches can be recommended, or directly releasing closed source software under licenses that effectively enable widespread use in Europe. Such considerations often apply to hardware, which today regularly tends to embody a significant amount of third-party IP which is not or sometimes even cannot be licensed as open source.

In addition, ongoing and sustainable development, support and maintenance for open-source technology is of critical importance to support its take-up and long-term use. In addition to relying on pro-bono work by open-source contributors, this should be backed by specific support projects, or by paid support/maintenance schemes and potentially further development by commercial parties.

5.5 Intellectual Property Rights

It is important to leave the door open to non-European suppliers in the HPC and AI space to foster healthy competition and diversity of solutions, but control of intellectual property created by EuroHPC funded R&D must remain in Europe. Intellectual property rights for the technological assets developed using EuroHPC funding must respect the applicable EU funding rules, including in extreme cases giving IPR to the funding authorities, to ensure availability of related intellectual property in Europe, and protect legitimate interests of academic and industrial beneficiaries. In particular, provisions should be made in grant agreements for R&D projects to safeguard exploitation in Europe, allow the granting of suitable technology licenses or sub-licenses, or if necessary, the transfer of ownership of results.

6 Coordination with other JUs and EU activities

EuroHPC shall work very closely with the EC to ensure that its activities are undertaken in close cooperation and coordination of those organised by the EC (e.g. Chips JU, EU Quantum Flagship), and shall monitor development in EOSC [45], GAIA-X, etc. In particular, tight collaboration is recommended with:

- **Chips JU**: EuroHPC shall work closely with the created Chips JU (formerly Key Digital Technologies JU) to leverage synergies in processor technology development.
- **EU AI initiatives**: many projects and initiatives are running or upcoming in the area or AI in the EU, and a good coordination between EuroHPC and those is important.
- **Cybersecurity Competence Centre:** to establish secure HPC/AI/QC infrastructures.
- **Data Infrastructures**: EuroHPC could consider working more closely with EOSC and ESFRIs, as well as projects like SPECTRUM [85] or SIMPL in order to position EuroHPC as the prime HPC infrastructure for data connectivity to large scale instruments like CERN, SKA, Einstein telescope, and many others, with a clear mutual agreement on the governance and on who will perform/fund the associated data services.
- **Cloud**: with GAIA-X and interested European private Cloud providers, EuroHPC could collaborate in establishing an end-to-end and sovereign federated offer supporting open R&I, confidential R&I, and commercial activities for industry and SMEs.
- **Quantum:** alignment and strong collaboration with other EU programs like the Quantum Flagship for the fundamental developments (Hardware, Software and Applications), with EuroQCI and the Quantum Internet Alliance (QIA) to upgrade the

connectivity with Quantum connectivity, the Chips JU to produce Quantum chips and CEN-CENELEC for Quantum Standardisation.

7 List of Acronyms

AAI: Authorisation, and Identification
AI: Artificial Intelligence
AIF: Artificial Intelligence Factory
API: Application Programming Interfaces
BDVA: Big Data Value Association
CAPEX: capital expenditure
CEF: Connecting Europe Facility
CI/CD: Continuous Integration/Continuous Deployment
CoE: Centre of Excellence
CPU: Central Processing Unit
DEP: Digital Europe (DIGITAL) Programme
DL: Deep Learning
DoS: Denial of Service
EC: European Commission
EDIH: European Digital Innovation Hub
EOSC: European Open Science Cloud
EOSS: European Open Software Stack
EPI: European Processor Initiative
ESFRI: European Strategy Forum on Research Infrastructures
ESS: European Software Stack
ETP4HPC: European Technology Platform for High Performance Computing
EU: European Union
EuroHPC: EuroHPC Joint Undertaking
EuroQCI: EU Quantum communication infra. startegy.
FoM: Figure of Merit
FPA: Framework Partnership Agreement
FPGA: Field Programmable Gate Array
GB: EuroHPC Governing Board
GenAI: Generative AI
GPP: General Purpose Processor
GPU: Graphic Processing Unit
HE: Hosting Entity
HEP: Horizon Europe Programme
HPC: High Performance Computing
HPC/AI/QC: mixed environment of HPC, AI, and QC. In this document we use the term loosely to refer to one or more of the three areas, the combination of two or three of these approaches in infrastructure, technologies and applications, and also about supporting a growing environment that potentially combines them (in pairs or all three together).
HPDA: High Performance Data Analytics
HPL: High Performance Linpack
HW: Hardware
IKOP: In-Kind financial contributions from Operational Projects
IOT: Internet of Things
IP: Intellectual Propriety
ISA: Instruction Set Architecture
ISV: Independent Software Vendor
IT: Information Technology
JEDEC: Joint Electron Device Engineering Council
JU: Joint Undertaking
KPI: Key Performance Indicators
MASP: Multi-Annual Strategic Programme
ML: Machine Learning
MLOps: Machine Learning based System Operations
NCC: National Competence Centre
NLP: Natural Language Processing
NREN: National Research and Education Network
PQC: Post-Quantum Cryptography
PS: Participating State
QC: Quantum Computing
QCoE: Quantum Centre of Excellence, aka Quantum Excellence Centre
QCS: Quantum Computer Science
QEC: Quantum Error Correction
QEM: Quantum Error Mitigation
QIA: Quantum Internet Alliance
QKD: Quantum Key Distribution
QML: Quantum Machine Learning
QPU: Quantum Processing Unit
QuIC: European Quantum Industry Consortium
R&I: Research and Innovation
ROI: Return on Investment
RRF: Recovery and Resiliency Facility
RSE: Research Software Engineers
RTO: Research and Technology Organisations
SGA: Specific Grant Agreement
SIMD: Single-Instruction-Multiple-Data
SLA: Service Level Agreement
SME: Small and Medium Enterprises
STEM: Science, Technology, Engineering and Mathematics
SW: Software
SWOT: Strengths, Weaknesses, Opportunities, and Threats
TPC: Trillion Parameter Consortium
TRL: Technology Readiness Level
UCIe: Universal Chiplet Interconnect Express

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