ESFRI LANDSCAPE ANALYSIS 2024 - SECTION 1

DATA, COMPUTING AND DIGITAL RESEARCH INFRASTRUCTURES

CONTENTS

DATA, COMPUTING AND DIGITAL RESEARCH INFRASTRUCTURES

> *A Digital Infrastructure is broadly defined as a set of information and communication technology components, which typically include physical parts – computer and networking hardware and facilities – but also various software components. Digital infrastructure is tightly linked to a number of digital services and data repositories.*

Digitalisation is a trend which is proceeding with increasing speed across all scientific domains. Essential components – such as computing, data, networks and software – work together forming an ecosystem where it is possible to transfer and analyse data in a much more extensive way than ever before. These components are together called **e-infrastructures**, a term which intends to indicate their horizontal nature serving all research infrastructures (RIs) at some level.

Digital Infrastructures are expected to boost research, growth, innovation and job creation. However, infrastructure as such is not the main target. To efficiently utilise the resources and understand the results with an ability to achieve high quality scientific breakthroughs, significant **development of skills and competencies** is needed. Priorities should include training software developers, data analysts, Artificial Intelligence (AI) and High-Performance Computing (HPC) experts, as well as domain scientists. This training, embracing the opportunity to work cross domain with the same e-infrastructure and services, ought to be a key goal for European advancement.

The e-infrastructure services at the European level are often being provided by federating national e-infrastructures in a collaborative setting. European initiatives are therefore dependent on the existence of strong and coherent **national e-infrastructure nodes.**

CURRENT STATUS IN THE DOMAIN

> *e-infrastructures address the needs of European researchers for digital services in terms of networking, computing and data management, and foster the emergence of Open Science as an essential block of the European Research Area (ERA)*[1]

1. European Research Area https://research-and-innovation.ec.europa.eu/strategy/strategy-2020-2024/our-digital-future/european-research-area_en

Federated, national Infrastructures and European initiatives serve scientific communities by providing trusted and open environments to store, share and re-use scientific data and results. These platforms benefit from fast connectivity, high-capacity cloud solutions, and supercomputing capability systems.

Currently, e-infrastructures, related services and expertise for RIs in Europe are provided by different stakeholders, including:

- Major **European initiatives**, such as EuroHPC (under the form of a Joint Undertaking) or EOSC (under the form of a European Partnership), and the various projects under their portfolio;
- **European collaborations between different centres** such as GÉANT[2], **ESFRI Landmark PRACE**[3], EUDAT[4] or EGI[5], which very often started as projects and have evolved into some forms of legal entities;
- **National centres**, often involved in the aforementioned initiative, which can also support directly several European RIs, according to national priorities and funding;
- **Thematic RIs** possessing their own RI-dedicated resources, collaborating via platforms like the ESFRI Clusters to address digital needs in projects across disciplines from a common wider do-

2. GÉANT https://geant.org/

3. PRACE https://prace-ri.eu/

4. EUDAT https://www.eudat.eu/

5. EGI https://www.egi.eu/

main (e.g. Environment, Life Science, Social Sciences and Humanities, Physics, Biomedical Science);

- Intergovernmental large-scale Research Infrastructures, notably CERN[6], EMBL[7], ESO[8] or ESA[9], or ECMWF[10] which possess significant capabilities in e-infrastructure.

THE NEW BUILDING BLOCKS: EUROHPC AND EOSC

Over the last decade, the European e-infrastructure ecosystem has undergone significant developments, characterised by two main features: the establishment of a new, sustainable European advanced computing infrastructure, powered by the EuroHPC initiative, and the emergence of the European Open Science Cloud (EOSC), which aims at building a European Data Space for Science, Research and Innovation, leveraging multiple data providers and pan-European e-infrastructures.

The EuroHPC Joint Undertaking[11] was established to raise European competitiveness in high performance computing (HPC) and enable effort coordination and resource-sharing at the European level. The objective is to deploy a world-class HPC infrastructure and a competitive innovation ecosystem in supercomputing technologies, applications, and skills in Europe. To address this objective, EuroHPC JU has co-funded a number of large-scale HPC systems in Europe. As of mid-2023, three so-called pre-exascale centres and ten smaller petascale centres have been decided upon, some of them already operational, and others in planning or deployment phases. The first two EuroHPC exascale centres have also been launched, and are expected to be operational in Germany in 2024 and in France in 2026. Due to EuroHPC, the quantity and quality of HPC resources available for European research is larger than ever before and still developing, a pivotal factor in enhancing the competitiveness of European computational and data science.

The European Open Science Cloud (EOSC)[12] intends to provide researchers with a virtual environment housing open and seamless services for storage, management, analysis and re-use of research data, across borders and scientific disciplines by federating existing data infrastructures. EOSC is being co-created through a series of projects funded by the European Commission (EC) and initiatives from Member States (MS) and Associated Countries (AC). The European Partnership for the EOSC was launched in June 2021, working closely with the MS and the respective research communities. The EOSC Partnership will ensure a coordinated approach until at least the end of 2030, involving the European Commission, MS, AC, and stakeholders in investments and initiatives in the EOSC ecosystem. The funding envisages an EU investment of almost €500 million and an in-kind contribution of another €500 million from partners between 2021 and 2027. The aim is to improve the storing, sharing, and reusing of research data across borders and scientific disciplines. The EOSC Association was established as an International non-profit Association under Belgian Law (AISBL) in July 2020. Members and Observers of the EOSC Association include research funders, research performing organisations, RIs, data service providers and others.

ESFRI DATA, COMPUTING AND DIGITAL INFRASTRUCTURES

Some ESFRI landmarks and projects are specialised in providing digital services across scientific domains.

The **ESFRI Landmark PRACE** (Partnership for Advanced Computing in Europe) is a collaborative initiative among European countries, established to provide HPC resources and develop related services. PRACE was founded in 2007 and has been implemented through a series of projects. It is now a legal entity, AISBL, under Belgian law. With the emergence of the EuroHPC initiative, PRACE's strategy and role are shifting towards increasing community engagement rather than providing computing cycles.

The **ESFRI Project SLICES**[13] (SLICES-RI) aims to provide a fully programmable and virtualised, remotely accessible, European-wide Research Infrastructure, providing advanced computing, storage and network components, interconnected by dedicated high-speed links. The project is intended to establish a flexible platform designed to support large-scale, experimental research focused on networking protocols, radio technologies, and services as well as data collection, distributed control and various edge-based computing architectures.

The **ESFRI Project SoBigData++**[14] (SBD++) seeks to establish a European infrastructure of big data and social data mining, using new methods and implementing it in different fields of data analysis. It aligns with current scientific trends in machine learning and data science to promote ethically sound and open research in large

6. CERN https://home.cern/

7. EMBL https://www.embl.org/

8. ESO https://www.eso.org

9. ESA https://www.esa.int/

10. ECMWF https://www.ecmwf.int/

11. Euro HPC Joint Undertaking https://eurohpc-ju.europa.eu/index_en

12. EOSC https://eosc-portal.eu/about/eosc

13. SLICES https://www.slices-ri.eu

14. SoBigData++ http://www.sobigdata.eu/

datasets that democratises the value of data science. SBD++ is expected to become a leading RI for realising large-scale social mining experiments.

The **ESFRI Project eBRAINS**[15] aims to develop a digital platform for brain research and neuroscience, as part of the wider Human Brain Project (HBP), a flagship research initiative focused on studying the human brain and developing new technologies and approaches for brain research. eBRAINS seeks to create a collaborative and integrated platform connecting researchers, data, and computational tools to advance our understanding of the brain and its functions. The platform is designed to facilitate data sharing, analysis, and modelling across different disciplines and research areas related to neuroscience.

The landscape of DIGIT Research Infrastructures is represented in ***Figure 1***.

15. EBRAINS https://www.ebrains.eu/

E-INFRASTRUCTURE IN THEMATIC RIs

Research Infrastructures have often been built to address common challenges which typically required strong collaboration and pooling of resources, including infrastructure resources. In Europe, this has resulted in the creation of the European Organisation for Nuclear Research (CERN) in the mid-1950s, for Particle Physics research, and the European Southern Observatory (ESO) for Astronomy in the early 1960s. Other major organisations include the European Space Agency (ESA), the European Molecular Biology Lab (EMBL), and the European Centre for Medium-range Weather Forecasts (ECMWF). From their early beginnings, all of these large RIs have faced the challenge of managing the vast amounts of data they produced and processed. Their digital solutions and services are being employed by a broad variety of users.

Today, ESFRIs are also joining forces in 'clusters' to address common challenges related to FAIR data management, as part of the wider EOSC framework. These clusters operate in different sci-

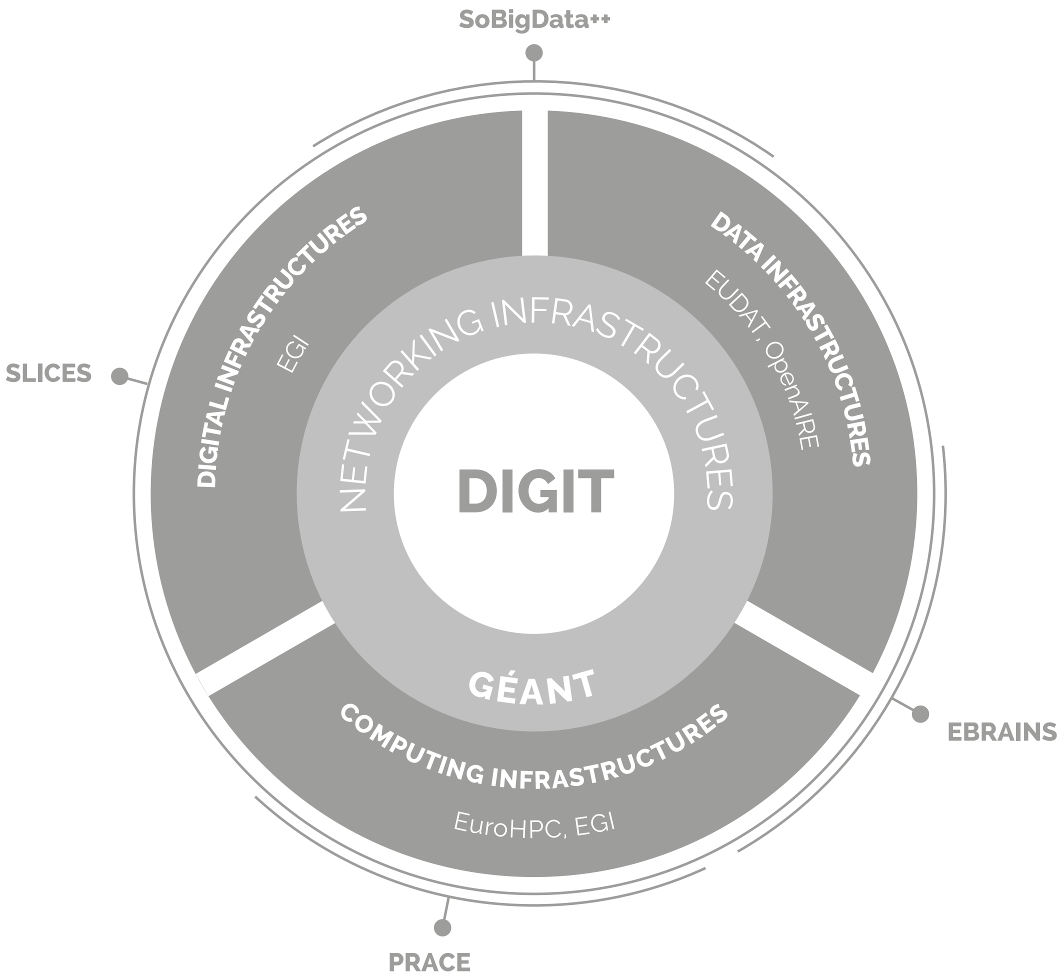

FIGURE 1.

The Landscape of the Data, Computing & Digital Research Infrastructures domain entific domains such as Environmental Sciences (ENVRI-FAIR[16]), Physics and Astrophysics (ESCAPE[17]), Biomedical Sciences (EOSC-Life[18]), Photon and Neutron (PANOSC[19]), and Social Sciences and Humanities (SSHOK[20]).

DIGITAL TWINS

The development in digital technologies and capabilities has led to the emergence of new approaches for doing research. Digital twins (DT)[21] are virtual representations of physical objects, processes or systems using real world data to create simulations that can predict how they will behave or perform. Widely used in engineering and manufacturing to simulate industrial processes, DTs are now being implemented in an increasing number of scientific domains, where they are expected to unlock the potential of digital modelling, leveraging high performance computing and AI as key technologies to model the Earth, oceans, biodiversity, traffic, the human, and more. Being able to simulate and study complex phenomena through digital twins in real time and with precision will considerably increase the quality of research and foster innovation but also help us address global challenges such as climate change.

Examples of European initiatives to develop digital twins include Destination Earth (DestinE[22]), a flagship initiative of the European Commission aiming to develop a highly accurate global-scale digital model of the Earth. This model will monitor, simulate and predict the interaction between natural phenomena and human activities. It will contribute to achieving the objectives of the transition towards green and digital as part of the European Commission's Green Deal[23] and Digital Strategy[24]. A number of other digital twins supported by the EC are being established for monitoring oceans (European DTO[25]), biodiversity (BioDT[26]), geographical extremes (DT-GEO[27]) or addressing multiple domains (InterTwin[28]).

DATA SPACES

The European strategy for data aims at creating a single, unified data market, ensuring Europe's global competitiveness and data sovereignty. As part of this strategy, common European data spaces[29] are being established in several domains to increase data availability for use in the economy and society, while maintaining control over companies and individuals who generate data. Common European data spaces bring together relevant data infrastructures and governance frameworks in order to facilitate data pooling and sharing. Targets for data spaces include:

- Deploying data-sharing tools and services for the pooling, processing and sharing of data by an open number of organisations, as well as federate energy-efficient and trustworthy cloud capacities and related services;
- Including data governance structures, compatible with relevant EU legislation, which determine, in a transparent and fair way, the rights concerning access to and processing of the data;
- Improving the availability, quality and interoperability of data, both in domain-specific settings and across sectors.

The February 2020 European data strategy[30] announced the creation of data spaces in eight strategic fields: health, agriculture, manufacturing, energy, mobility, financial, public administration and skills. EOSC has been added later to this list, as a crosscutting key priority meeting the Green Deal objectives.

16.
ENVRI-FAIR
https://envri.eu/home-envri-fair/

17.
ESCAPE
https://projectescape.eu/

18.
EOSC-Life
https://www.eosc-life.eu/

19.
PANOSC
https://www.panosc.eu/

20.
SSHOK
https://sshopencloud.eu/

21.
Digital twins
https://futurium.ec.europa.eu/en/connect-university/events/high-performance-computing-and-digital-twins-climate-action

22.
Destination Earth (DestinE)
https://destination-earth.eu/

23.
European Commission's Green Deal
https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

24.
European Digital Strategy
https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age_en

25.
European DTO
https://www.mercator-ocean.eu/en/digital-twin-ocean/

26.
BioDT
https://biodt.eu/

27.
DT-Geo
https://dtgeo.eu

28.
InterTwin
https://www.intertwin.eu

29.
Common European data spaces
https://dataspaces.info/common-european-data-spaces

30.
European data strategy
https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-data-strategy_en

NETWORKING SERVICES

Today, each European country hosts a National Research and Education Network (NREN[31]), connecting research and higher education institutions with high-performance networks, and offering a range of related services.

In terms of organisation and funding, European NRENs are diverse. Some receive direct government funding; others are funded by their connected institutions. Some are part of large organisations managing a variety of national e-infrastructures, while others are smaller organisations focusing solely on the network. Nevertheless, they have important similarities. All NRENs offer **high-performance networks suited to research and education needs**; they have the headroom required for the bursts in traffic and the capability to serve research collaborations like ESFRI's with specialised network support.

Additionally, all European NRENs offer **critical access and identity services** such as eduroam[32] and eduGAIN[33]. These trust and identity services make up the foundation of services that allow secure access to research data, authentication to shared resources, and support for mobility and collaboration. Many NRENs also offer storage services, computing services, and a range of security services.

Together, NRENs have formed the GÉANT Association, an organisation for European collaboration in research networks and the operator of the pan-European GÉANT network, with connectivity to other world regions. With support from the EC during decades of Framework Partnerships, the GÉANT network has been developed into a **world-leading network**, ensuring world-class connectivity to all European countries and making Europe a leading actor in global research networking and e-infrastructures.

> *Through its integrated catalogue of connectivity, collaboration and identity services, GÉANT provides users with highly reliable, unconstrained access to computing, analysis, storage, applications and other resources, ensuring Europe's forefront position in research.*

GÉANT interconnects 39 NREN partners, and is the largest and most advanced Research & Education (R&E) network in the world. Over 50 million users at more than 10,000 institutions across Europe are connected by GÉANT, across all scientific disciplines.

More than just an Infrastructure for e-Science, GÉANT stands as a positive example of European integration and collaboration. It develops and delivers advanced networks and associated e-infrastructure services. It supports open innovation, collaboration and knowledge sharing amongst its members, partners and the wider research and education networking community. GÉANT network also offers connectivity to other world regions through, for instance, AfricaConnect3[34], CAREN[35], EUMEDConnect3[36], EaPConnect[37], TANDEM[38] and others. In addition to current connections, more fibre is being built and planned from Europe to, for example, Northern America and Asia and to Latin America.

DATA SERVICES

The European data infrastructure is being developed through the combination of different initiatives, such as EUDAT, EGI, and OpenAIRE[39], as well as the various data spaces which are being established. In many of them, the borderline between data and computing has become less obvious and even obsolete: data is the essential driver for computing, and comprehending data without understanding computing becomes challenging.

EUDAT **supports the sharing and preservation of data across borders and disciplines**. European researchers and practitioners from any research discipline can safeguard, find, access, and process data in a trusted environment. EUDAT offers heterogeneous research data management services and storage resources, supporting multiple research communities as well as individuals, through a resilient and distributed network spanning across 15 European countries. Data is stored alongside some of Europe's most powerful supercomputers.

EGI creates and delivers **open solutions for science and RIs by federating digital capabilities, resources and expertise between communities and across national boundaries**. Researchers from all disciplines have easy, integrated and open access to the advanced scientific computing capabilities, resources and expertise needed to collaborate and to carry out data/compute inten-

31. NREN https://about.geant.org/nrens/

32. Eduroam https://eduroam.org/

33. eduGAIN https://edugain.org/

34. AfricaConnect3 https://africaconnect3.net

35. CAREN https://www.caren.geant.org/

36. EUMEDConnect3 https://eumedconnect3.net

37. EaPConnect https://eapconnect.eu

38. TANDEM https://cordis.europa.eu/project/id/654206

39. OpenAIRE https://www.openaire.eu

sive science and innovation. Regarding the services, EGI delivers advanced computing and data services to support scientists, multinational projects and RIs. EGI services are provided by EGI's federated cloud providers and data centres. The services can be requested by anyone involved in academic research and businesses and they can be categorised in the following groups: computing, storage, data and training. EGI provides access to CPUs, disk and tape storage, hosted by the partners in EGI. In addition to data services, EGI is distributing computing capacity – although owned by various EGI partners – due to which EGI could also be categorised under the computing infrastructures.

OpenAIRE aims to promote and facilitate open access to research outputs, including publications, data, and software, across Europe and beyond. Established in 2008, it has evolved into a significant player in the global Open Science movement. It provides a range of **services and tools for researchers, institutions, and funders to help them comply with open access mandates and policies.** Services include a repository of open access publications, data management and sharing tools, a directory of open access journals, and a helpdesk for support and guidance on open access issues.

In addition to these services, OpenAIRE also supports the development of Open Science policies and practices at the national and European levels through advocacy and engagement with stakeholders, including policymakers, funders, and research communities. The project has been instrumental in shaping the European open access landscape and promoting the benefits of Open Science for research and society as a whole.

Presently, EUDAT, EGI, and OpenAIRE collaborate as part of the European Open Science Cloud (EOSC) initiative. Together, they contribute to its construction, design, and implementation.

> *EOSC aims at providing a federated ecosystem for researchers across Europe, enabling them to collaborate and share data, tools and services in a trusted and secure environment. It is designed to promote and facilitate Open Science practices, making research more accessible, transparent and reproducible.*

EOSC is currently being implemented through a series of projects. As an example, in INFRAEOSC 2021-2022 calls 15 projects were funded comprising a total of €87 million in funding for 221 separate participants. In INFRAEOSC 2023 call €69 million funding is planned for six different topics and €61 million in the 2024 call for five topics. The objective for the project portfolio is to develop digital infrastructures and related services for a wide range of research areas, many of them related with data.

COMPUTING SERVICES

Computing services are intended to offer several types of infrastructure, depending on applications. Alongside traditional CPU systems, the use of GPU processors is increasing, reflecting the expanding application portfolio. In **High-Performance Computing** (HPC) applications, much of the computing resources – CPU or GPU, or both – are dedicated to a single large task, often requiring a super-fast, low-latency communication between the different processors. Another approach is **High-Throughput Computing** (HTC) in which a big number of smaller tasks are carried out with less requirement for communication between nodes, but still targeting to complete the task set as fast as possible in wall-clock time. Typical examples requiring HPC can be found in climate models, computational chemistry or material sciences, to name a few. CERN distributed computing is probably the best-known case, with numerous systems working with Large Hadron Collider (LHC) data, distributing computing tasks to partner countries.

At the European level, there are two significant infrastructures supporting HPC: the EuroHPC JU (EuroHPC Joint Undertaking, JU) and the **ESFRI Landmark PRACE**. In addition to this, it is important to note that a vast amount of computational resources in Europe are located in and run by national centres and thematic RIs.

PRACE, the Partnership for Advanced Computing in Europe, is a non-for-profit organisation incorporated in Belgium (AISBL) since 2010. PRACE is the persistent organisation resulting from nearly 20 years of initiatives structuring High Performance Computing in Europe. Members, each representing one of the current 25 member countries, coordinated their efforts to provide an **infrastructure to enable high-impact scientific research and innovation across all disciplines and industrial applications,** thereby enhancing European scientific, technological and economic competitiveness for the benefit of society. PRACE chiefly distributed resources on the Tier-0 world-class supercomputers of its Hosting Members on the basis of a globally recognised and transparent peer-review process based on scientific excellence. PRACE distributed more than 32.5 billion core hours to 947 scientific projects. Mainly through its EU-funded PRACE-IP projects, it promoted excellence in computational science and engineering by developing knowhow and expertise across all Europe, e.g. via application support, technology watch, and training (25.000 persons were trained). IPR was developed through collaboration with the European HPC industry and innovation was promoted by supporting industrial HPC users, in particular SMEs (SHAPE[40] programme).

The EuroHPC Joint Undertaking has acquired pre-exascale and petascale supercomputers (the EuroHPC supercomputers) which are located at and operated by supercomputing centres (Hosting Entities) in the European Union. **The EuroHPC JU will manage these supercomputers' access time,** which should range from 35% up to 50% of their total capacity, depending on the EU funding ratio. Resources are allocated to European scientific, industrial and public sector users, matching their demanding application requirements, according to the principles stated in the EuroHPC JU Council Regulation and the JU's Access Policy. All of the hosting entities offer these HPC resources, but also a wide variety of support for these computing services, such as technical support or code porting and optimization.

40. SHAPE access https://prace-ri.eu/hpc-access/shape-access/

The three pre-exascale supercomputers have been located at the following supercomputing centres:

- LUMI[41] in CSC – IT Center for Science, Finland;
- LEONARDO[42] in CINECA, Italy;
- Mare Nostrum 5[43] in Barcelona Supercomputing Centre, Spain.

LUMI has been operational since the beginning of 2022 and ranked first in Europe and third in the TOP500[44] list of world's fastest supercomputers in 2022 and 2023. LUMI is coordinated by CSC (Finland), and includes a consortium of 11 countries (Finland, Belgium, Czech Republic, Denmark, Estonia, Iceland, Norway, Poland, Sweden, Switzerland, and the Netherlands), which have all invested in the system and receive computing cycles accordingly.

LEONARDO was inaugurated in late 2022 and is available for wider use since 2023. In November 2022 LEONARDO ranked fourth in TOP500, right after LUMI. LEONARDO is coordinated by CINECA (Italy), with participation from Austria, Greece, Hungary, Slovakia, and Slovenia.

Mare Nostrum 5 will be inaugurated during summer 2023 and will be in operation in autumn. Mare Nostrum 5 is coordinated by BSC (Spain) and includes Turkey and Portugal as participating countries.

Currently, alongside the three pre-exascale systems, five out of the ten accepted petascale systems are operational. These systems, located in Slovenia, Czech Republic, Portugal, Luxembourg, and Bulgaria, complement the European HPC Ecosystem and contribute to a wider geographical distribution of computing resources.

This also has an impact for skills development, capacity building and integration of some European regions that previously had limited visibility within the European HPC landscape.

Computing resources in Europe can be obtained from all the EuroHPC centres, depending on the resource allocation policies and possible peer-review requirements. The share of the computing resources funded by EuroHPC JU will be available for all EuroHPC countries and beyond, depending on collaboration with an eligible country. In addition to the funding of hosting the systems, EuroHPC JU co-funds a number of projects targeted to support the work around the EuroHPC systems, similarly to EOSC. Currently, 39 projects from different areas – developing competencies, supporting research infrastructures or projects, and advancing technologies such as quantum – are being funded[45].

The ESFRI Landmark PRACE complements EuroHPC JU in the European HPC Ecosystem. PRACE currently has 25 members, representing European Union Member States and Associated Countries.

With the establishment of the EuroHPC JU, the access to leadership HPC systems for the European HPC user community is now provided by EuroHPC centres. To decrease the overlap, the PRACE Council (where all 25 Member states are represented) has agreed to transform PRACE into an Association of Users and HPC Centres in Europe. In April 2023 an overall agreement was reached on a new governance structure and member categories. The PRACE 3.0 will associate members from scientific and industrial ecosystems and European HPC centres.

Since the European HPC landscape has recently changed with EuroHPC and related investments, discussions about the role of PRACE are underway. PRACE has been a key player in European supercomputing since 2008, facilitating connections among research domains and centres through its implementation projects. Throughout 2023 and 2024, further deliberations did and will address the distribution of workloads between PRACE, EuroHPC JU, and other pertinent European initiatives. Additionally, discussions will focus on the specific services PRACE intends to offer the HPC community.

The services provided by PRACE are associated to two distinct categories: core services, funded via membership fees which target all PRACE members and European HPC stakeholders; and complementary services, financed through specific funding streams (service contracts, grants, or dedicated programmes) that contribute to the mission of PRACE while targeting specific actors involved in the corresponding projects or programmes.

OTHER SERVICES

In addition to HPC, data and network services, there is a need to focus on efficient use of these highly valuable (and costly) resources. Hence, various supplementary services are required in areas such as scalable application development, training and education, code porting and optimisation, and technical consultation, among others. These services are commonly provided by HPC centres, thematic centres, or collaboratively through EU projects.

41. LUMI https://www.lumi-supercomputer.eu

42. LEONARDO https://leonardo-supercomputer.cineca.eu

43. Mare Nostrum 5 https://www.bsc.es/ca/marenostrum/marenostrum-5

44. TOP500 https://www.top500.org

45. The list of projects is available at https://eurohpc-ju.europa.eu/participate/our-projects_en

IMPACT IN THE DOMAIN

e-infrastructures include elements – HPC, data, AI, network – which have become critical to all RIs, from Particle Physics to Astronomy, from climate modelling to Medicine. Much of science today is data driven. The demand for computing capacity continues to surge, driven by the necessity for more precise simulations and data analytics. The digital transition has fostered the development of new user communities, notably in fields like **Social Sciences & Humanities**. Additionally, the integration of AI applications, such as natural language processing, have significantly contributed to this escalating demand.

The development of high-performance computing has unlocked the potential of Artificial Intelligence techniques which can in turn greatly advance the quality and effectiveness of HPC simulations through Machine Learning, leading to even greater performance. With the advent of new AI-centric HPC systems – typically large-scale GPU based systems – and the consolidation of the European HPC ecosystem through the EuroHPC initiative, new capacities are underway and will lead to new insights supporting scientific discovery and innovation.

The European Open Science Cloud is expected to further consolidate the European Research Infrastructure ecosystem by offering researchers from all disciplines seamless, open access to advanced digital capabilities, resources and expertise they need to collaborate and to carry out data- and computing-intensive science.

Over the past decade, Open Science has become a policy priority in Europe, establishing itself as the standard method within the European Commission's research and innovation funding programmes.

> *The discussion around infrastructure, particularly e-infrastructure, is intricately tied to Open Science, relying extensively, and increasingly, on digital technologies.*

Digital transformation is reshaping research practice by introducing novel tools for accessing, analysing, sharing, and preserving research data. Open Science builds on this transformation, enabling enhanced discoverability and easier access to, and reuse of, scientific content.

The development of European infrastructures has also impacted funding methods, with an increasing pooling of resources from the European Commission and Member States. Previously, EU funding for horizontal digital infrastructures targeted project costs, primarily related to personnel costs, while computing and data management capacities relied heavily on national centres. In EuroHPC, funding is also directed towards acquiring the computing infrastructure itself, thus enabling European joint resourcing and clearer resource allocation processes. EuroHPC has also fostered collaboration between Member States on joint infrastructure deployment and operation. Tighter collaboration in Europe with EU incentives is poised to improve quality and cost efficiency, thereby contributing to the realisation and consolidation of the ERA.

TRENDS IN THE DOMAIN

Digitalisation of science stands as a prominent megatrend. The process of gathering, transferring, analysing and eventually understanding data requires digital tools and infrastructure. Artificial Intelligence has a growing role in assisting decision making and information retrieval. As datasets expand in size and resolution, computing capacity requirements surge due to simulation and modelling needs. Data is generated in fast cycles and the amount of data is growing rapidly. Competent individuals are in high demand, also across industries, revealing a scarcity in human resources in many areas, emphasising the need to set additional requirements in education and training in digital skills.

HPC

Despite rapid advancements in processor technology, large supercomputer installations such as FUKAGU[46] in Japan or Frontier[47] in the USA aim to prolong systems lifespans beyond the typical five years of most HPC centres. Extending the longevity of HPC technology can be enabled by investing in code optimisation and higher processor performance. This is possible since today code efficiency varies considerably, with some cases utilising only a small percentage of the hardware potential. The trend for the largest installations is to run longer in production than before.

In HPC, the rise of AI applications such as Large Language Models (LLM), has been a clear advancement, boosting the use and development for GPUs and related software. Applications such as ChatGPT divide opinions and impact developmental trajectories. Concerns from five years ago about GPU usability due to the lack of applications and high application porting efforts, seem not warranted anymore.

46. FUKAGU https://www.fujitsu.com/global/about/innovation/fugaku/

47. Frontier https://www.olcf.ornl.gov/frontier/

Traditionally, HPC systems have been purchased and maintained by national and regional centres, research organisations, or companies. However, in the future, owning HPC systems and hosting them locally may not remain the most efficient strategy for numerous service providers. This is the case especially when a change is identified in the behaviour of users which may want to shop for HPC resources the same way they presently do with cloud. Huge differences in operational cost, mainly due to the variation in electricity price, will drive the choices of future data centre locations and attract user communities or even nations to collaborate and possibly share cost and resources for joint HPC ownership and operation.

QUANTUM COMPUTING

In the future, the HPC systems will include quantum processors alongside traditional ones. However, it will take some years before quantum computers achieve the reliability necessary to solve practical problems. Nonetheless, ongoing technology and software developments are paving the way. Quantum computers are complementary solutions to supercomputers and will not replace them. Their problem-solving scope remains in fact limited to specific application areas yet to be fully explored. However, in these specific applications, quantum computing performance is expected to far surpass traditional supercomputers.

Although quantum computing applications are still in the future, Europe is actively advancing technology development and competence building. EuroHPC has funded a number of quantum projects (six initiated from a call launched in 2022, one from an earlier one), where various types of quantum computers are built and integrated to supercomputer systems. These projects collaborate with quantum computer vendors and technology centres aiming not only to advance technology and devices but also to explore their integration with supercomputer systems. The development of software stack and user interfaces will play a key role in future quantum integration.

DEFINING & DESIGNING DEMONSTRATORS AND TESTING OF NEW TECHNOLOGIES

The European HPC partners are globally at the forefront of the evaluation of new technologies, assessing their relevance for operations of new architectures and their efficiency in solving existing and novel scientific and technical challenges. EuroHPC and PRACE members can set up collaborative frameworks where new technologies are evaluated against specific needs of communities, particularly addressing industrial needs on the basis of proxy and benchmarking applications. New Horizon Europe funding boosts European research in data, computing, and AI technologies: a new set of calls has been launched worth over € 290 million from the 2023-2024 Horizon Europe Digital, Industry, and Space work programme.

GLOBAL COLLABORATION

ICT infrastructures have been recognized as "a crucial asset underpinning European research and innovation policies"[48]. Significant progress has been made in the deployment of pan-European ICT infrastructures for research support across multiple disciplines. Opportunities for synergy are expanding beyond European borders due to increasing global collaboration in research. Most RIs have been collaborating at the global level since their inception, with installations and research teams distributed around the world. Similar trends are foreseen at the e-infrastructure level, facilitated by agreements between the EU and other regions of the world. Digital Partnerships have been signed with Japan, South Korea and Singapore; specific agreements on AI and computing with the USA. What is more, discussions about the inclusion of countries outside Europe such as Canada, Australia, Japan, South Korea and Singapore in Horizon Europe are underway. A wider framework would thus be formed, enabling global collaboration on digital R&D, including e-infrastructure collaboration at a global scale.

On the connectivity side, two fibre sea cable projects, namely Far North Fibre and Polar Connect, have been initiated. These projects will establish connections to Asia via the northern route, with links to USA and Canada. Similar projects are running in other European regions, such as the BELLA-programme[49], which connects to Latin America, enabling faster data transfer globally.

GREEN TRANSITION

> *Green transition is the emerging trend in all digital services. Innovations to diminish the carbon footprint and reduce electricity consumption are being devised both at the data centre level, often yielding the largest benefits, and within chip design.*

Power Usage Efficiency (PUE) indicates the amount of electricity required for HPC systems cooling, which ideally is as close to 1 as possible. A value of 1 means that all electricity powers the system rather than overheads such as cooling. Advanced methods such as free cooling with outside air (especially in cold regions) can save energy and cost with lower carbon footprint. Another evolving trend, particularly in liquid-cooled systems, involves utilising waste heat for district heating, lowering both the carbon footprint and expenses.

48. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, ICT infrastructures for e-science
https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52009DC0108&from=DA

49. BELLA-programme
https://www.bella-programme.eu

At every level, there's a growing emphasis on environmental factors. The impact on the environment depends on the type of electricity used (renewable or non-renewable), how efficiently it is used (high or low PUE) and additional emissions reduction strategies (e.g. waste heat utilisation). To achieve as low a carbon footprint as possible is a major criterion in new data centre projects, as well as in other activities. Beyond the carbon footprint, focus needs to shift on **carbon handprint**, acknowledging actions taken for a positive climate impact. Projects like DestinE, aiming to study and develop actions against climate change, are good examples of efforts to improve the carbon handprint.

GAPS AND NEEDS IN THE DOMAIN

While there has been a number of successful initiatives linking RIs and e-infrastructures, there is still significant potential to enhance and intensify the collaboration. **Sharing competencies, tools and software development efforts**, for example, can significantly **reduce overlapping work**. Wider utilisation of European joint resources, such as those provided by the EuroHPC centres and other European or national centres, results in cost efficiency and potential to scale the application performance much higher. Data in various forms – also as capability to analyse and store it – is a key asset for the future, which can be addressed through the European RI and e-infrastructure collaboration.

Today, computing systems have passed the exaflop milestone. However, **prioritising comprehension of results holds greater significance than mere computational speed**. For that reason, the focus should be put increasingly in competence building, for example in application development and scaling/porting work of scientific applications. In many areas, even if the supercomputer would calculate fast in theory, only a fraction of this power can be utilised due to limitations in methodology or scaling. This trend of processors advancing in speed while applications lag behind underscores the necessity for competent experts and an enhanced education system.

There are also huge opportunities in establishing a **closer interaction between EuroHPC and EOSC**. They share stakeholders and customer base, e.g. European research and industry. Indeed, all elements of this ecosystem – HPC, AI, data, networks, applications, competence etc. – interact and link together.

The success of the future EOSC as a European Data Space for Science, Research and Innovation does not only depend on the possibility to access valuable data types, including research data, scientific publications and other research outputs; it also hinges on providing researchers with the most advanced computing and data management resources at scale to process and analyse these data, allowing them to make new discoveries and insights.

While HPC and advanced computing resources have traditionally been allocated through scientific peer-review, there's a need to actively **promote the introduction of new, open, and flexible allocation methods to cater to a wider set of users**. These methods should encompass diverse usage scenarios, ranging from high-throughput to high-performance computing, from virtual machines running on a few cores to more demanding operations running on a larger number of servers. Furthermore, these methods should support Machine Learning and AI use cases on state-of-the-art accelerator devices.

TURNING HPC AND AI TO A COMPETITIVE ADVANTAGE FOR EUROPE

HPC and AI are poised to become the two cornerstones of the next Digital Europe Program (DEP). Each has seen substantial advancements as independent fields in recent years. Increased investments in both areas hold the promise of enhancing Europe's competitiveness in the global digital economy and bolstering its technological autonomy. However, the real breakthrough is likely to come from the convergence and the joint power of these two domains: Europe needs to act in a coordinated way to harness the full potential of this revolution.

In order to make the most of these assets, it is important to adopt a holistic approach supporting the **convergent use of HPC and AI infrastructures**. This requires additional interaction between the HPC and AI communities to discuss common issues, such as how to organise the provision of large-scale, on-demand computing resources at the European level to boost AI developments; or how to support skills development and training so that the next generation of data scientists can make the most of the new technology. Data handling is another crucial aspect. Fast access to relevant data and safe storage of large sets of data and algorithms need to be organised, in compliance with GDPR and following the FAIR principles (Findable, Accessible, Interoperable, and Reusable).

DECREASING THE GAPS

Fast development in digital infrastructures results in a number of gaps and needs that must be promptly addressed to fully benefit from the rapidly advancing technology. Closing these gaps may involve investing in critical areas, such as:

- Competence development;
- Synergy and collaboration between EuroHPC and EOSC;
- Software development and scaling;
- Sustainability and green transition;
- Quality and usability of data.

Efforts to federate resources and service provision for research are key development targets influencing both EuroHPC and EOSC. The ability to share resources across national and disciplinary borders and combine them together is crucial for maximising performance and efficient resource and competencies utilisation. The two initiatives do have similarities, and their closer integration/interoperability can help RIs find optimal services.

CROSS-DOMAIN ASPECTS

In the previous sections, numerous cross-domain aspects have been described. Given the myriad opportunities for synergies across different domains in both digital infrastructure and services, increased collaboration and information exchange between stakeholders can yield significant positive outcomes. It's highly advisable to consider cross-domain aspects when planning for developments in digital infrastructures.

The need for addressing cross-domain aspects has been identified earlier on. Some of the ESFRI working groups and ESFRI Clusters, and other European or national bodies, have already been working across different domains. Notably, two initiatives – European e-infrastructure reflection group (e-IRG[50]) and Research Data Alliance (RDA[51]) – are geared towards coordinating and facilitating e-infrastructure and related services.

50.
e-IRG
https://e-irg.eu/

51.
RDA
https://rd-alliance.org

e-IRG serves as a strategic body facilitating integration in the area of European e-infrastructures and connected services, within and between member states, at the European level and globally.

The mission of e-IRG is to support **coherent, innovative and strategic European e-infrastructure policy making** on one side, and the **development of convergent and sustainable e-infrastructure services** on the other. It brings together representatives from EU Member States, Associated Countries, and other stakeholders to discuss e-infrastructures issues such as data management, computing resources, and networking.

RDA, established in 2013, is an international organisation focused on **developing and promoting solutions, standards, and best practices for research data sharing and management.** RDA is community-driven and brings together researchers, data scientists, librarians, industry representatives, and other stakeholders to address the challenges of data-driven research. Both e-IRG and RDA signal potential cross-domain aspects and aim to facilitate actions to address them, albeit funding and resourcing of the actions will fall under the responsibility of others.