

European Strategy Forum
on Research Infrastructures

ESFRI



ESFRI
**LANDSCAPE
ANALYSIS
2024**



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ANALYSIS
2024**

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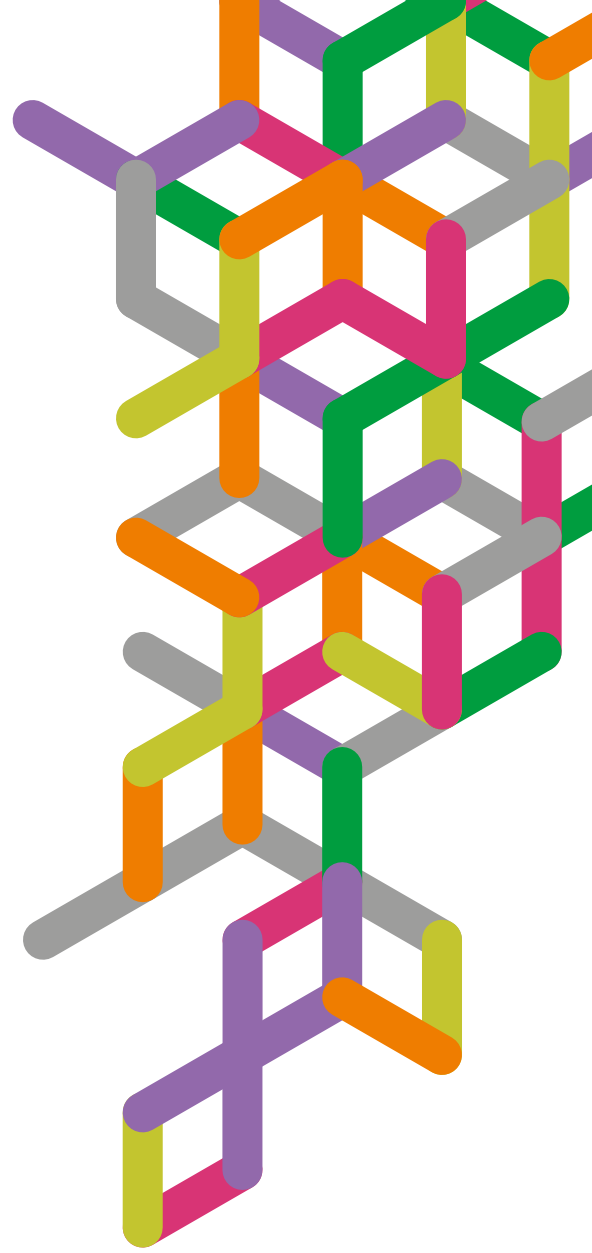
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Browse the First Edition (2024) of the RIs Portfolio and download RIs cards at ri-portfolio.esfri.eu

For more information, visit www.esfri.eu or www.ec.europa.eu/research-and-innovation

The Landscape Analysis is an indicative reference document central to the ESFRI Methodology and does not represent an anticipation of prioritization in the ESFRI Roadmap nor in any way a national, financial and political commitment.



ESFRI LANDSCAPE ANALYSIS 2024

EXECUTIVE SUMMARY

Since 2016, ESFRI has introduced the Landscape Analysis in its Roadmaps, providing an overview of the European Research Infrastructure (RI) ecosystem, identifying key RIs and their global positioning.

The ESFRI Landscape Analysis 2024 presents three main novelties:

It is the first Landscape Analysis report to be decoupled from the Roadmap, providing the framework and the rationale for the next Roadmap;

It includes the first version of the ESFRI RIs Portfolio, developed as an online tool to ensure up-to-date and readily usable information about all ESFRI RIs;

For the first time, the analysis performed has also been based on inputs received directly from the main stakeholders.

The landscape of European Research Infrastructures is at a transformative crossroads, marked by rapid technological advancements, evolving governance dynamics, and pressing societal challenges while facing constrained budgets.

The ESFRI Landscape Analysis 2024 offers a comprehensive analysis of this dynamic environment, encapsulating current states, services, impact, future trends, challenges, and opportunities combining domain specific findings along the six ESFRI Scientific domains (Data, Computing and Digital Research Infrastructures, Energy, Environment, Health and Food, Physical Sciences and Engineering, Social Sciences and Humanities), with broader cross-domain views.

Technological Convergence and Innovation: The RI landscape is predominantly driven by advanced technologies such as Artificial Intelligence, quantum computing, and digitalisation. These technologies revolutionise research methodologies across various domains, fostering a fundamental shift towards more holistic and efficient scientific discovery, innovation and a diverse services portfolio.

Sustainability and Green Innovation: A strong commitment to environmental stewardship and sustainable development characterises the RI landscape, with initiatives supporting climate change policies and emphasising the development of low carbon energy sources and environmental sustainability.

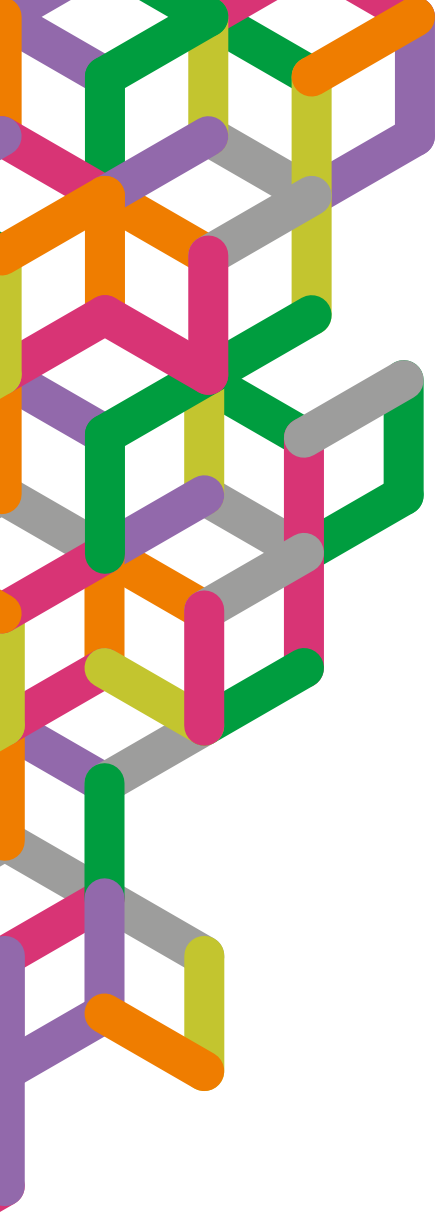
Adaptive Response to Global Challenges: The RIs' capacity for rapid adaptation and response to global crises, including health emergencies and climate change, underscores their vital role in addressing urgent societal needs through flexible infrastructures and rapid response mechanisms.

Data-Driven Research Paradigm: A significant trend towards data-intensive research methodologies is reshaping scientific inquiry. This transformative shift is being enabled by enhanced data capabilities and digitalisation, leading to breakthroughs across various domains.

Ethical and Societal Responsibility: Ethical considerations and societal impact are increasingly prioritised, ensuring that technological and research advancements align with societal values and standards.

Challenges and Future Outlook: The RI landscape faces multifaceted challenges, including sustainable funding, interdisciplinary collaboration, and alignment with EU policies and societal goals.

The ESFRI RIs Landscape Analysis 2024 reflects a dynamic and responsive approach to the needs of the European research ecosystem. This dynamic evolution needs strategic alignment, interoperability, openness, digital transformation adaptability, engagement with societal challenges, and support for cross-domain research.



ESFRI LANDSCAPE ANALYSIS 2024

INTRODUCTION



Since 2016, ESFRI has introduced the Landscape Analysis (LA) in its Roadmaps. The Landscape Analysis provides an overview of the European RI ecosystem by identifying the main RIs operating transnational access in Europe, in all fields of research, and major new or ongoing projects. In addition to providing an outlook to the global landscape of relevance it also provides an opportunity to help identify potentially critical gaps in the current landscape. The Landscape Analysis has progressively evolved (2018, 2021) towards a more comprehensive and strategic document, now including trend analysis and the first examples of RIs services and their impacts in specific areas.

To underline the strategic relevance of the Landscape Analysis, ESFRI has decided to de-couple it from the Roadmap. The LA 2024 is now a stand-alone document, that could be used by the scientific community to record their future needs, requests or available resources.

According to the new ERA Action 8, the ESFRI Landscape Analysis 2024 provides the framework for the next ESFRI Roadmap. It also contributes to the EOSC Strategic Research and Innovation Agenda and promotes the development of new Research Infrastructure services, including, when needed, infrastructure clustering for pan-European thematic or interdisciplinary services. In accordance with the Competitiveness Council conclusions¹, the ESFRI LA 2024 is based on a comprehensive analysis of the European RI landscape. Its objective is to identify existing synergies and complementarities, expose persistent deficiencies, shortcomings and gaps, and propose improvements on accessibility, networking, clustering, associating and even merging of European, national and regional RIs, and their deeper integration in a fully functional and interoperable European RI ecosystem.

¹ Research Infrastructures - Council conclusions (approved on 2 December 2022), 15429/22

The ESFRI LA 2024 provides a more consolidated gap analysis based on user needs. It includes RI services, technology, instrumentation, and data aspects, alongside societal and economic impact; it covers the different domains and multiple dimensions across them. Lastly, it encompasses the evolution of needs to pinpoint priorities for future developments.

For this new concept of the Landscape Analysis, ESFRI has developed a new methodology building upon previous ESFRI experience and introducing an active role for the main stakeholders. The ESFRI LA Drafting Group has developed the new methodology, coordinated the entire process, and prepared the final report. Specific questionnaires tailored for RIs and Science Cluster Projects were utilised to gather relevant information on their current status, trends and future developments, as well as impact. For the first time, ESFRI has organised an open collection of information from key stakeholders to ensure capturing all relevant needs, priorities and trends; their strategic insights are publicly accessible on the ESFRI website. High-level experts were identified to support the work of the LA Drafting Group, with a focus on thematic aspects aligned with the Strategic Working Groups (SWGs), to elevate the analysis to a higher level of detail and complexity. The experts were asked to analyse the outcome of surveys received from RIs and stakeholders identified by ESFRI, to provide a broad perspective on the needs, drivers, and directions of Research Infrastructure (RI) landscape development in Europe, and to contribute to the draft of the Landscape Analysis.



Given the complexity of the RIs ecosystem and the large variety of related topics, in LA 2024 ESFRI chose to focus the analysis only on specific critical areas, such as crises, Horizon Europe Missions², and digital and green transition.

This LA 2024 report also serves ESFRI as a platform to test the new methodology based on direct contributions from RIs and stakeholders, alongside the involvement of external experts for a deeper analysis. This methodology will undergo further refinement for the forthcoming LA reports, expected after 2026.

2. [European Missions - Council conclusions \(adopted on 10 June 2022\), 10124/22](#)

The ESFRI Landscape Analysis Report 2024 includes two main sections: Section 1 focuses on each of the six ESFRI Scientific domain (DIGIT, ENE, ENV, H&F, PSE, SSH), while Section 2 offers a broader view across all domains.

SECTION 1

THEMATIC AREAS

PAGE 8

provides an overview of the current landscape, encompassing the most pertinent Research Infrastructures (RIs) available to European scientists and technology developers, within and beyond ESFRI. It includes assessments of the current status, services offered, potential impact, trends, gaps and needs identified for each scientific domain as well as cross-domain aspects as identified from the specific domain. This section has been prepared by the ESFRI SWGs, which have used insights from external experts, RIs and main stakeholders.

SECTION 2

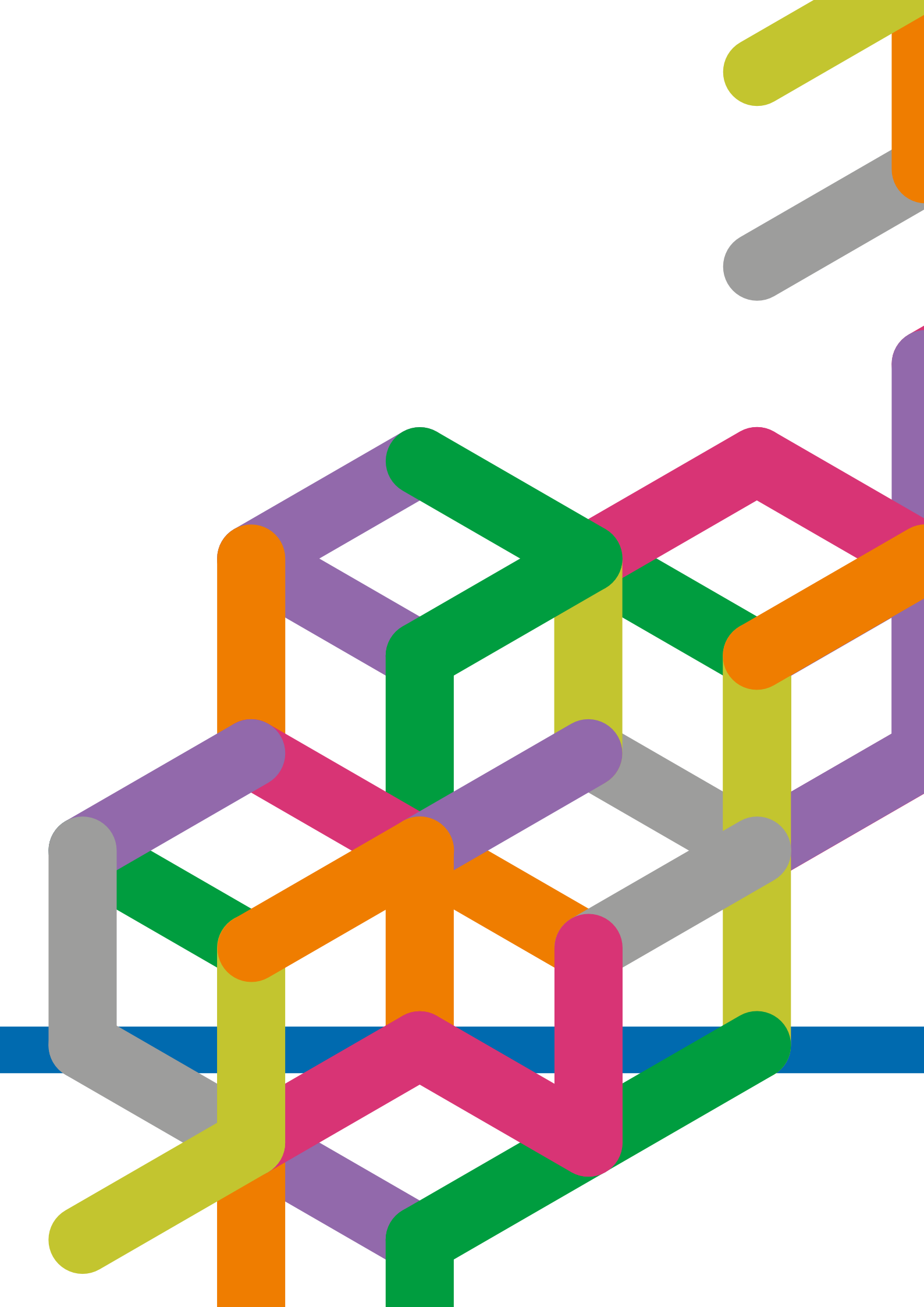
CROSS-DOMAIN TRENDS AND CHALLENGES

PAGE 112

offers an insightful analysis on trans-disciplinary aspects concerning ESFRI Research Infrastructures (RIs). It encompasses current status, future trends, challenges, and opportunities of ESFRI RIs considered in their overarching characteristics, thus complementing the cluster-focused Section 1. This section has been prepared by a team of selected external experts who have integrated analyses from the thematic areas of Section 1 along with input received from RIs and main stakeholders.

In addition to the Landscape Analysis 2024 report, the ESFRI RIs Portfolio³ has been developed, an online tool that serves both as a component of the ESFRI LA 2024 and as a stand-alone, living source of information. It provides a two-page description of each ESFRI RI, picturing the "state of the art" of ESFRI RIs categorised by the six ESFRI research areas. The ESFRI RIs Portfolio will be periodically updated to ensure that up-to-date and easily usable information on ESFRI RIs is accessible to the scientific and stakeholders community.

3. [RIs Portfolio](#)
ri-portfolio.esfri.eu





SECTION 1

ESFRI LANDSCAPE ANALYSIS 2024

THEMATIC AREAS



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ESFRI LANDSCAPE ANALYSIS 2024 - SECTION 1

DATA, COMPUTING AND DIGITAL RESEARCH INFRASTRUCTURES

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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 00

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 GÉANT², ESFRI

2. GÉANT
<https://geant.org/>

Landmark PRACE³, EUDAT⁴ or EGI⁵, 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-

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 CERN⁶, EMBL⁷, ESO⁸ or ESA⁹, or ECMWF¹⁰ 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

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-portaleu/about/eosc>

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

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 eBRAINS¹⁵** 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-

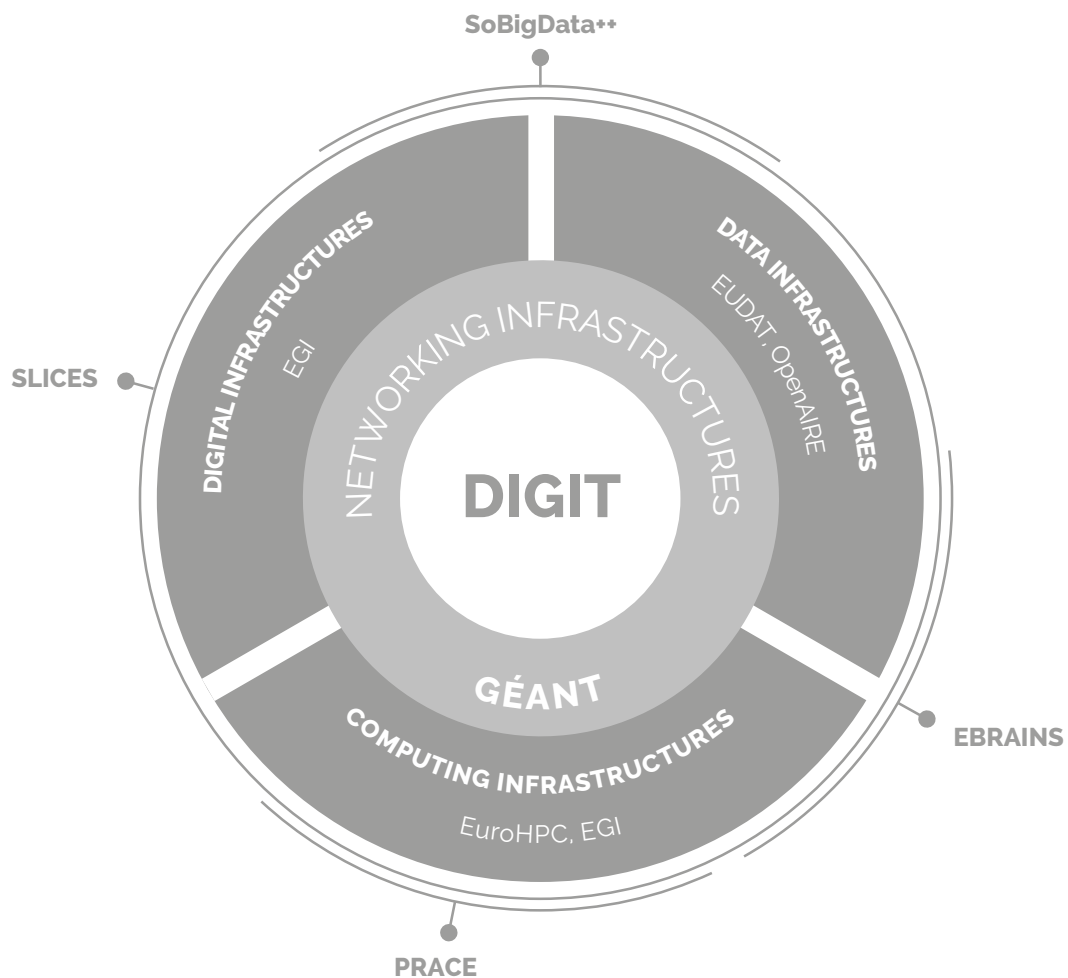


FIGURE 1.
 The Landscape of the Data, Computing &
 Digital Research Infrastructures domain

entific domains such as Environmental Sciences ([ENVRI-FAIR¹⁶](#)), Physics and Astrophysics ([ESCAPE¹⁷](#)), Biomedical Sciences ([EO-SC-Life¹⁸](#)), Photon and Neutron ([PANOSC¹⁹](#)), and Social Sciences and Humanities ([SSHOK²⁰](#)).

([European DTO²⁵](#)), biodiversity ([BioDT²⁶](#)), geographical extremes ([DT-GEO²⁷](#)) or addressing multiple domains ([InterTwin²⁸](#)).

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 \(DestinE²²\)](#), 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 Deal²³ and Digital Strategy²⁴. A number of other digital twins supported by the EC are being established for monitoring oceans

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 spaces²⁹](#) 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 strategy³⁰](#) 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.panosoc.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://biодt.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 (NREN³¹), 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 ESFRIs with specialised network support.

Additionally, all European NRENs offer critical access and identity services such as eduroam³² and eduGAIN³³. 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, AfricaConnect³⁴, CAREN³⁵, EUMEDConnect3³⁶,

EaPConnect³⁷, TANDEM³⁸ 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 OpenAIRE³⁹, 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 (SHAPE⁴⁰ 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:

- LUMI⁴¹ in CSC – IT Center for Science, Finland;
- LEONARDO⁴² in CINECA, Italy;
- Mare Nostrum 5⁴³ in Barcelona Supercomputing Centre, Spain.

LUMI has been operational since the beginning of 2022 and ranked first in Europe and third in the TOP500⁴⁴ 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 funded⁴⁵.

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: Eu-

rope 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-IRG⁵⁰) and Research Data Alliance (RDA⁵¹) – 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.



ESFRI LANDSCAPE ANALYSIS 2024 - SECTION 1

ENERGY



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CURRENT STATUS IN THE DOMAIN 00

The energy sector is vast, multi-faceted and complex. Continuous access to reliable, dispatchable energy is of fundamental importance for modern societies, including transport, industry and housing. The Ukraine conflict, impacting the supply of easily available and cheap natural gas, is forcing Europe to reconsider its energy future to ensure the security of supply. The large-scale adoption of new, energy-effective, cost-efficient and socially, politically and environmentally acceptable technologies is necessary to address current challenges.

It is vital to recall that the ways we use energy today were shaped by the era of cheap fossil fuels, with limited appreciation of environmental impacts. This needs serious reconsideration. Major investments in research, including new Research Infrastructures (RIs), are imperative, together with a holistic consideration of the net effect of new technologies on environment and climate.

The RIs in the energy sector are not necessarily and far from exclusively industrial facilities. Rather, they perform functions which cannot and will not be addressed by

the commercial sector alone and are vital to cope with current challenges. The **urgency of fighting climate change** has led to broadening the spectrum of research from solely addressing energy production to developing other technologies including carbon capture and energy storage. The latter is necessitated by the rapid adoption of non-dispatchable production technologies, such as wind and solar.

Energy systems evolve, sometimes rapidly, driven by technological developments and driving forces in society. Where competing

technologies perceived to be similarly environmentally benign exist (e.g., for electricity production) the more cost-efficient option is likely to be preferred, which is why fossil fuels have dominated until now. The **security of energy supplies** is currently highly relevant. Forces driving change in the energy sector include environmental loads, such as CO₂ emissions from combustion of fossil fuels in energy production and transport; pollution, for instance from metals due to component production; and the disruption of ecosystems from land-use for energy production (e.g., energy biomass or solar fields in industrial scale) and use (e.g., transport).

The large-scale implementation of a new energy technology is often extremely costly, and the practical lifetime of constructed facilities may span several decades. In particular, the (unsubsidised) costs of modifications to the energy system (system costs) that are necessary to accommodate dispatchable and non-dispatchable energy sources should be estimated and taken into account. Choices based on comprehensive considerations must be made and identified challenges addressed. Furthermore,

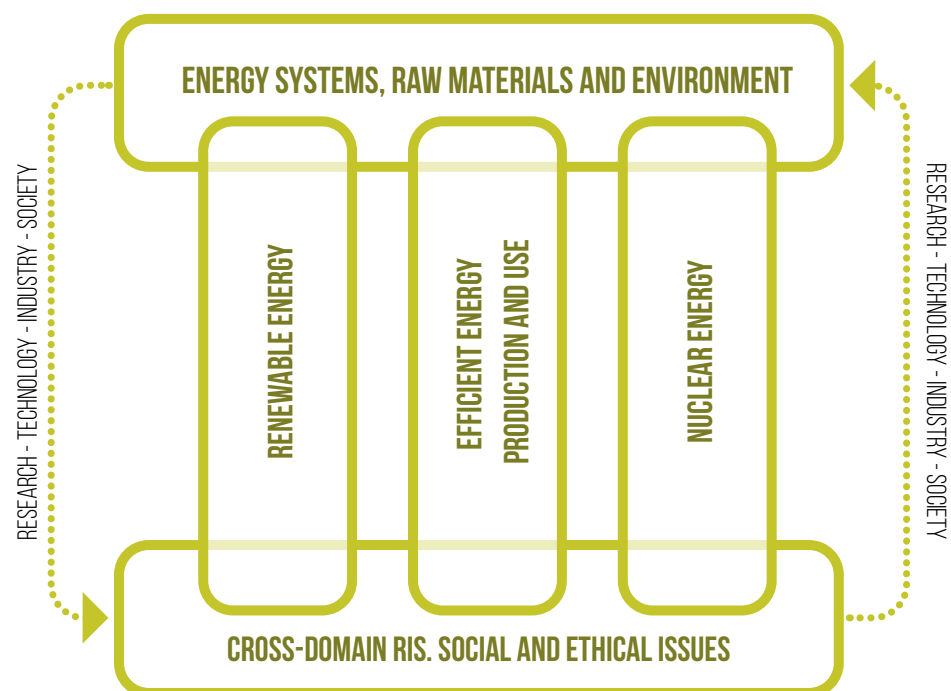


FIGURE 1.
Energy RIs Interplay.

unforeseen developments may still greatly impact the longer-term trajectory of the energy sector. Consequently, there's a strong rationale for research on a broad front.

While there are many local, national and international RIs supporting energy research, **only relatively few ESFRI energy RIs exist.** Given the current ambitions for significant changes in the energy sector, this appears surprising. One important factor is that, unlike RIs in other sectors, the character of many potential energy RIs does not fit optimally with the current ESFRI concept; for instance, due to intimate interactions with the commercial/industrial sector. The geographically distributed nature of some energy RIs can also be a complicating factor.

Currently, ESFRI RIs encompass **ESFRI Landmark EU-SOLARIS** (solar energy), **ESFRI Landmark ECCSEL ERIC** (carbon capture, sequestration and valorisation), **ESFRI Landmark JHR** (Jules Horowitz Reactor, fission reactor to study materials), together with the **ESFRI Project Marinerg-i** (marine energy including wind), and **ESFRI Project IFMIF-DONES** (installation for the study of materials suitable for fusion reactors). The research carried out in these facilities is augmented by other non-ESFRI RIs around Europe, as exemplified below.

While **Figure 1** displays the interplay of the fields and energy RIs, **Figure 2** gives a comprehensive overview of the portfolio of ESFRI Energy RIs.

SOLAR ENERGY

The **ESFRI Landmark EU-SOLARIS ERIC¹** focuses on several key areas of **concentrated solar power.** Plataforma Solar de Almería (PSA) in Spain operates a set of test facilities, including solar thermal and photovoltaic systems, addressing different technologies, energy storage, and integration strategies. Other participants include the Fraunhofer Institute for Solar Energy Systems (ISE) in Germany, which addresses solar energy on a broader front. It houses multiple testing and research facilities, including the Outdoor Test Facility, which allows for the evaluation and characteriza-

1. **EU-SOLARIS ERIC**
<https://eu-solaris.eu>

tion of different solar technologies under real-world conditions.

WIND POWER

The **ESFRI Project MARINERG-i²** consists of distributed testing infrastructures, united to create an integrated centre for delivering **Offshore Renewable Energy.** Currently, the main thrust is on off-shore wind power, but the potential of wave and tidal energy is also explored. While wind power technology is already established, there are several institutes involved in improving the design and efficiency of wind turbines. Wind Europe³ oversees several RIs focused on wind energy, including large-scale test sites such as the Osterild and Høvsøre test centres in Denmark. These sites, as well as those provided by the Fraunhofer Institute for Wind Energy Systems (IWES)⁴ in Germany, provide researchers and industry partners with access to full-scale wind turbines for testing and validation of new technologies and concepts. Wind tunnel testing of wind turbines is facilitated by German-Dutch Wind Tunnels, DNW⁵.

CARBON CAPTURE, USE AND STORAGE (CCUS)

Carbon capture, utilisation and storage (CCS and CCUS) potentially allow the continued large-scale use of fossil fuels with low CO₂ release, and several large projects are underway around the world. The **ESFRI Landmark ECCSEL ERIC⁶** is a distributed RI that includes several research centres, universities, and industry partners across Europe. It aims at addressing all different

2. **MARINERG-i**
<https://marinerg-i.eu>

3. **Wind Europe**
<https://windeurope.org/>
Note that in this document we can only refer to a few of the very many relevant organisations, and those included should be regarded as examples.

4. **Fraunhofer Institute for Wind Energy Systems**
<https://www.iwes.fraunhofer.de/>

5. **German-Dutch Wind Tunnels**
<https://www.dnw.aero/>

6. **ECCSEL ERIC**
<https://eccsel.org/>

components of CCUS. Capture technologies, such as absorption or adsorption, and membrane separation, are developed to improve CO₂ removal from industrial processes and chemical production plants. Methods to use CO₂ as gaseous feedstock to produce chemical intermediates, renewable fuels (e.g., CH₄, methanol, Dimethyl Ether DME), and other products are also considered. Research on CO₂ storage comprises both the safe transport to the location of the final deposition and developing means and safeguards for how the deposited CO₂ can be stored permanently and kept from entering the atmosphere.

NUCLEAR FISSION

The **ESFRI Landmark Jules Horowitz Reactor (JHR)⁷** is under construction in France. The lifetime extensions of existing Nuclear Power Plants (NPPs), and prolonged storage of radioactive waste (RW), need **experiments on materials under ionising radiation**, which is what JHR can provide. At the same time, it will alleviate the lack of irradiation facilities in Europe. Since nuclear fission plays an important role, providing stable CO₂-free base load electricity in the EU (about 25% in 2018), the main strategic objectives are **safety aspects and long-term waste disposal.** The MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications)⁸ is part of an overall approach – Partitioning & Transmutation (P&T) – to **reduce the amount of waste that requires a geological repository.** Other research in this field includes reactor technology, fuel cycle, safety, decommissioning of nuclear installations and waste management. These topics are addressed, among others, by the French CEA, the Belgian SCK/CEN, the Czech ÚJV Řež, a. s.⁹, the Italian ENEA Bologna, Brasimone, Casaccia, and the Swiss Nuclear and Safety Department of the Paul Scherrer Institute¹⁰, which are also open to international collaboration.

7. **JHR (Jules Horowitz Reactor)**
<https://jhreactor.com>

8. **MYRRHA**
<https://myrrha.be>

9. **ÚJV Řež, a. s.**
<http://www.czech-research.com/rd-environment/research-organizations/ujv-rez/>

10. **Paul Scherrer Institute, Nuclear Energy and Safety Research Division**
<https://www.psi.ch/en/nes>

NUCLEAR FUSION

The **ESFRI Project IFMIF-DONES** (International Fusion Materials Irradiation Facility – Demo Oriented Neutron Source)¹¹ is a planned facility to provide an intense neutron source for the testing and development of materials that will be used in future fusion reactors. Currently the prototype of the IFMIF-DONES accelerator, unique as a high-intensity device, is being tested at Rokkasho, Japan. Other specific key technologies developed will be the complex lithium loop system and a sophisticated remote handling system required to extract and manipulate the irradiated samples. With the recent breakthroughs in fusion energy research¹², the focus is moving from basic science towards technology and engineering. IFMIF-DONES is an important complement to the International Thermonuclear Experimental Reactor (ITER)¹³ which is being built in Cadarache, France, in collaboration with six other international partners (China,

India, Japan, Korea, Russia, and the United States), with Europe being the main funding partner.

OTHER FIELDS

There are numerous national and European initiatives addressing many different energy research and technology challenges that are not represented within ESFRI. Several fields, including energy production, storage and use, have significant EU support. Examples are geothermal energy, and batteries and hydrogen technologies for storage on different time scales. The latter is coordinated on a European scale through the Hydrogen Europe Research consortium¹⁴ within the Clean Hydrogen Partnership. In addition, large efforts to build and upscale infrastructures for Research and Innovation (R&I) and interconnect actors in this field are on the way within the framework of the emerging EU Hydrogen Valleys.

Despite the various existing initiatives, it is assessed that investments in European energy RIs are currently low compared to the challenges facing society. This is further discussed in section E.

11. IRMIF-DONES
<https://ifmif-dones.es>

12. In Europe, research is coordinated by EUROfusion
<https://euro-fusion.org/>

13. ITER
<https://iter.org>

14. Hydrogen Europe
<https://hydrogeneurope.eu>

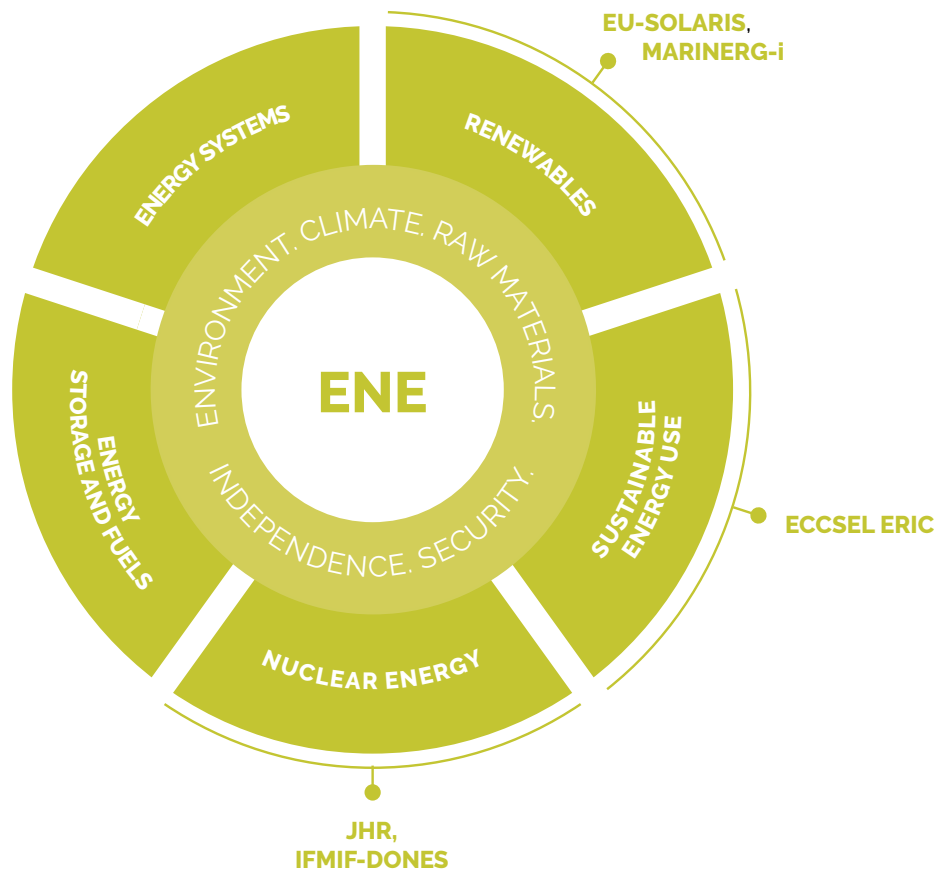


FIGURE 2.
The Landscape of the Energy domain.

Energy RIs should provide access to a range of experimental facilities, such as test beds, laboratories, and pilot plants, allowing researchers to test and validate new energy technologies and solutions. They should also provide access to data, analysis tools and expertise. Providing balanced information to the public and decision-makers regarding, for instance, the true potential (and possible drawbacks) of a given technology can also be an important service. Transnational collaboration and offering services across national boundaries is crucial within ESFRI. This can include supporting transnational access to RI facilities¹⁵, data and competence; most ESFRI-affiliated RIs offer TNA (Trans-National Access) programs.

¹⁵ Access to European Research Infrastructures
https://research-and-innovation.ec.europa.eu/partners-networking/access-research-infrastructure/access-european-research-infrastructures_en

While some energy RIs encompass advanced technologies and instruments, offering, for instance, analytical services to a large number of genuinely external researchers, many of them support developments of a specific technology. Because of the focus of such RIs, many of the researchers and institutions using the facilities may be active partners in running and developing the RI, or having a direct interest in the field, and are in this sense not "external". At the same time, the group of researchers involved may represent a major part of the total relevant European research community.

The pan-European RI **ECCSEL ERIC** features 93 research facilities from 23 differ-

ent facility owners within the five member countries. 30% of the user time is allocated to organisations outside the member countries. The selection of these projects is based on a peer-review of the applications. Among the services to industry, the ECCSEL lists **community building** (scouting, brokerage, awareness creation, dissemination, ecosystem building) and **market intelligence** (market assessments, road mapping, technology watch).

The **EU-SOLARIS ERIC** offers services within the partners' facilities, primarily **experimental** in nature and including **access, training, and studies**. For example, certain services are required for on-site diagnos-

tics of the Concentrated Solar Thermal (CST) system, such as measuring thermal or vacuum losses in receivers, piping, storage tanks, or for experimental verification of the performance of sub-components, plants, or complete systems.

The infrastructures Jules Horowitz Reactor, IFMIF-DONES and Marinerg-i are either under construction or in their early stages of planning, development and construction, so that no services are currently being offered. In the case of the **JHR**, collaborations in the design and delivery of some components are performed during the construction phase. **IFMIF-DONES** is designed specifically to offer services for testing and developing materials to be used in the extreme environment of a nuclear fusion reactor. In addition, beyond high-flux irradiation of fusion materials, services envisaged by applying mid- and low-flux irradiation areas encompass fundamental nuclear physics research, materials testing, and radioisotope production for medical and industrial applications. **Marinerg-i** plans to offer services supporting the design and advancement of the Offshore Renewable Energy (ORE) systems, including hydrodynamics, aerodynamics and fluid-structure interaction, material science, electro-technical engineering, ICT, naval architecture, sensors, oceanography, environmental and social sciences, business management, economics and legal sciences.

The breadth and complexity of the challenges motivates a broad range of energy-related research, much of which demands access to well-tailored Research Infrastructures. In this section, we outline the main positive impacts stemming from existing RIs, followed by important societal impacts, reflections on what the future may hold, and where new, major RI initiatives may be necessary.

Competing technologies exist for harvesting different forms of primary energy, for transforming it into secondary, more suitable forms, and for how it is used by society (industry, transport, services). Which technologies will dominate is likely to depend not only on future technological developments, but also on the societal acceptance of the impacts that they will have on the environment, climate and everyday life. Collective efforts by different ESFRI SWGs and the corresponding RIs can play a crucial role here.

Despite ambitions to the contrary, the world, including Europe, is still heavily dependent upon fossil fuels¹⁶. CCS (Carbon capture and storage) and CCUS (including use of the captured carbon as industrial feedstock) have major potential to reduce greenhouse gas emissions while at present continuing extensive use of fossil fuels. Developments driven by programs such as ECCSEL have showcased viable technologies to the extent that many countries are now seriously considering the implementation of large scale CCS.

An infrastructure having concrete connections with the relevant industry can lead to rapid industrial implementation of research results. A successful example of this is the collaboration between ECCSEL and Air Products. The company has secured an exclusive license agreement with NTNU Technology Transfer, a Norwegian University, for

¹⁶ With the data and methodology used in <https://ourworldindata.org/grapher/global-primary-energy>, 85% to total global primary energy was from fossil fuels in 2022, with 13% from renewables which includes 0.8% Solar power and 1.3% Wind power. <https://ourworldindata.org/grapher/elec-mix-bar> shows some energy consumption data. Many countries, including in Europe, continue to rely heavily on fossil fuels for electricity.

proprietary fixed site carrier (FSC) membrane technology. This technology, aimed at capturing CO₂, was developed at one of the facilities belonging to ECCSEL in Trondheim.

The use of solar energy is rapidly increasing. Currently, solar cells have a cost-advantage relative to concentrated solar power (CSP). However, CSP possesses a major benefit in that heat can be stored relatively easily, making electricity production more flexible over time. This may become increasingly important if the proportion of non-dispatchable renewable electricity in the grid system continues to rise. EU-SOLARIS impacts industry by testing and verifying different technologies and sub-components in a consistent manner, allowing the selection of the best solutions for future development.

The impact of a strongly growing energy sector based on non-dispatchable sources has started to show, so far predominantly in the form of extremely volatile electricity prices. The very low energy density (a few watts per square metre) of some renewable sources necessitates the use of large areas of land, causing visible impact. A third, sometimes underestimated, future impact relates to the vast amounts of non-renewable material required by some of the technologies required for harnessing renewable energy, demanding extensive mining.

Transport may be driven by grid-connected electricity, batteries, fuel cells, or inter-

nal combustion engines (fossil or synthetic fuels, including hydrogen and biofuels). A future electricity system heavily based on non-dispatchable renewables such as wind and solar power is likely to demand major new efficient energy storage facilities, perhaps in the form of hydrogen or other synfuel. All activities on the relevant scale, such as mining for battery materials, are likely to have significant environmental and social impacts, such as mining for battery materials. It follows that while we are likely to see the growth of major novel industries in such sectors, it is not yet clear which technologies will dominate in the longer term. Understanding which technology is likely to be most attractive in different applications demands solid insights into the pros and cons of potentially competing ones.

The most significant short-term impacts in the field of fission-based energy production may be related to the prolongation of the operating Nuclear Power Plants (NPP) and safe waste disposal. The latter includes the use of transmutation to reduce the volume of material to be disposed of in geological repository. When completed, the JHR will allow the study of materials under nuclear irradiation, a key point for the safe operation of NPPs and their life extension. The development of new generations of safer and more efficient fission reactors is likely to greatly benefit from the MYRRHA facility (presently a Belgian effort on the site of SCK/CEN). At the completion of MYRRHA phase 1 scheduled for 2026, a 100 MeV linear proton accelerator will be used to provide a "Radioactive Ion Beam (RIB)", allowing for fundamental research in several scientific domains even beyond the energy sector. At its definitive completion in 2036, MYRRHA will provide a facility for the study of accelerator driven systems and transmutation of active wastes, alleviating the issue of long-term repository. MYRRHA also offers innovation services to applications such as the development of Heavy-Liquid-Metal-based SMR (Small Modular Reactor)¹⁷ systems.

¹⁷ Small Modular Reactors https://energy.ec.europa.eu/topics/nuclear-energy/small-modular-reactors_en

When constructed, the relatively new **ESFRI Project IFMIF-DONES** will complement the (partly European funded) ITER fusion energy program by allowing studies of the **behaviour of materials in the special environment of a future nuclear fusion reactor**. If the suite of projects related to the development of fusion power is successful, this is likely to be of vast significance for society.

All ESFRI Projects and Landmarks have many societal impacts by developing **innovative answers to advanced technology issues**. They contribute to European economic growth in a globally competitive market by providing the necessary innovation and by maintaining the industry competencies. ESFRI RIs can also **help decision makers** weigh different competing technologies against each other

prior to major political decisions. As the energy system is evolving, driven partly by technological development, partly by other factors such as national economic and strategic considerations, the longer-term future for a given technology may not be completely clear. One consequence is the potential risk of significant shortages in the necessary highly competent personnel across various energy fields, especially in cases requiring rapid large-scale implementation of new technology. By offering cutting-edge research opportunities, these RIs are an ideal place for **training young talents** to become the future technology leaders both in academia and industry. Also, being at the forefront of Research and Development (R&D), RIs often offer **outreach programs**, which in turn attract new generations to Science and Technology.

TRENDS IN THE DOMAIN

Society constantly seeks the fast development of new, **better energy solutions**, in terms of **efficiency, energy services, sustainability through circularity, security of supply and true (unsubsidised) cost**. Innovations enabling more efficient use of energy are constantly and successfully sought after. Despite this, **global energy consumption has tended to increase** gradually as energy is used for new purposes. Indeed, there is a strong ongoing **trend towards electrification**, characterised by the utilisation of electricity in more functions than before, rather than some other form of energy, which can be notably seen in road transport. The trend towards electrification must be accompanied by enormous increase in the production of electricity; thus, it is not clear how far electrification will extend over the coming decades. Electrification also implies fewer alternatives, such as diesel fuel, for the maintenance of society's functions, implying that the future electrical grid system and associated balancing functions must be extremely secure, robust and reliable, significantly more than today.

Geography, climate and industry can differ greatly between European countries. This entails that their energy systems may develop rather differently, implying the need for a broad range of energy research. Current major trends include **ambitions to reduce greenhouse gas emissions while keeping energy security, independence and services**, and at the same time **keeping prices at levels which are acceptable to society**. These ambitions have motivated significant investments in "renewable" energy production, such as wind or solar. More recently, other "low-carbon" technologies like nuclear power, biofuel, geothermal energy, or CCS, have gained increased interest in several European countries. This is partly due to the non-dispatchability of some renewable electricity sources, which means that their large-scale implementation demands substantial new components in the energy system to achieve the necessary instantaneous balance between electricity production and consumption. This challenge intensifies as the proportion of such sources in the system grows. Recent pronounced volatility in electricity prices illustrates the extent of the challenges. Additional system costs may include energy storage in batteries, or as synfuel or heat, and the adjustment of demand using smart-grid technolo-

gies. Costs, system efficiency, and market effects must be considered and evaluated.

Fuel cells and hydrogen (FCH), as well as derived technologies like synfuels, may play a key role in the future energy system, offering low CO₂ emission solutions for different sectors and applications, including contributing to grid system balancing, mobility and transport, heating and cooling, and as feedstock for industrial applications. The potential of hydrogen was seen already 20 years ago, but its energy and cost efficiencies are yet to be determined. Therefore, major adaptation of hydrogen technologies is limited. Many of the relevant technologies require innovative development to become fully attractive.

The use of **batteries** for transport and other functions has significantly surged and is foreseen to increase further. New developments are desired to reduce costs, lower weight, and extend their lifetime. Innovations are needed to allow less reliance upon battery raw materials which are expensive, scarce, and environmentally problematical. This field currently stands as a dynamic research area, which is likely to require substantial future investments in RIs.

Solar cells have decreased greatly in unit cost, which has led to dramatic increase in their adoption. However, due to their relative low energy density, future developments are needed to both enhance their efficiency and reduce environmental costs. One current focus area requiring further research pertains to the interplay between local solar electricity production and consumption. New RIs exploring real-life situations may be strongly motivated.

The revived interest in **nuclear power from fission**, triggered by the challenges of the energy transition and by the recent geopolitical and energy crisis, has led to specific EU initiatives in this sector as well as the creation of new companies worldwide, sometimes with significant private investments. A newcomer in energy production is the **Small Modular Reactor (SMR)**, delivering up to about 300 MWe, with the potential of low costs and high reactor safety. Energy produced by SMRs could also be used fuel-efficiently to supply heat;

for instance, for industry or neighbourhood heating systems. SMRs are attracting strong interest from governments and industry, despite some public concerns about safety and waste disposal. Since technical solutions for nuclear waste disposal exist and their implementation in some countries is imminent, the long-term storage and disposal of nuclear waste is essentially a political challenge that **Social Sciences** may help to address and mitigate. Additionally, there are ongoing developments in new nuclear reactor designs that are safer and more efficient than older ones. Research aimed at further enhancing safety while containing costs must be adequately supported.

Research in the field of **Fusion Energy** has made significant leaps over the past years and, consequently, a substantial number of private companies doing R&D have appeared¹⁸. These have followed both the **magnetic confinement approach**, foundational to the ITER project, and the **inertial confinement scheme**, which has received significant attention following the NIF experiments (USA) that resulted in ignition in December 2022. In terms of funding, private efforts, mainly concentrated in the USA and the UK but also in the EU, constitute only a small fraction of the overall fusion R&D budget. These developments, which in some cases also involve public funding, cannot be ignored but have to be approached with proper caution, as some of these projects are limited in scope and propose unrealistic calendars for the objective of fusion energy generation.

Private Public Partnerships (PPP) are increasingly important for energy research and RIs. Such Partnership is natural since it will benefit society if advanced RIs, which may be publicly funded or partly industry-funded, are used to enhance commercial development. For instance, there are recently US PPP awards granted to eight companies active in fusion, along with a US-EU PPP¹⁹ in the field of Small Modular Reactors (SMR), and the EU PPP in the field of Hydrogen and Fuel Cells²⁰.

18. _____
E.g., Fusion Industry Association
<https://www.fusionindustryassociation.org/>

19. _____
Small Modular Reactor Public-Private Program, International Trade Administration
<https://www.trade.gov/eu-smr>

20. _____
Public-private partnership for hydrogen and fuel cells, EUR-Lex
<https://eur-lex.europa.eu/EN/legal-content/summary/public-private-partnership-for-hydrogen-and-fuel-cells.html>

PPPs can take various forms. The most basic form is an agreement between an RI and industry to jointly conduct an R&D programme, where the cost- and IP-sharing is well defined. Other forms may include the establishment of formal structures such as 'Joint Undertaking' (JU)²¹, 'European Technology Platforms' (ETPs)²², or contractual public-private partnerships (CPPPs). Other legal structures can include Milestone-based PPP, where public funds are awarded to a research institution with matching funds from industry. Besides the protection of IP, key to the success of a PPP is often a light management structure, able to respond quickly and effectively to changes provoked by the ongoing R&D activities.

New solutions based on energy research are necessary and are likely to shape future society. New products, services, and markets can boost economic growth while also reducing environmental loads and offering benefits to society, for instance in the form of new jobs.

The challenges and possibilities in different countries and regions differ, and new technologies tailored for Europe are needed, considering energy sources, patterns of energy use, economic effects, environmental effects on public health and ecosystems, employment, and geostrategic and security considerations. It is also important to stress that large-scale introduction of new energy technologies should be preceded by a thorough analysis of all potential impacts, including environmental effects, supply considerations, energy independence, and social acceptance.

21. _____
Joint Undertakings, EUR-Lex
<https://eur-lex.europa.eu/EN/legal-content/glossary/joint-undertakings.html>

22. _____
European Technology Platforms, ERA Learn
<https://www.era-learn.eu/partnerships-in-a-nutshell/type-of-networks/partnerships-under-horizon-2020/other-era-relevant-partnership-initiatives/overview-etp>

GAPS AND NEEDS IN THE DOMAIN

Recent changes in world politics have revealed the vulnerability of the European energy economy, in particular where there is dependency on resources and products from foreign countries. If the goal is **strategic independence in the energy economy**, the gaps to address in the energy system as a whole now appear significantly more diverse and abundant than a few years ago. In particular, with the rapidly growing demand of minerals (for batteries, as an example) the social and ethical questions related to mining should not be overlooked and call for cross-domain studies.

Energy research and the development of new solutions for future energy systems stand as one of today's biggest societal challenges. Consequently, this field of research per se encompasses all aspects from ground-breaking basic research to application and marketability of new technologies, i.e. the full chain of Research & Innovation (R&I). This means that **infrastructures in the field should include several integrated TRLs** (Technological Readiness Levels) and should not only cover basic research. Consequently, most of the existing Energy ES-FRI infrastructures (**EU-SOLARIS**, **ECSEL**, **Marinerg-i**, and, when operational, **JHR** and **IFMIF-DONES**) are open for both academia and industry, and are rightly expected to serve both communities. **The distinction between Research Infrastructures (RI) and Technology Infrastructures (TI) is thus not applicable in the energy field.** Therefore, a broad spectrum of R&D from very basic to applied research should be an integral part of the future European research landscape.

Relevant stakeholders should be encouraged to consider and discuss if existing RIs or TIs cover all relevant aspects, or if the creation of appropriate new RIs or new services from existing RIs should be considered. As a final remark, in view of the crucial importance of energy for the EU, one must note the **low number of ESFRI RIs**. A vigorous program to encourage the establishment of new RIs and TIs should be considered to remediate existing needs.

Relevant areas where new RIs should be considered and existing ones further devel-

oped include **energy production (electricity, heat and synfuel), energy transmission, energy storage, and energy use** in a host of applications including transport, industry, services and buildings. Taking the energy use as an example, it should be **energy efficient** (encompassing each component's construction, use and end-of-life) **effective** (for instance, in the sense of buildings being comfortable or supplying the expected services), and **responsible both environmentally and socially**, (with system design appropriately respecting end-of-life waste products and circularity). In some cases, evolving choices by individual energy consumers may significantly influence which technical solutions are most appropriate; thus, investigating consumers' energy behaviour may be well motivated. Other aspects, including legal, economic and political perspectives as well as the responsibility of the energy users are also important, and merit dedicated cross-disciplinary studies and/or RI initiatives.

As illustrated above, listing all possibly important "gaps" in the energy research landscape is not feasible, but in the following we identify some relevant issues.

Electrification will impact many sectors, from high-tech applications to heating, although for the latter direct use of low-grade forms of energy may be more efficient. The implications of electrification in such applications should be carefully investigated, considering the relative efficiencies and associated environmental loads. In particular, as electricity supply and demand must balance instantaneously, the extensive use of non-dispatchable forms of electricity may demand storing large amounts of electricity (synfuels, hydrogen, heat storage, see below), possibly with limited efficiency. Vulnerabilities of a society fully relying on electricity should be carefully identified, with lessons from the Ukraine crisis.

Significant **energy storage** of various types has existed for many years in our energy system. This can take the form of storage of the primary energy resource, such as biomass, fossil fuel, hydropower or geothermal heat. A strong **move towards non-dispatch-**

able renewables will require new, major storage components in the electricity system, such as chemical storage (hydrogen, synfuel), pumped hydroelectricity, and batteries. Flexible generation sources, such as renewable methane (CCU) and hydropower facilities, can provide backup power and quickly ramp up or down their output to balance supply and demand fluctuations. Such sources will be vital to bridge the gap when renewable energy generation is low. As the system evolves, focus will be on ensuring flexibility while minimising reliance on fossil fuel-based generation. Various nascent technologies, such as compressed gas storage, may have significant potential; but major developments are necessary if these are to become more energy- and cost-efficient. This will require a number of RIs of different characters. As the round-trip efficiency of storing large quantities of electricity can be quite low (e.g. 20-30%) for some candidate technologies, the real-world relative merits of the production of more virgin electricity contra storage should be assessed.

Energy for heating or cooling can be stored thermally; this method may offer higher efficiency compared to storing electricity. This is especially the case for larger facilities, such as district heating and cooling systems. Storage on the relevant scale is a relatively new concept, and research using large field facilities appears necessary to fully exploit its potential. RIs monitoring and modelling energy use (and production) in urban environments, including heating, cooling and consumer behaviour, may be necessary.

Synthetic fuels are industrially produced material which can be combusted. **Biofuels** are liquid or gaseous transport fuels, such as biodiesel, bioethanol and biomethanol, made from biomass. These serve as a **renewable alternative to fossil fuels in the transport sector**, possibly helping to reduce greenhouse gas emissions and improve the security of supply. Synfuels can be produced using carbon dioxide captured from industrial processes or even from the atmosphere. One of the main needs for the deployment of synthetic fuels is continued technological development to make the

production of these fuels more energy efficient, cost-effective, and scalable. Furthermore, it is currently not clear to what extent these fuels actually reduce GHG emissions. Comprehensive, dedicated studies are needed to establish the lifecycle GHG inventory of these processes.

The "Hydrogen economy" is often discussed as a novel means for storing renewable energy in the form of synfuel hydrogen. Although commercially available solutions for the production and use of hydrogen do already exist, there are pressing **needs for R&I to find novel materials and technologies for production and use**, from catalytic systems up to large-scale generation, in order to make hydrogen technologies more inexpensive, efficient, safe and resource-saving. These technologies have to be tested in infrastructural research and development environments to demonstrate that they can be successfully scaled up. Integrating hydrogen into the energy supply chain and managing all components is a key challenge needing investments from both the private and the public sector.

The **Battery industry** is a rapidly growing area, not least in the Far East. Europe is becoming increasingly dependent on batteries, in transport and in the electricity system. Batteries are attractive for electricity storage in that they have high round-trip efficiency. However, while their use might reduce dependence on fossil fuels, the production of the vast quantities of batteries needed for transport and electricity storage requires **unprecedented amounts of raw materials**, currently including lithium, copper and nickel. The nature and scale of environmental and climate loads, as well as social and human rights issues, associated with exploitation of material resources for energy and their use in the corresponding energy domains should be carefully investigated, to avoid possible near- and long-term problems.

Energy materials may represent about 50% of the costs of the so-called clean energy & clean mobility technologies and are **critical in terms of scarceness and geopolitical distribution**. The exploitation of, and valorisation from, the ore also pose serious environmental and social issues. Furthermore, advanced materials are the key to accelerate the transformation of the European energy system. Objectives for material research that would enable low-carbon energy supply are reduction in cost, increase in performance, extension of lifetime, as well as replacement of critical raw materials. One example is the development of post-Li-battery technologies. All this needs extensive materials research using materials development and testing facilities as well as high-throughput methods supported by enormous databases and high-performance data processing.

Innovation can require processing information coming from multiple sources of data. With the compelling need to rapidly develop new energy technologies along the value chain, from materials up to the whole energy system, the latest **high-performance computing technologies and novel software solutions based on Artificial Intelligence** have to be implemented and tailored to the specific requirements of energy applications of all kinds. New ways of generating, collecting, managing, analysing data (such as the Open Science Initiative) are expected to speed up the innovation process, for instance in developing materials and technologies with improved performance and optimising the steering and performance of integrated energy systems.

The energy system is becoming increasingly dependent upon interconnection between different regions and countries, allowing for the exchange of electricity across a wider geographical area. This, together with Smart-Grid technologies, enables the sharing of non-dispatchable energy resources and helps balance supply and demand variations. Because of this, in some cases geographically distributed RIs are natural and necessary. The **high voltage electrical grid system**, local distribution networks, and consumer-system interactions are important for a major move towards renewables. These areas require access to interacting RIs which can provide the respective hardware and data and deliver expertise tailored to the different needs of research for energy applications. For example, advanced forecasting of demand and renewable electricity production, real-time monitoring, and grid automation, can enhance the ability to balance supply and demand while managing risks.

Electricity production from biomass and geothermal energy, solar cells, CSP, nuclear fission and, in the future, nuclear fusion, are all areas where strong development is ongoing and new RIs may be strongly motivated. While technology for hydropower is well-developed, new technical solutions are needed to meet new demands on traditional facilities. These include requirements for continuous and sometimes rapid changes in production to help balance production from time-varying renewable sources. The potential of non-traditional hydro-power using moving water (tides, river-flow, waves, etc.) may require new RIs to develop and fully assess the technology. Fossil fuels may continue to be relevant, especially if used together with CCS or CCSU, motivating further investment in related RIs.

The cost of building nuclear power plants is high compared to other energy sources, and the **associated financial risks** are significant. Since nuclear energy provides dispatchable, low-carbon energy production, research on various energy mix scenarios is needed to fully assess its benefits and risks in the context of the energy policy for the reduction of the greenhouse gases and a secure electricity supply. Given that a significant portion of heating in Europe is still reliant on fossil fuels, it is crucial to conduct a thorough examination of the suitability of small modular reactors designed solely for heat production. If applicable, these reactors could potentially yield the largest reduction in CO₂ emissions witnessed in Europe thus far.

Sustainable funding of RIs throughout their life cycle is an important management issue. Upgrades to and/or renewals of existing infrastructures may be needed to support the development of new technologies and to ensure that the infrastructure is capable of handling increased capacity. Collaboration between RIs, industry, and academia, knowledge sharing services should be expanded to identify and address common research and capacity building needs. The latter notably entails training younger co-workers. As women are still underrepresented in significant parts of the energy sector and energy research, reaching out to and mobilising this underexploited resource should be a priority.

Last but not least, while much of the research at dedicated RIs is typically devoted to a specific technology, there is an elephant in the room that needs to be seen. **The adoption of non-dispatchable energy sources has been surprisingly fast**, leading to situations that call for attention. Already today, there are times when so much

wind power is produced that electricity prices plummet to zero – or even enter negative values. While new major power storage facilities, smart-grids, system modelling and integration, and improved meteorological modelling for wind power production may help al-

leviate the problems, the current situation, together with merit-order pricing, may discourage construction of dispatchable power. This may jeopardise not only the electricity market but even reliable continuous access to electricity.

Systems of linked RIs are likely to be necessary to address the challenges of designing and constructing fully reliable, cost-effective, and truly environmentally benign future energy systems.

CROSS-DOMAIN ASPECTS

The energy field is clearly intersecting many other domains.

Numerous activities in society involve the energy sector through the **production of energy**, the necessary **raw materials**, the **use of energy** for instance in transport, buildings and industry, and the **end-of-life waste** related to the production and use of energy. All mass implementation of new energy technologies, from solar to wind power, batteries and grid systems, will require the use of enormous quantities of raw materials. While the character of environmental impact from different technologies varies and numerical assessments of impacts may differ, all types of electricity production generate significant environmental loads, in the form of mining, land use that can compete with agriculture, impact on landscape or protection of ecology, noise, or risk of environmental accidents.

Energy policies should be appropriately based on assessment of the environmental loads throughout the full life cycle of elements of energy systems and their connections into a full network in a holistic way. The determination of the respective internal and external costs (using an agreed-upon methodology) and of geopolitical interdependencies is also crucial for informed energy policies. The trend towards electrification, with the associated need of increasing electricity production, is an example where such studies are acutely needed. Therefore, RIs involved in environmental, socio-economic and ecosystem modelling, such as those in the **Environment** domain, play a vital role in understanding the current and possible future impacts of energy-related activities. Numerous examples of such links already exist, including the production of carbon dioxide and aerosols (**ICOS ERIC**, **ACTRIS ERIC**), ecosystem monitoring and modelling in areas relevant for biomass energy, the discovery and use of geological raw materials (**EPOS ERIC**), and marine environment study and preservation (**EMSO ERIC**). Links between different RIs from different ESFRI domains can take the form of specific Memoranda of Understanding (MoUs), signed to perform and better valorise cross-cutting activities of common interest. Existing examples include MoUs signed between **ECCSEL ERIC** and **EPOS ERIC**, and by **ECCSEL ERIC** and **EMSO ERIC**.

Generally speaking, all technological advances and changes require some degree of awareness by the political governance and, more importantly, by the public. **Social Sciences** play a role in investigating the behaviours of society at large and of specific groups

therein. Investigating if and how effectively science and technology prospects are translated into policies is likely to be a key facilitator for a positive change. Moreover, it is central to understanding how all relevant groups, distinguished by nationality, background, economic status and gender, may adopt, contribute to and interact with major changes in the energy sector.

Findings from material science are needed for different applications, spanning new photovoltaic technologies, batteries, the life extension of fission plants, advanced fission reactors, and nuclear fusion, to name just a few. A particular cross-domain regards thermal-hydraulics and material behaviour in presence of hot fluids like molten salts, which is of interest for concentrating solar power and for next generation fission reactors or waste transmutation systems, as well as for fusion plants. Additive manufacturing, in particular metal printing, is a relatively new technology domain which is of interest for several energy sectors. The field of massive recycling, involving both materials science and environmental research, is also gaining relevance, partly due to the dramatic rise in the volume of solar and wind energy components that becomes obsolete due to ageing or power increase. More cooperation among researchers and RIs working in different sectors but on similar issues is desirable and recommendable.

High power computation resources (provided, for instance, by **SLICES**) are needed for various types of energy research, especially when complex multi-parameter simulation is involved. Other sophisticated digital technologies can be used for monitoring and controlling energy production and use, to forecast energy demand and availability (solar, wind), and to balance the network. The unrestricted exchange of (huge) data in all fields of energy research, in line with **EOSC** activities and new advancements in AI (such as for system research or digital twins), is poised to become crucial. RI and software development depend on each other and have to progress in parallel.

There is also a broad spectrum of side developments from Energy RIs that are of potential interest for other applications. For example, concentrated solar power systems (**EU-SOLARIS ERIC**) may be used to test materials under high temperature conditions, to produce and purify fresh water, or in the detoxification of waste. **IFMIF-DONES** and **JHR** will be useful for materials testing and the

production of medical radioisotopes. **ECCSEL ERIC** has presented an amendment request to expand its research and activities to CCUS-aligned sustainable subsurface energy systems, and **Marinerg-i** installations can offer offshore services to non-energy applications. Superconductivity, especially the high-temperature, high-field (HTS) magnet technology, developed in the **Physics and Engineering** domain, has advanced with large leaps in fusion applications and is potentially of vast importance for several energy technologies.

Although there exist strong scientific links between the mentioned areas, the focus of the present ESFRI Energy RIs on developing specific technologies has resulted in limited interaction between the ESFRI energy RIs and those in other domains through joint projects. Due to the strong penetration of the energy sector in all aspects of human life in modern societies, this ought to change. As mentioned in Section A, the way energy is exploited today is based on a limited appreciation of its effects on climate, ecosystems and environment.

*In order to pave the way for a sustainable future in Europe, strong emphasis has to be invested in rationalising the energy use to minimise its impact not only on climate but also environment and human health. This calls for cross-domain studies involving at least the **Environment** and **Social Sciences** domains, but also RIs within the **Health and Food** domain.*

As an example of interdependences between the ESFRI domains, a potential future RI focussed on understanding consumer behaviour within an electricity system heavily reliant on non-dispatchable renewables would require deep insights into the characters of electricity generation and storage technologies which are under development.



ESFRI LANDSCAPE ANALYSIS 2024 - SECTION 1

ENVIRONMENT



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ENVIRONMENT

CURRENT STATUS IN THE DOMAIN

Environmental research as a scientific domain focuses on understanding how the Earth system works at various spatial and temporal scales. Such knowledge is a prerequisite for environmental management. Proper management of environmental problems starts with an analysis of available data, understanding the main drivers, and the subsequent identification of options for measures. Environmental research requires comprehensive observations integrated with relevant experimental and modelling approaches. A federated approach to IT resources and e-Science facilities is also necessary, together with reliable data policies compliant with FAIR principles.

Research Infrastructures (RIs) can be – and often already are – directly or indirectly associated with the observation and production of data that allow for understanding of the environmental issues in space and time. While many environmental authorities maintain their separate official monitoring networks in the context of environmental regulations, the contribution from RIs is often a ‘precursor’ of such **monitoring** (i.e., testing of measurement technologies, focus on new aspects) and provides much needed **contextual information** (e.g., broader geographical scale information). Hence, specialists on both sides can ensure, or contribute to, the necessary complementarity and interplay between research and environmental management.

In addition to targeted research on **sub-domain-specific phenomena**, holistic research using **cross-disciplinary approaches** is needed to tackle environmental and societal challenges. The quality of the environmental science base affects our capability to tackle (narrowly defined) environmental problems, and (broadly defined) societal challenges, where solutions depend on environmental information among other influencing factors.

The Environmental RIs in the ESFRI landscape play a crucial role in advancing progress on both fronts. This section’s presentation of the landscape demonstrates many similarities and connections between environmental and societal challenges, showcasing how we can benefit from the RIs performance as they advance individually and jointly. Creative research beyond the traditional silos is needed to develop innovative solutions for protective and preventive measures and to identify the optimal mechanisms for their implementation.

To assist with new research and innovation Missions, the environmental RIs aim at:

- Addressing global and regional challenges by deepening the **understanding of drivers and impacts of Earth system processes** and **improving the link between scientific understanding and policy making**;
- Achieving **national and international objectives for a resilient society, sustainable economies, and a healthy environment worldwide**;
- **Fostering new economic opportunities, improving efficiency, and reducing costs** to public sector budgets through innovation and collaboration.

The current ESFRI landscape includes eight Environmental Landmarks (**EPOS ERIC**, **EISCAT_3D**, **IAGOS**, **ACTRIS ERIC**, **ICOS ERIC**, **EMSO ERIC**, **LifeWatch ERIC** and **Euro-Argo ERIC**), and three RI Projects (**DiSSCo**, **eLTER RI**, **DANUBIUS-RI**). DANUBIUS-RI is in its implementation phase, targeting start of operations in 2024-25, while eLTER RI and DiSSCo are in preparation phase. All Landmarks and Projects are pan-European distributed RIs, except for EISCAT_3D, which is single-sited.

Six Landmarks (EPOS ERIC, ACTRIS ERIC, ICOS ERIC, EMSO ERIC, LifeWatch ERIC, Euro-Argo ERIC) operate under intergovernmental agreements as separate legal entities (European Research Infrastructure Consortiums, ERIC). IAGOS operates as an International non-profit Association under Belgian Law (AISBL) and EISCAT_3D as an international scientific society.

Figure 1 provides a picture of the landscape of RIs with a focus on the environment, subdivided in the four sub-domains (atmosphere, biosphere, hydrosphere and geosphere).



EXCELLENT RESEARCH ON THE EARTH SYSTEM: A FIRST DRIVER FOR KNOWLEDGE

ENV Research Infrastructures are at the core of a multi-disciplinary research strategy aimed at developing a seamless holistic understanding of the Earth as a system. They provide the foundation for advancing scientific knowledge on natural processes while developing new scientific and technological capabilities that can underpin broader and applied services.

It's thus essential to continually improve and deepen our understanding of how each component (geosphere, hydrosphere, atmosphere, and the overlapping biosphere) functions. Additionally, investigating their interactions is crucial, as the biosphere drives the evolutions of a variety

of processes including energy, water and carbon cycles, climate change, pollution, and biodiversity. Interactions with Space (Solar-Terrestrial Physics) also need to be accounted for due to their impact on parts of the Earth system.

National examples such as Italy's ITINERIS and France's Data Terra are vital in Earth system and environmental research, and are currently implemented. ITINERIS establishes an Italian hub for interdisciplinary environmental study, covering areas such as the atmosphere, marine, biosphere, and geosphere. Data Terra, on the other hand, focuses on creating a global facility for Earth observation data and services. It is organised into multiple Data Hubs, each representing different Earth system compartments. Together, ITINERIS and Data Terra exemplify national instances that can serve as models for the implementation of RIs at the European level.

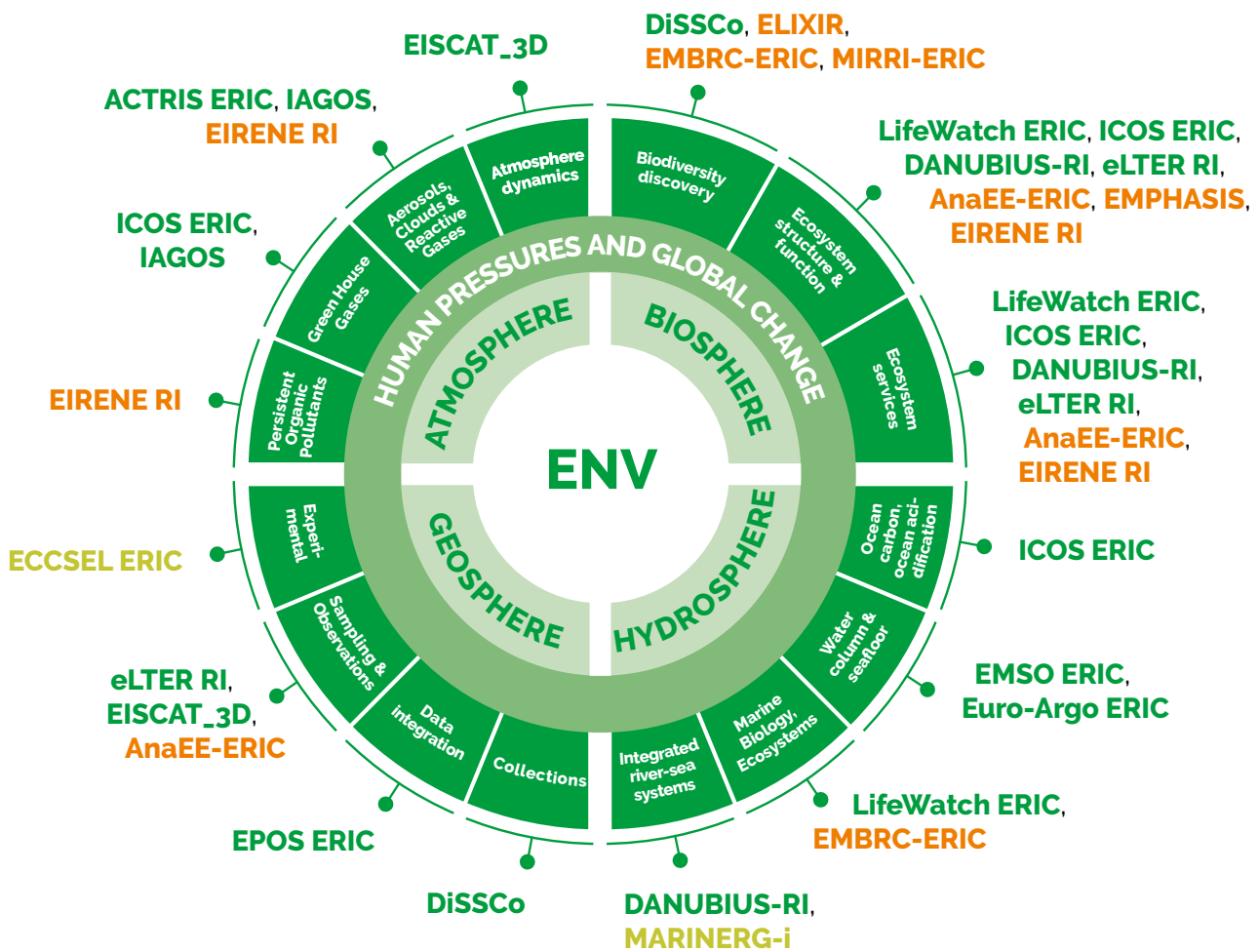


FIGURE 1.
The Landscape of the Environment domain.

GEOSPHERE

The RIs within the Solid Earth domain play a key role in understanding the natural processes connecting the solid Earth's dynamics to natural resources, climate change, and ecosystem services. They enable fundamental scientific advancements in understanding and protecting planet Earth and its societies from multi-hazards.

Solid Earth Sciences connect multi-scale features, reaching from thousands of kilometres to micrometres and from billions of years to microseconds: combining physical processes (e.g., plate tectonics, earthquakes, volcanic activity, magmatism, orogeny, isostasy, sedimentation), mechanical processes (e.g., folding, faulting, shearing, compression or extension), chemical processes (e.g., rock cycle, magma generation and metamorphism, weathering, pedogenesis) and biological processes (e.g., carbon cycle, nitrogen cycle, microbial interactions with minerals, biomineralization, biogenesis). Many of these interconnected processes remain not fully understood; therefore, broad RIs provide the basis for scientists to reveal answers to planet Earth's complexity. They are used to observe, monitor, and analyse both natural and man-caused hazards in order to strengthen capacities to protect planet Earth.

The **ESFRI Landmark EPOS ERIC** integrates several hundreds of individual RIs in the Solid Earth domain. The large community of RI operators and users chose to establish an all-encompassing RI framework, including all the different RI classes covering seis-

mology, near-fault observatories, geodetic data and products, volcano observations, satellite data, geomagnetic observations, anthropogenic hazards, geological information and modelling, multi-scale laboratories. The overall objective is to provide the long-term integration of the operational services at European scale and to increase global coordination in Solid Earth observing systems. Therefore, EPOS ERIC is interconnected with other geosciences and projects operating globally, including SoWa RI (Soil and Water ecosystems in context of sustainable landscape use)¹, the Joint Research Centre's Soil Atlas of Europe in the European Soil Data Centre (ESDAC)², as well as the International Ocean Discovery Program (IODP)³, and the InterContinental Scientific Drilling Program (ICDP)⁴.

1. _____
SoWa RI
<https://soilwater.eu/>

2. _____
European Soil Data Centre's Soil Atlas of Europe
<https://esdac.jrc.ec.europa.eu/content/soil-atlas-europe>

3. _____
International Ocean Discovery Program (IODP)
www.iodp.org

4. _____
InterContinental Scientific Drilling Program (ICDP)
www.icdp-online.org

An outstanding challenge in Solid Earth Sciences lies in the interconnection of natural and anthropogenic processes, forging deep links between Solid Earth dynamics and disciplines like climate science, ecosystem management, and resource conservation. The rising demand for minerals and rare earth elements, and for responsible geo-resource use becomes imperative. This knowledge integration fosters a holistic view of our planet's functioning and on the profound impacts of human activities, including mining, pollution, and land use changes for a sustainable development.

In the future, Europe must provide and ensure access to strategic minerals and metals from primary and secondary sources as they are required for the green transition of industry and society (including transport, ICT, home electronics, etc.). Utilising underground resources can support sustainable energy production and contribute to achieving climate neutrality.

The establishment of new RIs and the acquisition of updated data are urgent necessities in the fields of geo-resources and mining to attain energy and mineral security in Europe. Laboratories – such as rock deformation labs, deep underground labs, technologies for environmentally friendly bio-mining, analytical facilities for geochemistry and mineral resources – and modelling facilities are crucial ingredients to achieve this goal.

HYDROSPHERE

Water is essential for life and plays a critical role in many environmental processes. Much of the current science relies on access to existing water bodies, often requiring the aid from specific and dedicated large-scale Research Infrastructures.

Much of environmental data is collected in the field for direct use, e.g., by environmental agencies for management purposes. Due to differing management regimes and access modalities, there has long been a clear split between research on freshwater (surface water, groundwater) and seawater.

While there is a drive to enable more systemic approaches, infrastructures operating in the transitional domains (e.g., DANUBIUS-RI for river-sea systems; JERICO network for coastal processes) and necessary tools for integrated research across the entire hydrological cycle (or integration between physical, chemical and biological phenomena) are presently less developed compared to earlier established, more focused and dedicated RIs on parts of the systems (e.g., Euro-Argo, EMSO).

The **ESFRI Landmark Euro-Argo ERIC** contributes to the international ARGO array of ocean profiling floats acquiring *in situ* observations of temperature, pressure, salinity, biochemical, and radiative in the global ocean for marine and climate research. The **ESFRI Landmark EMSO ERIC** (European Multidisciplinary Seafloor and water-column Observatory) integrates a variety of fixed European ocean *in situ* observatories and facilities dedicated to multi-disciplinary observation of the full water column, seafloor and subseafloor in a variety of environments, from polar to tropical. These facilities serve the purpose of testing innovative sensors, contributing to the advancement of our understanding of both natural processes and anthropogenic effects. The **ESFRI Project DANUBIUS-RI** (the International Centre for Advanced Studies on River-Sea Systems), in the process of becoming an ERIC, will integrate European re-

mote-sensing and *in situ* observation systems, experimental facilities, laboratories, and modelling tools to boost interdisciplinary research, innovation and knowledge exchange on River-Sea Systems. It is also meant to support management of societal risks associated with extreme events and climate change, building on environmental, social and economic sciences.

Water comes into play in many other environmental RIs, and RIs from other domains: in long-term ecosystem monitoring (**eLTER RI**) and other ecosystem studies (**LifeWatch ERIC**), in geological and geomorphological research (**EPOS ERIC**) and carbon-cycle studies (**ICOS ERIC**), as a growth medium (**AnaEE-ERIC**) and a renewable energy carrier (**Marinerg-i**), or in satellite-based observations (**ESA**, **EUMETSAT**) and Copernicus information services (**CMEMS**, **C3S**). Each case focuses on data pertinent to the feature under investigation.

Marine RIs are diverse, spanning from fixed observatories and data centres to research vessels and autonomous vehicles. This wide spectrum allows to **generate, analyse and apply *in situ*, remote sensed and modelled data, providing an array of services that aim to inform science, policy and society.** These data and associated services are essential for ocean and coastal sea monitoring, biolog-

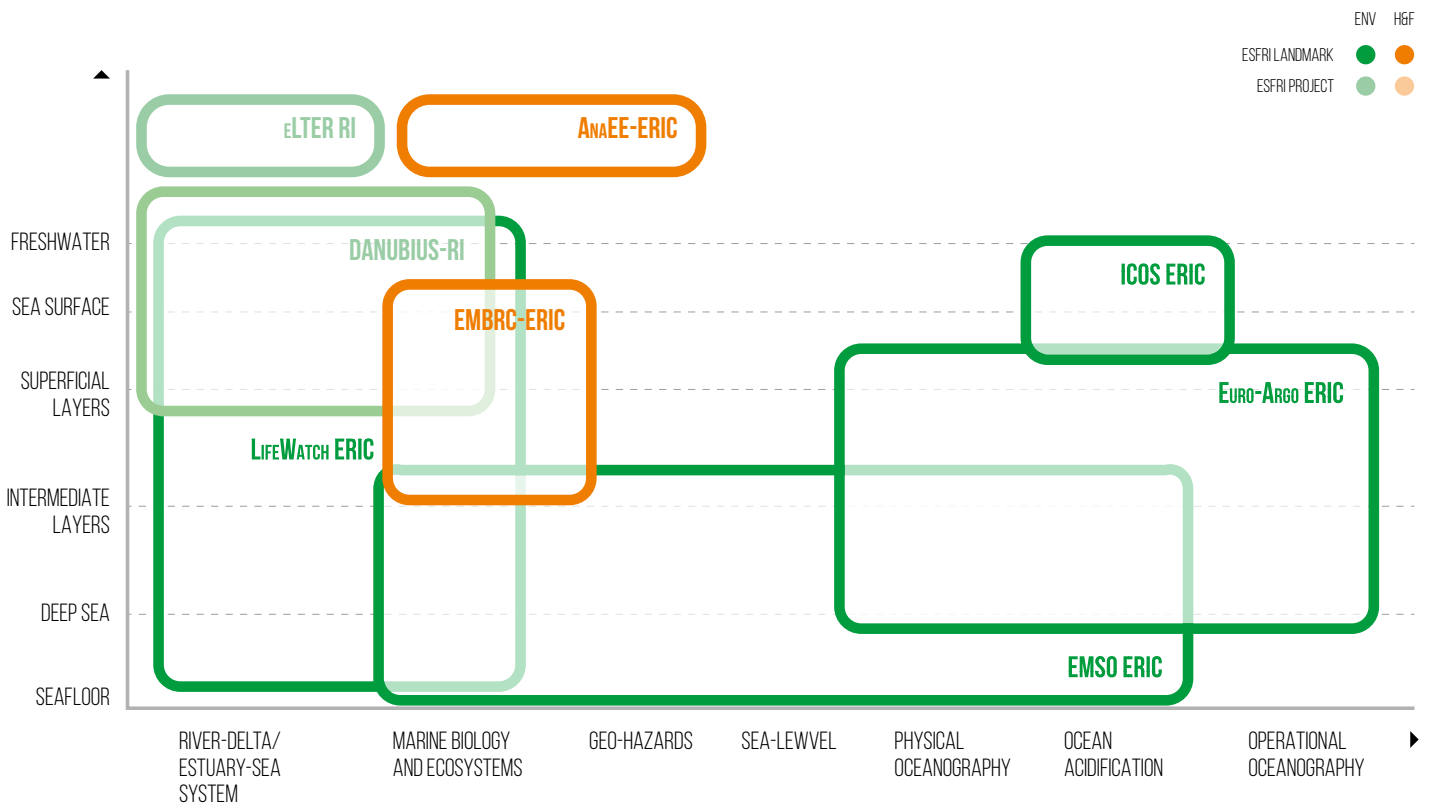


FIGURE 2.

Simplified diagram of the observation capabilities of ESFRI Landmarks and Projects respect to the hydrosphere components (Y axis) and to the environmental processes therein (X axis).

ical and ecological research. As occurred in other spheres, the rapid technological advances have reduced earlier limitations (e.g., miniaturisation, new materials, robotics for access to hostile environments like the deep ocean), but many possibilities still remain underexplored. Experimental facilities for water research existing in many countries often have a focus on practical applications (for instance, mesocosms focus on controlled environments, hydrological laboratories centre on navigation, hydropower, etc.). Modelling studies often combine numerical representation of processes with observational data

input in a wide variety of possible approaches as regards the phenomena that are covered, and the geographical and temporal scales addressed.

Europe needs a dense, highly instrumented network of water monitoring, as well as simulation and experimental platforms. Freshwater, groundwater, marine water monitoring and experimental super-sites should serve as calibration, validation and development services for remote sensing applications, as well as for ecosystem service modelling. Very specific services are

often required to deepen our understanding of water-related processes and depict the role of water in environmental phenomena. While many of these specific gaps and needs have been identified in the development agendas of the existing RIs, potentially the **larger gaps still exist in the hydrological system component areas** ('freshwater', 'coastal', and 'soil and subsoil').

Figure 2 pictures a schematic landscape of ESFRI RIs for water-related research.

ATMOSPHERE: FROM NEAR TO THE GROUND TO THE NEAR SPACE

The atmosphere hosts many physical and chemical processes, playing a significant role in the Earth's environment. The atmosphere is central for climate, weather, and transport of chemical species (natural and man-made gases and aerosols) over large distances. Disturbances or disruptions in the atmosphere can have far-reaching effects on various thematic areas, including climate change, air quality, environmental hazards and risks, and terrestrial and ocean ecosystems.

Research on the atmosphere is multidisciplinary, embracing atmospheric chemistry, physics, dynamics, and radiation. It combines observations and modelling, covering the full altitude range from the planetary boundary layer near the surface across the tropopause and stratosphere, up to the middle atmosphere. Atmospheric processes are multiscale in time and space, ranging from the sub-second, sub-micron microscopic scales to the decadal global scale characterising climate change. In this context, **the atmospheric infrastructures should be sufficiently equipped to be able to inform across a similar range of scales.**

The European atmospheric landscape covers a wide range of actions ranging from the establishment of ESFRI long-term atmospheric RIs to EU-funded projects (see **Figure 3** on ESFRI atmospheric RIs). The next generation European Incoherent Scatter radar system upgrade (**ESFRI Landmark EISCAT_3D**) will use a new incoherent scatter radar system to observe the atmosphere and near-Earth space environment above the Fenno-Scandinavian Arctic, investigat-

ing how solar-terrestrial physics couple the atmosphere to space.

The Aerosol, Clouds and Trace Gases Research Infrastructure (**ESFRI Landmark ACTRIS ERIC**) operates networks of in situ observation, ground-based remote sensing systems, acquiring high-quality observations of aerosols, clouds and short-lived trace gases. Related technological platforms deliver high-precision data for use in process studies, air quality monitoring and prediction services, climate research and calibration/validation of satellite observations.

The In-service Aircraft for a Global Observing System (**ESFRI Landmark IAGOS**) operates a global monitoring system for trace gases, water vapour, aerosols and clouds based on in situ observations collected by commercial aircraft equipped with standard sensor packages. Its aim is to deliver essential data on a day-to-day basis for research on air quality and climate change.

The Integrated Carbon Observation System (**ESFRI Landmark ICOS ERIC**) conducts

long-term observations in the lower atmosphere, upper ocean, and various terrestrial ecosystems. It generates high-precision data to monitor and understand surface fluxes (emissions and up-take) of greenhouse gases and the global carbon cycle and their evolutions, predict related environmental changes and mitigate their impacts. There is a high level of interoperability between these infrastructures, especially between ACTRIS, ICOS and IAGOS (as demonstrated by the joint **ATMO-ACCESS** project).

These RIs are complemented by the international atmospheric monitoring networks supporting European and international policies. Examples include the European Monitoring and Evaluation programme (**EMEP**)⁵, established in support of the Long-Range Transboundary Air Pollution (UNECE LRTAP) Convention; the Global Air Passive Sampling (**GAPS**); the MONitoring NETwork (**MONET**) passive air monitoring programmes, supporting the effectiveness evaluation of the UN Stockholm Convention on Persistent Organic Pollutants (POPs); the Global Mercury Observation System (EU project **GMOS**), in support of the UN Minamata Convention; the Arctic Monitoring and Assessment Programme (**AMAP**). The atmospheric landscape includes European ERA NETs, such as the **European Network for Observing our Changing Planet**. A number of other initiatives can be listed as part of the landscape: **ERA PLANET**⁶, **GEO Flag-**

5. European Monitoring and Evaluation programme (EMEP) <https://www.emep.int/>

6. ERA PLANET <http://www.era-planet.eu/>

ships and Initiatives (Global Observation System for Mercury, GOS4M and the Global Observation System for POPs, GOS4POP), exploratory Platforms (EUROCHAMP-2020 project), e-infrastructures (the Infrastructure for the European Network for Earth System Modelling, IS-ENES⁷), and networking activities (Airborne platforms for field experiments, EUFAR).

The European atmospheric research community holds international recognition and it has an undisputed leadership in many specific research topics. Atmospheric RIs play a pivotal role in strengthening

7. Infrastructure for the European Network for Earth System Modelling (IS-ENES) <https://is.enes.org/>

the EU position and leadership in this research area by providing unique information, services, tools, and reference methodologies extensively utilised by a broad global community, extending beyond Europe.

At the same time, the European landscape of atmospheric RIs shows a **lack of facilities supporting research on chemical pollution of the atmosphere** other than particulate matter, trace, and greenhouse gases (e.g., POPs and other semivolatile compounds). This can be filled by the new **ESFRI Project EIRENE RI**, which focuses on chemical exposures. Climate change also poses a foremost scientific challenge because of large uncertainties in our current knowledge on climate change processes.

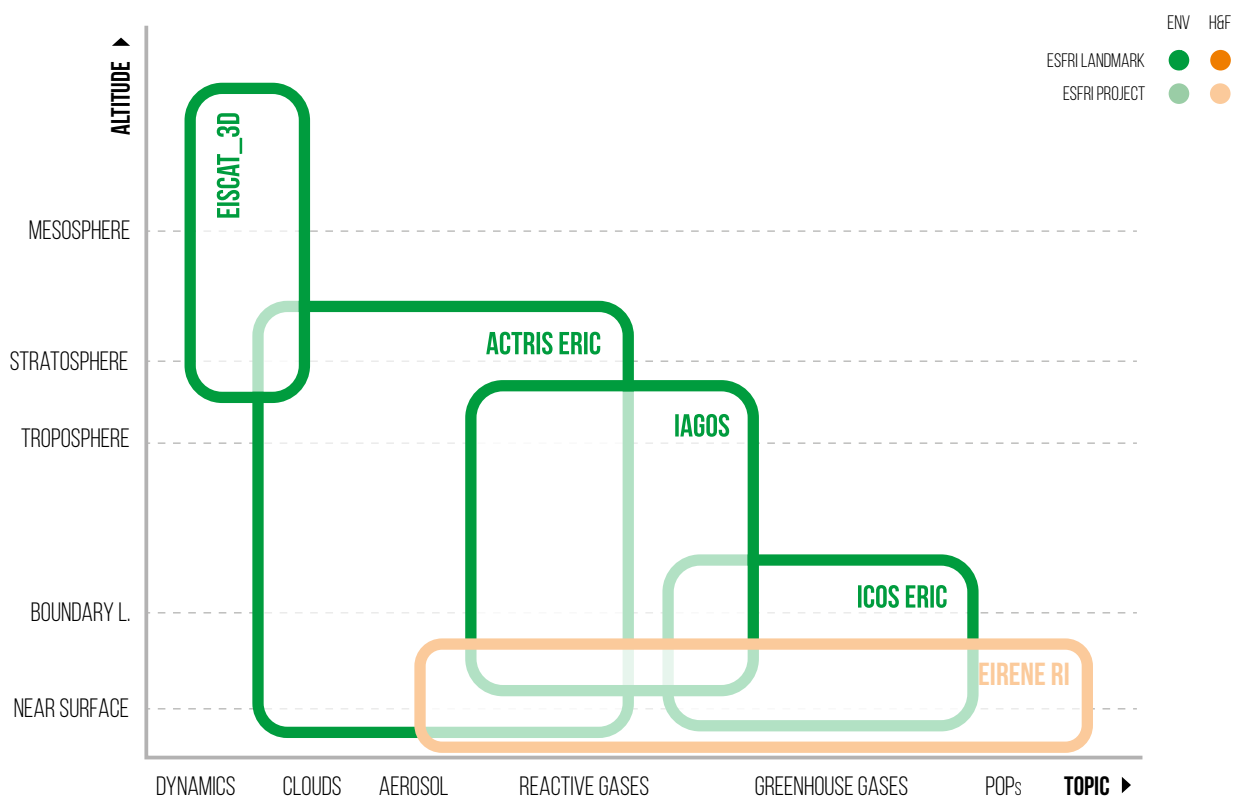


FIGURE 3.

Schematic overview of the ESFRI RI landscape for the atmosphere sub-domain

BIOSPHERE: BIODIVERSITY AND ECOSYSTEMS

*Biodiversity is the diversity of biological systems at all levels, including genes, species, and ecosystems. Research in this area spans a wide range of disciplines and fields of application, related to big questions such as understanding the drivers of biodiversity loss, quantifying ecosystem services, or developing methods for conservation or restoration. These pursuits are closely linked to related areas such as **Health & Food**, and **Energy**. Understanding and monitoring biodiversity components in terrestrial, marine, and freshwater ecosystems, along with the interplay among themselves and with human societal activities, constitute foundational knowledge critical to addressing these questions and to ensure a sustainable Earth for the future.*

In the current landscape, RIs support research on biodiversity and ecosystems by providing observatories and monitoring facilities with different focus: **ESFRI Landmark ICOS ERIC** on gas fluxes in terrestrial ecosystems, **ESFRI Landmark EMBRC-ERIC** on marine biodiversity, **ESFRI Project DANUBIUS-RI** on river-sea systems, **ESFRI Project eLTER RI** in long-term ecological monitoring, and **JERICCO-RI** on coastal ecosystems. Other RIs support research based on in situ and in vivo experimentation: **ESFRI Landmark AnaEE-ERIC**. A third class of RIs provide biological collections, data infrastructures and reference data: **ESFRI Project DiSSCo** on natural history collections, **ESFRI Landmark ELIXIR** on genetic and genomic data and **ESFRI Landmark MIRRI-ERIC** on microbial biodiversity. With its focus on the human exposome, **ESFRI Project EIRENE RI** represents a link to the environmental exposure risk assessment. An overarching RI that provides e-infrastructures for data, analysis and modelling is **ESFRI Landmark LifeWatch ERIC**. Some of these RIs connect with other infrastructures to provide global RI support, as is the case of DiSSCo and LifeWatch for species and occurrence data, eLTER RI on ecological data, and ELIXIR for sequence data. **Figure 4** gives a schematic overview of ESFRI RIs focusing on the biosphere.

Most of the RIs dedicated to biodiversity and ecosystems support research through data provision, to which they add value in

terms of availability, accessibility, and quality. Data mobilisation can be originated by internal environmental sampling (eLTER, ICOS), but in other cases it is through data aggregation (LifeWatch, DiSSCo). Invariably, none of the RIs in biodiversity can collect and manage all types of biodiversity and ecosystem data, even if it focuses on a specific sub-domain. Therefore, **ensuring interoperability between RIs' datasets and services** becomes crucial, along with, whenever possible, ensuring collocation to provide users with facilities and data ready and fit for use. This implies high levels of coordination with RIs from other regions at the global level (as is the case of **GeoBON**, **GenBank**, **iBOL**, **GBIF**). Through coordination, RIs enable an organised, fair and transparent system to share knowledge and resources, and in doing so, they contribute to the pooling of data, facilities and equipment, thereby avoiding unnecessary duplication of effort.

RIs provide integrated data services that speed up discovery and access by users. But they also provide these services to other RIs and networks, in the same or in related domains, as is the case of **Health & Food**. For example, understanding crop pests or the impact of invasive species is important to agriculture research. Furthermore, RIs in biodiversity and ecosystems can promote and benefit from technological advances, for example, in tracking animal movement through satellite, using remote sensing to

map and monitor changes in biodiversity and ecosystems, or using AI to help taxonomic classification of specimens in digital images.

Some of the **Grand Challenges** related to biodiversity and ecosystems research still miss a counterpart support by the existing RIs. For instance, tackling the need to increase protected areas, restore degraded ecosystems, reverse the decline of pollinators, increase biodiversity-rich landscapes on agricultural lands remains inadequately addressed. Research on biodiversity threats such as habitat fragmentation, land use change or invasive species is only partially supported by current RIs. The framework provided by the **Essential Biodiversity Variables**⁸, promoted by GeoBON to detect changes in biodiversity, is still far from being implemented at scale. Urged by biodiversity loss, the taxonomic gap needs to be overcome, in order to discover and describe the three-quarters of the biodiversity still to be known. Rapid **advances in genetic sequencing and ICT**, including big data analysis of genetic sequences, and **mass digitisation** can be integrated to provide **more automated systems concerning genomics, species and ecosystem analysis**. Nevertheless, full interoperability between sequence data and occurrence and species data still needs to be achieved.

Another aspect requiring further attention is **environmental contamination and its interplay with climate change, hazards and risks associated with toxic mixtures**, especially endocrine disruptors. Testing platforms for elucidation of adverse outcome pathways are also required. The manifold connections to other fields, particularly **Health & Food (EIRENE RI)** as well as **Social Sciences (SHARE ERIC)** and **Energy (MARINERG-i)**, are apparent. Human activities, energy production, construction, traffic, and agriculture directly affect ecosystem integrity which itself is an important factor for human health or food security. Environmental literacy and behaviour are important interfaces to Social Sciences.

8. Essential Biodiversity Variables
<https://doi.org/10.1126/science.1229931>

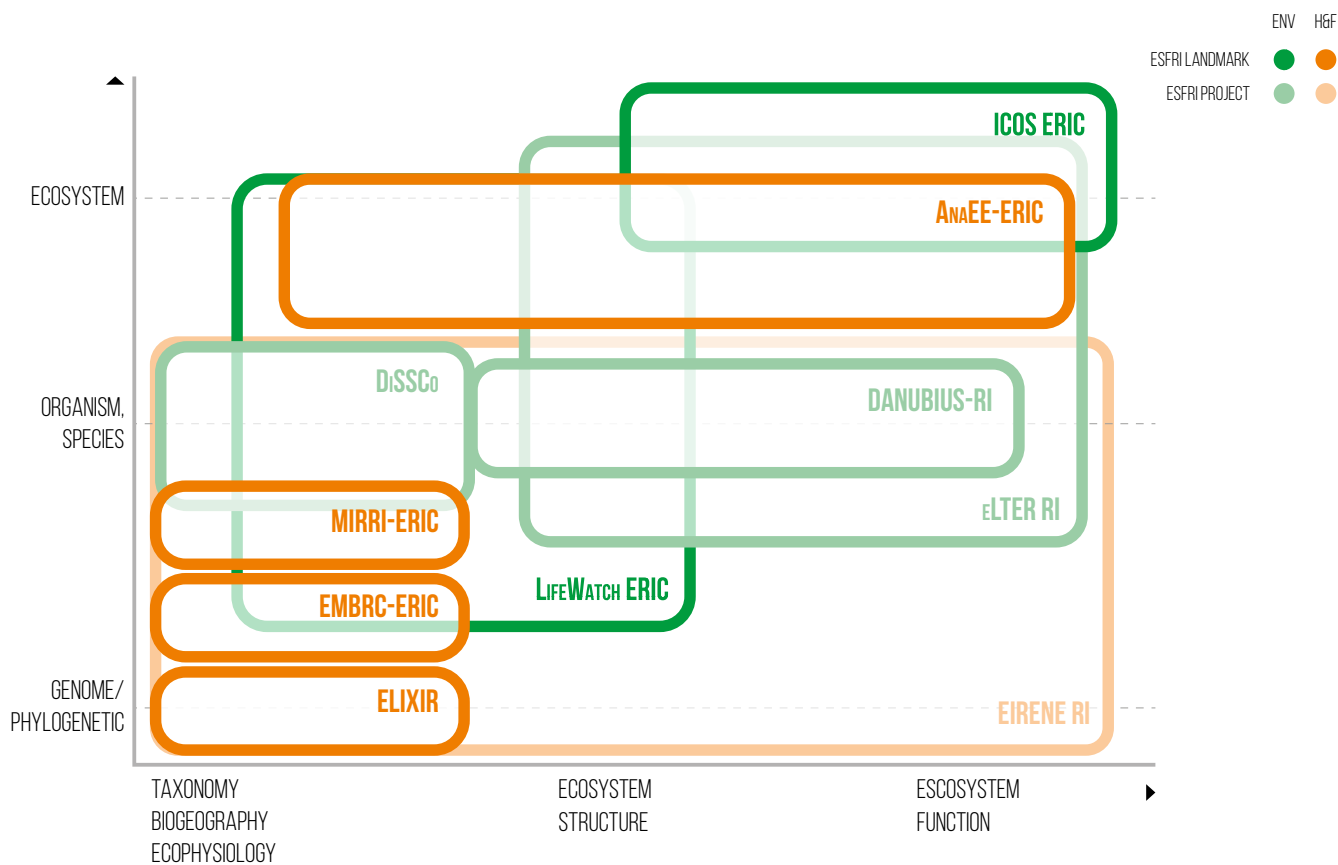


FIGURE 4.

Schematic landscape of biodiversity and ecosystem ESFRI Research Infrastructures.

IMPACT, GAPS AND NEEDS

Environmental Research Infrastructures provide elementary knowledge and services needed to address environmental issues. The services with which RIs can contribute range from providing data to advanced diagnostics and even contribution to solutions mitigating the impact of the problem or leading to its resolution. Human impacts generally need to be better understood, attributed, and predicted to support adequate policy responses. However, many human impacts on the Earth are still to be discovered and assessed.

The connections between individual environmental RIs and the bodies responsible for addressing a specific environmental challenge (at any scale) are highly varied; the description below is merely a sample of such arrangements. The (institutional) links between the RIs and the application of their knowledge and services, the so-called 'science-policy interface', is multifaceted and in many cases there is ample room for improvement of its effectiveness and efficiency.

RIs CONTRIBUTE TO UNDERSTANDING ENVIRONMENTAL CHALLENGES

GEOSPHERE

IMPACTS

In relation to Earth-related environmental issues, RIs provide support to **monitoring of natural hazards** (e.g., earthquakes, volcanic

eruptions, rock falls, landslides, soil liquefaction, tsunamis, avalanches) **and human-caused hazards** (e.g., droughts, wildfires or forest fires, landslides, groundwater depletion, floods). The monitoring of natural resources has been identified as an essential component for their sustainable management. Increased knowledge from Solid Earth RIs can help predict future developments of the

Earth's systems and increase the predictive and mitigation capacities to protect the planet. Therefore, international collaboration is essential for Solid Earth RIs given the fact that these problems do not respect national boundaries. Services offered by RIs in relation to natural hazards already offer **long-term, high quality and interoperable data**. They make monitoring infrastructures, experimental facilities, and expertise available to optimise sustainable exploration and exploitation of geo-resources and monitoring of natural resources (geothermal energy and groundwater), underground storage (carbon, gas, nuclear waste), raw materials, minerals and rare earth elements. Within the **global GEO network**, a worldwide network is creating innovative solutions (e.g., Volcano observatories, EU MARSite-Near Fault Observatories/EPOS).

GAPS AND NEEDS

New RIs and data are urgent in the fields of geo-resources and mining to achieve energy and mineral security in Europe. Laboratories – rock deformation labs, deep underground labs, technologies for environmentally friendly bio-mining, analytical facilities for geochemistry and mineral resources – and modelling facilities are key required ingredients. Solid Earth RIs need to interact with on-going European initiatives in Geothermal Energy (e.g., **ETIP-Geo-Thermal**) to support both technical development and data coordination to fulfil the implementation roadmap towards European leadership in sustainable production of heat, electricity, and cooling from underground resources. There is also a need for RIs to enable Member States to fulfil the requirements for scientific research and technological development for the **safe management of high and medium-grade nuclear waste**.

HYDROSPHERE

IMPACTS

Terrestrial environmental water policy has become more integrated over time, especially in Europe. This evolution necessitates that managers consider the many functions and services provided by aquatic ecosystems, within the geographic land-use context of the water systems. This also means that services from RIs need to increase their capabilities to provide the framework for a more integrated approach, which is the philosophy behind **DANUBIUS-RI**. **Water availability is becoming an increasingly pressing issue for many sectors as the risk of water scarcity increases**. Long time series have been instrumental in understanding the coupling between the water cycle, the changing climate, environmental pollution, and ecosystems. Coastal areas are often under multiple pressures from human activities (e.g., marine wind farms, industry, urbanisation, harbour and maritime transport activities, war threats), requiring particular attention. In the marine environment, the RIs **Euro-Argo ERIC** and **EMSO ERIC** are providing evidence of the human impacts on the oceans and the seafloor.

GAPS AND NEEDS

The issues of **pollution and habitat degradation** are still pending for solutions. They include problems such as drought, flooding, pollution and destruction of natural freshwaters and watercourses and their environmental and societal impacts. For the comprehensive analysis of the changes in the aquatic ecosystems, the integrated basin approach of **Ocean Digital Twins** is necessary: it allows to understand the impact of different drivers and to find measures

for sustainable water resources planning and management. In the marine environment, efforts to scale up the measurement capabilities of different infrastructures, as is the case for **Euro-Argo ERIC** (in need of OneArgo capacity), federated under the **Global Ocean Observation System** (GOOS), are necessary. It is vital for a deeper **understanding of the key role the ocean plays in the Earth system**, and of the rapid ongoing changes driven by large-scale processes such as climate change, pollution and overfishing, which increasingly affect entire ecosystems. While the key physical and chemical parameters of the ocean can mostly be measured routinely and relatively cheaply, the capabilities to make biological or ecological observations have not been automated to the same degree and are now subject to rapid developments. To comprehensively analyse changes in the coastal ecosystems, better understand the impacts of different drivers, and find the most efficient measures for coastal preservation, management and planning, an **integrated basin approach and experimental facilities that study complex water-related phenomena** are needed. **Economy of scale** in measurement of ecological and biological processes should be also applied.

ATMOSPHERE

IMPACTS

Air pollution is a major environmental risk to health. The climates of the global atmosphere and ocean are changing, with wide-ranging effects with numerous interconnections and feedback loops, which have ramifications in many domains. As an example, **ACTRIS ERIC** supports policy makers in their networks established under environmental regulations. It can assist in the **evaluation of environmental (air quality and climate) policies and the evolution of emission abatement** through direct evaluation of atmospheric trends at a regional/European scale. It can further support **scenario studies** with high-quality long-term data. Its network of experts can be called upon in the event of extreme atmospheric events. This is also happening in the context of existing international atmospheric monitoring networks that were set up in support of the European and international policies (UN-ECE LRTAP, UN Stockholm or Minamata Conventions). In climate policy, the **Paris Agreement** recognises “the need for an effective and progressive response to the urgent threat of climate change on the basis of the best available scientific knowledge”. **ICOS**'s recent initiative to publish a magazine, **FLUXES**, is one way in which new scientific knowledge can create impact.

GAPS AND NEEDS

There is great interest in utilising cheap sensors that could be deployed in larger numbers compared to the usual costly and labour-intensive instrumentation. However, the **sensors' precision and accuracy** must be carefully evaluated, a place where the RIs can play a major role. **Long-term data records for atmospheric parameters**, which are relevant for both air quality and climate research, are inadequate at the moment. **Monitoring of the stratosphere** is also crucial to study the properties of smoke injected from increasingly extreme forest fires. These observations are critical for assessing the impact of smoke on stratospheric dynamics and studying possible implications for geoengineering. Gaps also exist in understanding **toxic chemicals** of global concern due to their persistence in the environment, their potential for long-range transport, their ability to bioaccumulate in ecosystems, as well as their significant negative impacts on human health and the envi-

ronment. Furthermore, new variables such as the **oxidative potential** have recently been discussed as potential markers for health effects, but are largely missing in RIs. **EIRENE RI** could play an important role here and — together with **ACTRIS ERIC** and other atmospheric RIs expanding their perimeters — contribute to filling the above-mentioned gaps. Interconnections with other domains (**Health & Food**, **Humanities**) need to be better explored.

BIOSPHERE

IMPACTS AND TRENDS

Biodiversity can be considered the main infrastructure to support humankind with air to respire, clothes to wear, food to eat. As a fundamental infrastructure, it needs to be protected and recovered. The progression in European legislation for the protection of nature and ecosystems consists of a scaling-up of the existing approaches (namely protected areas and nature restoration) which is embedded in the **European Union Biodiversity Strategy for 2030**. The Biodiversity Strategy also covers objectives for aquatic environments, urban environment, the reduction of pollution affecting ecosystems and policies to combat invasive alien species. In line with the European Green Deal, this strategy bolsters Europe's role in the global landscape towards stopping

biodiversity loss, in the context of the UN SDGs 14 and 15 and the Post-2020 Global Biodiversity Framework, in the scope of the Convention on Biodiversity. RI services can contribute to aiding environmental policies through **data, knowledge generation, simulation and testing of intervention strategies** (e.g., for invasive species), **innovation, as well as citizen involvement** (citizen science).

GAPS AND NEEDS

Better **data interoperability** is needed for the development of a new generation of ecosystem models including the complex interactions of nature and food systems with humans (e.g., zoonoses) and society. Rapid advances in **genetic sequencing** are needed, including digitalisation and big data analysis of genetic sequences. Complementary to that, the **open availability of trait data** is essential to enable functional analysis of species and ecosystems. This relates to the need for better connections with the **Health & Food** domain, for instance through plant phenotyping (**EMPHASIS**), and impact of food systems in ecosystems (**AnaEE-ERIC**). Recognising the close links between environmental and human health impacts of human activities (e.g., chemical exposures, global changes, food security overexploitation) as well as impacts of environmental deterioration on public health is vital. Further development of the **Environ-**

mental Health and **One Health** concepts should be supported by existing and newly developed capacities in the Environment and Health & Food domains. The current anthropocentric understanding of the exposome concept should be also extended to wildlife.

The link to the **Social Sciences & Humanities** domain should also be strengthened, in order to explore and better understand the connections between nature and society. Ensuring continuation of ecosystem long-term data series, integration and expansion of current observations, and linking routine monitoring with remote sensing and high-resolution data are vital to support research in the area, as well as to **enhance societal benefits**. This effort requires the bridging of RI components in terms of infrastructure and services across the different spheres, embedded in a culture of open scientific cooperation as stated by the EOSC Declaration (EC, 2017). This is already happening through collaborative projects, often fostered in the **ENVRI Community**⁹ context. The **ENVRIplus** and **ENVRI-FAIR** projects have created a robust conceptual and technical framework for enhancing interoperability and multidisciplinary integration of digital services.

9. ENVRI Community
<https://envri.eu/>

ENV RIs CONTRIBUTE TO THE SUSTAINABLE DEVELOPMENT GOALS

Environmental pressures play an important role in the most critical global challenges that humanity faces today, including those related to sustainable energy, food production, water supply, human health and well-being. The mitigation of and adaptation to climate change, the prevention of environmental pollution, the conservation and the sustainable use of key natural resources and of ecosystem services are vital. Modern society is progressively vulnerable to the increased frequency of natural hazards causing life loss and enormous impacts on society: environmental catastrophes can shutter societal security and cause migration with related security problems.

This recognition is reflected in EU member states national priorities and in a series of

strategic documents including the United Nations 2030 Agenda for Sustainable De-

velopment (2015)¹⁰, the European Green Deal (2019)¹¹, United in Science (2020)¹² and Making Peace with Nature (2021)¹³. Out of the 17 Sustainable Development Goals (SDGs) calling for action to protect the planet and ensure future prosperity, three (SDG13 Climate action, SDG14 Life below water, SDG15 Life on land) are directly focused on sustainable management

10. United Nations 2030 Agenda for Sustainable Development – Sustainable Development Goals
<https://sdgs.un.org/2030agenda>

11. European Green Deal
https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

12. United in Science
https://public.wmo.int/en/resources/united_in_science

13. Making Peace with Nature
<https://www.unep.org/resources/making-peace-nature>

of natural resources, while numerous others strongly depend on them. Even the most generic goals cannot be achieved without a sustainable management of our environment. To reach the SDGs, the EU introduced the Green Deal as a new European growth strategy towards a prosperous society with a resource-efficient economy and no net emissions of greenhouse gases. To support these political goals, the **Horizon Europe Research and Innovation Programme** was launched, with a strong focus on Global challenges and European Industrial Competitiveness, together with five clearly defined **Research and Innovation Mission Areas**:

- **Adaptation to Climate Change**: support at least 150 European regions, local authorities and communities to become climate-resilient by 2030;
- **Restore our Ocean and Waters by 2030**;
- **A Soil Deal for Europe**: 100 living labs and lighthouses to lead the transition towards healthy soils by 2030;
- **100 Climate-Neutral and Smart cities by 2030**;
- **Cancer**: improving the lives of more than 3 million people by 2030 through prevention and cure and ensuring a longer and better life for those affected by cancer and their families.

European environmental RIs are able to look for integrated and sustainable solutions and invest in critical science to put the planet back on the path towards long-term global sustainability. They have a large impact at the European level by providing quality-assured data in six Services of the European Union's flagship **Copernicus programme** (land monitoring, marine monitoring, atmosphere monitoring, emergency management, security, and climate change). Additional linkages are being developed with the **INSPIRE Directive** and on-going Joint Programming Initiatives. They further assist the European component of **GEO** in linking Earth Observation resources world-wide across multiple **Societal Benefit Areas** (e.g., climate, disasters, weather, water, ecosystems, biodiversity, agriculture, energy, or health) making them available for better informed decision-making.

The recent publication *Flipping the Science Model: A Roadmap to Science Missions for Sustainability*¹⁴ however recognises that new ways of doing science must be developed to progress faster. The International Science Council highlighted in its *Unleashing Science* report a need for making knowledge actionable, less siloed, and truly engaged with stakeholders. Environmental RIs should strengthen efforts to structurally **link generated data with the socio-economic values they influence and depend on**. Two related approaches, **Eco-**

14. [Flipping the Science Model: A Roadmap to Science Missions for Sustainability \(2023\)](https://council.science/publications/flipping-the-science-model/)
<https://council.science/publications/flipping-the-science-model/>

system Services¹⁵ and **Nature Contributions to People**¹⁶, represent frameworks for integrating the environmental, social and economic spheres. They develop a perspective of coherent consideration of the real world, linking natural and socio-economic factors. Increased attention should be given to networks cutting across RIs and disciplines. Boundaries between domains should become zones of permeation. Additionally, communication with the citizens demands special attention. Facilitating and implementing **citizen science** as a method to acquire novel environmental data that can be integrated in large RIs can help build trust in science.

MULTIPLE EUROPEAN POLICIES BENEFIT FROM ENV RIs

Environmental RIs have a prominent role in providing services to **support international policy initiatives, programmes and conventions**. Building on the best available scientific evidence is often a legal requirement in international conventions. The successful uptake of scientific findings produced through RI services depends on RIs capabilities to liaison and connect with societal actors which could be considered as the societal **'problem owners'**. These include entities or people with a management or regulatory responsibility in policy and society (e.g., environmental authorities) and primary contributors to the problem. The environmental RI community is acutely aware of its ability to deepen understanding and actively contributes to the body of evidence required to address these issues in an appropriate way.

At the global scale, European RIs have established a key role by **contributing to the UN Framework Conventions** (e.g., the Convention on Climate Change, the Stockholm Convention on Persistent Organic Pollutants, the Minamata Convention on Mercury, or the Convention on Biological Diversity) and to the **global data systems**. Furthermore, environmental RIs are recognised contributors to the **intergovernmental panels** which strongly rely on recent scientific advances to produce assessments underpinning policies: the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), as well as the newly developed International Panel on Chemical Pollution.

15. [Natural Capital and Ecosystem Services](https://www.eea.europa.eu/soer/2015/europe/natural-capital-and-ecosystem-services)
<https://www.eea.europa.eu/soer/2015/europe/natural-capital-and-ecosystem-services>

16. [Nature Contributions to People](https://www.ipbes.net/global-assessment)
<https://www.ipbes.net/global-assessment> and <https://www.science.org/doi/10.1126/science.aap8826>

RIs IN THE ENV DOMAIN ARE 'BRIDGING' WHILE UNDERGOING SIMILAR DEVELOPMENTS THAT CAN BOOST THEIR IMPACT

The complex character of environmental challenges (such as climate change, chemical pollution, and biodiversity loss) requires the exploitation of synergies between RIs across different domains. It necessitates joint development of **more holistic approaches** and **interdisciplinary capacity to produce knowledge and innovation** underpinning future solutions. RIs within the Environment domain are actively pursuing development plans and strategies aimed at enhancing their impacts, whether for basic scientific understanding, or increased ability to predict and respond to natural hazards, prevent ecosystem losses, or comprehend the interactions of nature and society. While these developments can happen in parallel, many of them are strongly intertwined and affected by common trends.

INCREASED IT CAPABILITIES (JOINT WORK ON FAIR DATA, AI APPLICATIONS, DIGITAL TWIN CAPABILITIES)

The environmental challenges addressed require data on a wide array of variables, often across a broad spectrum of space and time scales. While enhancing the capability and capacity of observing systems is often required (both in terms of quality and quantity), there is a strong drive to ensure that, whatever data is already being collected, it is fit to (re-)use in multiple circumstances. The **capabilities for analysis** and other computation need to follow a pace, preferably without bottlenecks in processing. Service access portal systems need to be improved and the use of **High-Power Computing and cloud resources** increased. The intensifying use of **Artificial Intelligence (AI) technologies** will affect how RI services can be developed in combination, enabling direct extraction of information required by decision and policy makers. RIs will need to further advance towards delivering scientific knowledge produced in a digital format. The **Destination Earth** flagship initiative of the European Commission (EC) aims at developing a highly accurate **digital model of the Earth** on a global scale, to **simulate and predict**

the interaction between natural and human activities so to provide information on environmental disasters and pressing socio-economic challenges. Destination Earth is a mission-led science project that provides the opportunity for developing multidisciplinary approaches and cross-RI integrated services. It concurrently focuses on modernising RIs' interoperability capacities and digital infrastructures, thereby increasing the benefit derived from tools and methods coming from data-driven science. The work has already started in several EC-funded Digital Twin projects.

CHALLENGE-DRIVEN SERVICE PROVISION FOR WIDER USER COMMUNITIES

Only few RIs (such as **ICOS ERIC** for carbon cycle or **EIRENE RI** for environmental health) have been initially designed to provide thematic, challenge-related services. Most of them have been set up to provide discipline-, domain- or sphere-related services. Still, environmental RIs may serve wider user communities by aligning and integrating their service components. Recently EC-funded **IN-FRASERV-projects** will accelerate the joint provision of **integrated challenge-driven services to tackle environmental challenges**. The sustainability of jointly developed services needs to be solved during the projects. To be successful on this, trusted relations, open dialogue, and support from stakeholders to find long-term business models for service provision are needed. In a broader perspective, co-design and co-development involves more sustained dialogue with stakeholders, so that the resulting service or product meets knowledge requirements of downstream users. Environmental RIs also engage in joint activities with operational services providers. The **mutual dependence of the operational and research ecosystems** is a specific feature of the Environment domain. Science-based operational information services (such as Copernicus, weather, and risk management services) rely on research results and RI service provision, especially in the areas of modelling and observation. Conversely, research communities take advantage of operational observations and model outputs in shaping observation strategies. This synergy is a multiplier of the impact of RIs in the field of management of environmental risks. Environmental sciences are eminently suitable to **involve stakeholders and citizens**. Miniaturisation for certain measurements by cheap sensors and mobile application, coupled with the proliferation of online data tools for data submission, have allowed for broader participation in many disciplines: scientific data and workflows can involve people beyond institutional scientific experts, in a multitude of new creative initiatives.

ENABLED PARTICIPATION IN GLOBAL FRAMEWORKS

Many European environmental RIs have **counterparts in other continents** or are **part of global networks**. The overall science support context consists of, for example, the World Meteorological Organisation, the Intergovernmental Oceanographic Commission of UNESCO, the United Nations Environment Programme, the International Council of Scientific Unions, and the Organisation for Economic Co-operation and Development. Global environmental science is also important in domains such as agriculture and fisheries. A notable global initiative aimed at security and fast hazard response, based on large infrastructure investments and strong European participation from scientific and public sectors, is the **Global Earth Observation System of Systems (GEOSS)** initiative of the Group on Earth Observations (GEO). This initiative consists of a worldwide network creating innovative solutions to global challenges at a time of exponential data growth, human development and climate change that transcend national and disciplinary boundaries. Global collaboration among experts helps **identify gaps and reduce duplication** in the areas of sustainable development and sound environmental management. Among the major users of atmospheric RIs data products and services is **COPERNICUS Atmosphere Monitoring service (CAMS)**. Data coming from the ESFRI Landmarks **ACTRIS ERIC**, **IAGOS** and **ICOS ERIC** are used by CAMS, for example, for Near-Real Time Model Validation, Monitoring Air Quality and providing an air quality forecast for European cities (as shown daily on EURONEWS). ACTRIS can make a substantial contribution to improve air quality and study the climatological effects of short-lived atmospheric constituents; while ICOS is of paramount importance in achieving climate neutrality. However, as anticipated, there remains a gap in RIs supporting research on chemical pollution in the atmosphere beyond particulate matter, trace, and greenhouse gases.

SOCIO-TECHNOLOGICAL ADVANCES ENABLING ENHANCED IMPACTS

In addition to IT advances and falling costs of related services, environmental research can benefit from breakthroughs in many other domains including physical, material, and life sciences (genetic analysis, omics technologies) and from increasing experience with multi-actor cooperation. The rapid technological advances, the openness of science at international level (Open Science), the increased multidisciplinary in environmental sciences, and the drive towards co-creation between scientists and knowledge users with changing societal attitudes and willingness to cooperate, are all unfolding at the same time. This convergence, resulting from pure combinatorics, presents a myriad of opportunities, many of which can be true enablers for enhanced impact of all RIs. RIs can serve as **test beds for tailor-made solutions in different settings designed in dialogue with and close to the users**. However, all RIs are facing the common challenge of deciding which avenues to pursue to benefit most from theoretical possibilities. A limiting factor for implementation is often **availability of resources**. A diffusion of best practices can be enhanced by learning through analysis of 'impact stories' across the landscape of the environmental RIs.



Securing long-time access to natural resources is fundamental for the economic competitiveness of the EU. There is a growing concern about the effects of environmental deterioration on both ecosystems and humans. Urbanisation, land degradation, climate change, chemical pollution, infectious agents, biodiversity loss, and disruption of ecosystems services were shown to work together to damage health and quality of life, affecting disproportionately socially disadvantaged and vulnerable populations.

It has been acknowledged that it is necessary to increase the value given to natural ecosystems, sustainable use of resources and improved human health: a transformational change in these areas is most needed and potentially most beneficial for the EU economy, society and natural environment. The **Green Deal**, developed as an integral part of the Commission's strategy to achieve the Sustainable Development Goals and the Global 2050 Vision of 'Living in harmony with nature', covers numerous policy objectives and strategies including **climate neutrality by 2050, biodiversity preservation, sustainable food, circular economy and the overarching zero pollution ambition**.

Political strategies must be accompanied by research strategies aimed at improved understanding of environmental processes and the impacts of various stressors. Based on extensive consultations of scientific communities and other relevant stakeholders including policy makers, local authorities, NGOs, and industries across Europe, the **European research agenda for the Environment, Climate & Health for 2020-2030** was developed within the H2020 HERA project¹⁷. Resulting research priorities included: (i) reduction of the effects of ecological degradation and climate change on health; (ii) elimination of environmental exposures to chemicals, wastes, and biological agents harmful to health; (iii) improved health impact assessment of environmental factors; (iv) promotion of healthy lives in sustainable societies; and (v) promotion of intervention research.

The identified needs have been addressed in the European research and innovation framework programme **Horizon Europe**, namely in the Global Challenges and European Industrial Competitiveness pillar containing Clusters on Food, Bioeconomy, Natural Resources, Agriculture and Environment, but also on Climate, Energy, and Mobility. To increase the effectiveness of funding by pursuing clearly defined targets, research and innovation Missions were incorporated into Horizon Europe. However, none of these Missions can be carried out without **interdisciplinary research collaboration across traditional domains**. This collaboration is essential, not only within the environmental sciences but also at the **Environment, Health & Food, Energy, and Humanities** interface. It opens new opportunities for the joint development of services delivered by RIs operating in these domains.

¹⁷ Horizon 2020 HERA project
<https://www.heraresearcheu.eu/>

Key implementation tools of Horizon Europe are the **European Partnerships bringing private and public partners together** to address some of Europe's most pressing challenges through concerted research and innovation initiatives. There are numerous partnerships relevant for the Environment domain in the areas of food, bioeconomy, natural resources, agriculture and environment, including the European Partnership (EP) for Water Security for the Planet, and the EP for Rescuing Biodiversity to Safeguard Life on Earth. What is more, there exist partnerships enabling cross-disciplinary collaboration, for instance: EP for Agriculture of Data, EP for Safe and Sustainable Food Systems, EP for Animal Health and Welfare, EP "Accelerating farming systems transition: agroecology living labs and research infrastructure", EP for a Circular Bio-based Europe, and EP for a "Climate neutral, sustainable and productive Blue Economy". Additional EPs on zero-emission energy and transport are currently under development under the Climate, Energy and Mobility Cluster. EP for chemicals risk assessment (PARC) in the Health domain is meant to bridge the Environment and Health domains. **European Open Science Cloud (EOSC) Partnership**, **EIT Climate-KIC**, and **EIT Food-KIC** operate across various themes. Lately, the European Commission presented 10 new proposals for new candidate partnerships to be launched during the second half of Horizon Europe, among which **Forests and Forestry for a Sustainable Future** and **In-Orbit Demonstration and Validation**.

The partnerships should significantly contribute to reducing the fragmentation of the research and innovation landscape in the EU and achieving the EU's political priorities including the Green Deal. Collaborating with new Horizon Europe Partnerships should help further develop the Landscape of environmental RIs to keep up with holistic research pursuing all five Missions, and bridging those Missions together by providing an environmental perspective to the Cancer mission and a health perspective to the other four Missions.

These new instruments of Horizon Europe (missions and partnerships) provide a cross-sectoral approach to bridge the relevant Clusters and science-policy-society interface to leverage the impact and increase the relevance and uptake of new tools, innovations, and knowledge to the direct benefit of citizens. Research Infrastructures can provide a framework enabling wide accessibility of resulting knowledge and innovation, as well as long-term sustainability and continuous development of these tools and services.

ENV RIs act as a pluri-disciplinary community. If the Environment domain RIs start to transcend the approach 'by sphere' through myriad possible interlinkages at the level of individual science disciplines, this becomes an even wider endeavour when societal issues are in focus.

For instance, in the nexus between environment and human health, abundant opportunities exist to develop new services between RIs possessing data on the atmosphere (e.g., **ACTRIS ERIC**, **ICOS ERIC**) and on impact of environmental exposures (**EIRENE RI**). In addition to direct impacts of environmental factors (chemical pollution, extreme heat, noise and light pollution) on population health, there are also bi-directional links between the Environment and Health & Food domains. Agriculture and food production have an impact on both the environment (chemical pollution) and human health (nutrition, chemical exposure). There is thus potential for joint services between **METROFOOD-RI** and **EIRENE RI**. These relationships can be studied in longitudinal cohorts investigated across the domains (**SHARE ERIC** or **GGP** in Social, **EIRENE RI** or **BBMRI-ERIC** in Health & Food domains).

More broadly, several RIs aim to broaden their scope to include the capability to link with social and economic determinants. Take **eL-TER RI**, for instance: with its distributed physical infrastructure and

scientific expertise, this RI aspires to provide the scientific capacity needed to improve understanding of ecosystem dynamics in a broader sense. By adopting a socio-ecological approach to studying integrated human-nature systems and with the commitment to integrate stakeholder knowledge, eLTER aims to provide a solid foundation to inform evidence-based policy making and management solutions addressing current and emerging environmental challenges. It interacts with H&F RIs dealing with ecosystems such as **AnaEE-ERIC** or with **EMPHASIS**. Biological RIs such as **EM-BRC-ERIC** on marine biology, **MIRRI-ERIC** on microbial resources, or **ERINHA** on highly pathogenic agents offer relevant resources to be applied in environmental research. **ELIXIR** infrastructure for life-science data provides integrated bioinformatic resources that can be also used across the domains.

Expectations are high regarding how innovative research can help find the best approaches and support the achievement of the political goals. RIs should better facilitate trans-disciplinary research, enabling researchers to work in a more integrated manner across multiple domains. They should inspire new **transformational approaches to addressing environmental and societal challenges in their full complexity including ethical, political, socio-economic, equity, sustainability, and communication aspects**. Knowledge gained from such a holistic approach will help define how to walk the delicate balance of utilising natural resources with minimum impact on the environment and ensure that today's actions do not impede the well-being of future generations.



ESFRI LANDSCAPE ANALYSIS 2024 - SECTION 1

HEALTH & FOOD



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HEALTH & FOOD

CURRENT STATUS IN THE DOMAIN

Today's global challenges in the Health & Food domain are vast and complex. They include, among others: the rising burden of common complex diseases such as cancer, cardiovascular diseases, antimicrobial resistance, nutrition related diseases; emerging zoonosis of worldwide importance; pandemics; livestock epidemics; the affordability of the health care systems¹; the resilience and sustainability (economic, environmental, societal and cultural) of the entire agro-food value chain; food and nutrition security and safety, especially in light of shocks (environmental, economic, geopolitical) and the circular bioeconomy. Europe has high ambitions for meeting these challenges. At the core of its strategy, ESFRI landmark Research Infrastructures (RIs) play a major role.

1. EC Expert Group on Public Health
https://health.ec.europa.eu/non-communicable-diseases/expert-group-public-health_en

Currently about **two thirds of all deaths in the European region are due to non-communicable diseases** such as cardiovascular diseases, cancer, chronic respiratory diseases, mental health conditions, nutrition related diseases². This prevalence is set to increase with an ageing population. These epidemics are global, affecting low-, middle- and high-income countries, and have three consequences, each exacerbated by health inequalities: avoidable human suffering; undesirable societal costs;

and crises in primary prevention, primary care and secondary care.

There are strong connections between environmental, food, lifestyle and health issues: food production

2. Cause of death statistics – Eurostat
https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Causes_of_death_statistics#Major_causes_of_death_in_the_EU_in_2020

and processing depend on the environment and also affect it³. In fact, nutritional habits and food quality strongly affect health; food safety and the food composition depends on the healthy and unpolluted environment. **The agro-food sector is an important source of greenhouse gas emissions but can also contribute to GHG emission mitigation⁴**. The COVID crisis has highlighted the links between food, biodiversity, health and climate and the need for the **'One Health' approach**.

Beyond non-communicable diseases, there has been global progress in **reducing disease burden due to a number of communicable diseases**, including diarrheal diseases, lower respiratory infections, tuberculosis, syphilis,

3. See, e.g., Walter L. F. et al. (2022), "An overview of the interactions between food production and climate change", *Science of The Total Environment*, Vol. 838, Part 3, 2022 <https://doi.org/10.1016/j.scitotenv.2022.156438>

4. Smith P. et al. (2007), "Agriculture", in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, US.

typhoid, paratyphoid, and vaccine-preventable infections such as hepatitis B, measles, tetanus, COVID-19 and Hemophilus influenzae type b. Adding to these successes, the last decade has seen profound **declines in the burden from HIV/AIDS**. A number of **emerging and growing health threats** also deserve special attention in policy planning, including infectious diseases such as outbreaks of antimicrobial-resistant pathogens, pandemic influenza, Ebola virus disease, Zika virus, and dengue fever, which represent acute threats to life and highlight health-system deficiencies where they occur, substance abuse disorders, particularly of opioids and cocaine, in Eastern Europe.

To address the emerging Health & Food issues, European countries have issued national health, nutrition and food guidelines and regulations. The European Commission (EC) has launched the **Healthier together – EU Non-Communicable Diseases Initiative⁵** to support EU countries in identifying and implementing effective policies and actions to reduce the burden of major non-communicable diseases (NCDs) and improve citizens' health and well-being. EU countries need support to prepare and respond together to health crises, make sure that medical supplies are available, affordable and innovative, and countries work together to improve prevention, treatment and aftercare for diseases. Responding to these necessities, the EC is building the **European Health Union⁶**, with the **European Health Data Space (EHDS)⁷** as a

5. Healthier together – EU Non-Communicable Diseases Initiative
https://health.ec.europa.eu/system/files/2022-07/ncd_initiative_factsheet.pdf

6. European Health Union
https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/promoting-our-european-way-life/european-health-union_en

7. European Health Data Space (EHDS)
https://health.ec.europa.eu/publications/proposal-regulation-european-health-data-space_en

central building block and key actions on pandemic preparedness, cancer, mental health and pharmaceutical legislation. The **United Nations Decade of Healthy Ageing**⁸ (2021–2030), in turn, stands out as a global collaboration aligned with the last ten years of the Sustainable Development Goals (SDGs), with the aim to improve the lives of older people, their families, and the communities in which they live. Another EC initiative is the **European Green Deal**⁹, which calls for no net emissions of greenhouse gases by 2050, a goal which will require efforts and impact all sectors. As for the agro-food sector, the **Farm to Fork Strategy** sets out goals for agro-food systems that are fair, healthy and environmentally friendly and aims to accelerate our transition to a more sustainable agro-food value chain.

RIs are more important than ever as they are key to support world-class research, providing access to state-of-the-art resources, services, data, and training.

8. United Nations Decade of Healthy Ageing
<https://www.who.int/initiatives/decade-of-healthy-ageing>

9. European Green Deal
https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

In the ESFRI Health & Food (H&F) domain, a number of internationally recognised excellent RIs exist. As an umbrella to Life Sciences, the **ESFRI Landmark ELIXIR** enables researchers to access and analyse Life Science data and aims at improving the value and impact of Life Science research on public health, the environment and the economy. In the Health domain, the spectrum of biomedical research spans from clinical research (**ESFRI Landmarks ECRIN ERIC, BBMRI-ERIC, EATRIS ERIC, Euro-BioImaging ERIC**), to drug design and development (**ESFRI Landmarks Instruct-ERIC, EU-OPENSCREEN ERIC**), including creating models for disease (**ESFRI Landmark INFRAFRONTIER**). In the food area, infrastructures cover a large part of the value chain, from ecosystem analysis and experimentation (**ESFRI Landmark AnaEE-ERIC**), to plant/crop phenotyping (**ESFRI Project EMPHASIS**) and food and nutrition metrology (**ESFRI Project METROFOOD-RI**) to industrial biotechnological innovation (**ESFRI Project IBISBA**). Other RIs cover both the Health and the Food areas. For instance, the **ESFRI Landmark MIRRI-ERIC-ERIC** focuses on the preservation, systematic investigation, provision and valorisation of microbial resources and bio

diversity, the **ESFRI Landmark EMBRC-ERIC** specialises in marine biological resources, while the **ESFRI Project EIRENE RI** supports research on human exposome.

Refer to **Figure 1** for an overview of ESFRI RIs in the H&F domain. **Figure 2** provides a focus on the Health domain, while **Figure 3** centres on the Food domain.

These RIs complement infrastructures included in other ESFRI domains. For example, **ESFRI Project eLTER RI** focuses on ecosystems observation, and **ESFRI Landmark LifeWatch ERIC** provides e-Science research facilities on biodiversity and ecosystem functions and services in order to support society in addressing key planetary challenges. **ESFRI Landmark ICOS ERIC** measures carbon, **ESFRI Landmark ACTRIS ERIC** looks at aerosols, clouds and trace gases in the air, and **ESFRI Landmark SHARE ERIC** studies the effects of health, social, economic and environmental policies over the life course of European citizens. Or consider **ESFRI Landmark ESRF-EBS**, a centre of excellence for fundamental and innovation-driven research in condensed and living matter science.

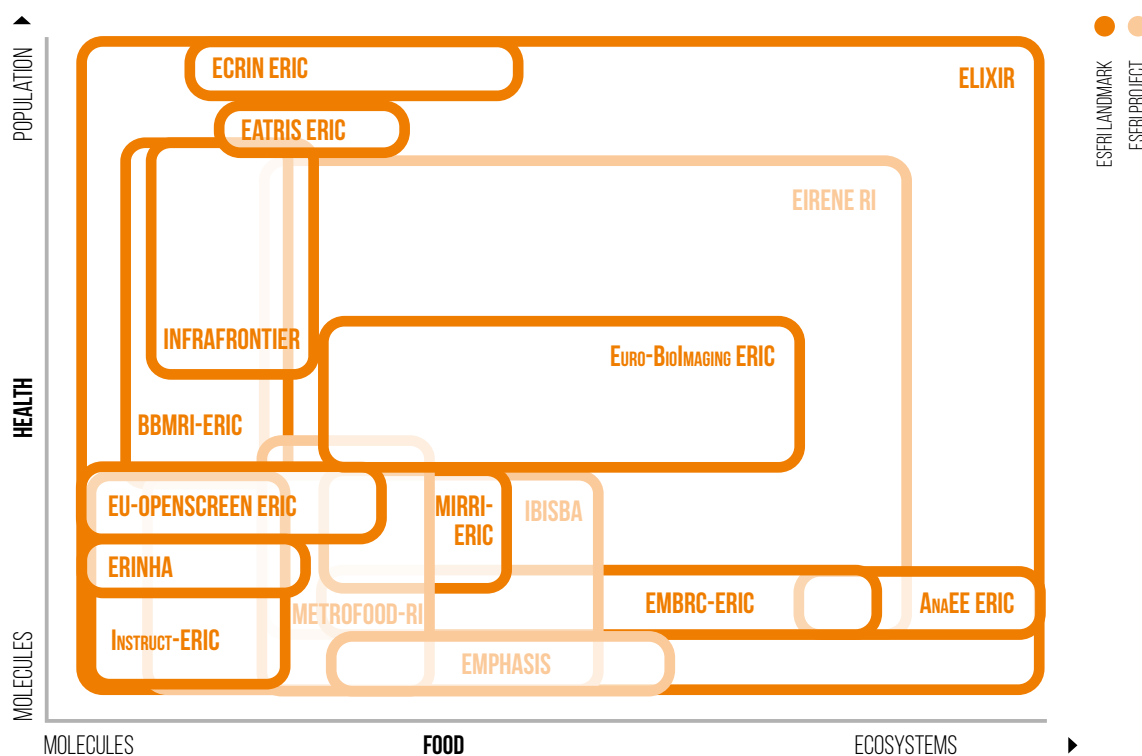


FIGURE 1.

The indicative position of ESFRI RIs relative to the different levels of organisation in the Health & Food domain.

The Health & Food RIs provide services and expertise of the highest level to a range of facilities and cover most aspects of the scientific and societal challenges. The services provided cover a very wide range of areas including fundamental biological science, medical- and food-oriented research as well as biotechnological applications of clinical and agro-food aspects involving animals, plants and humans. They include a large amount of scientific equipment or sets of instruments such as technological platforms, e-infrastructures, knowledge-based resources, biological resources collections (biobanks, archives and scientific data). Communication networks, training and tools that are essential to achieve excellence in Research and Innovation (R&I) are prerequisites for the respective RIs. The main users of these services are public and private research institutions including universities, small and medium-sized enterprises (SMEs), and industry.

RIs in the H&F domain are mainly organised as distributed infrastructures based on national centres and platforms at different locations, coordinated by a central hub.

The breadth of services made available have proven the maturity and readiness of the H&F RIs in their capacity to handle crises like the recent COVID-19 pandemic. The top-notch technologies and highest-level services and expertise provided by these RIs enable new discoveries and pave the way to innovative solutions and new industrial and societal applications. A prerequisite for making this possible is to keep the highest level of excellence, ensuring a continuous innovation of technologies to keep the competitiveness of the RIs.

The services provided by the H&F RIs cover a very wide range of areas. They can schematically be grouped within these four areas: i) fundamental biological research; ii) medical-oriented research; iii) biotechnological applications; and iv) food-oriented research.

Today's global challenges are vast and complex, and the core of the research landscape in the H&F domain requires fundamental biological research support. This includes biologically relevant instrumenta-

tion, advanced digital solutions, technical support, resources, bioinformatics, biomolecular data as well as knowledge and experience of interoperability and networking.

As for **fundamental research**, RIs services allow the characterisation of systems of different levels of complexity and dimension through techniques and approaches working at different levels of resolution. They span from the detailed characterisation of biomolecules with atomic-level resolution, possibly in a cellular context, to the analysis of entire cells and tissues to living organisms including humans. Tools and expertise are then available for designing, screening and optimising candidate drugs, as well as for providing culture collections and for identifying new compounds from different sources and environments.

High-end structural biology technologies needed for structural characterisation of biological molecular and macromolecular complexes including within the cellular context are made available by the **ESFRI Landmark Instruct-ERIC**. This RI provides the highest-level equipment for the more classical methods such as X-ray crystallography, NMR and cryo-EM. Moreover, it grants users access to a palette of techniques ranging

from advanced molecular biology for the production of samples, to biophysical tools for their analysis, to nanobodies mostly used for structural stabilisation.

Through the **ESFRI Landmark Euro-BioImaging ERIC** scientists have access to **imaging technologies in biological and biomedical sciences** to perform research spanning from the single cell to the biomedical imaging technologies for studies in animals, plants and human subjects. This is achieved through access to cutting-edge instrumentation at various levels of resolution. They span from light microscopy to multimodal correlative microscopies, super-resolution microscopies, to cryo-electron microscopy and tomography, to imaging performed on *ex vivo* materials, on plants, on animals and on humans.

Access to **high-capacity screening platforms**, needed to develop novel molecular tool compounds and early therapeutic candidate molecules, is made possible by the **ESFRI Landmark EU-OPENSCREEN ERIC**. This RI provides access to high-throughput screening platforms and to medicinal chemistry services. EU-OPENSCREEN ERIC can contribute collections of drug-like small molecules, for the identification of initial 'hit' compounds against a defined target. The identified compounds can then be chemically optimised in terms of selectivity and potency into lead compounds through medicinal chemical services.

Research on **marine organisms and related materials** is supported by the **ESFRI Landmark EMBRC-ERIC** through facilities and platforms necessary to study them. As an RI for Marine Biology and Ecology, its services are very broad and diverse. They guarantee access to biological resources, from marine biological organisms and their derivatives (one of the core missions of the RI), to the Europe's most important marine culture collections, to a broad range of cultures of marine 'model' organisms in the laboratory. EMBRC-ERIC also includes experimental facilities, from dry and wet laboratories for sample processing and analysis to coastal vessels, aquariums and tanks for environmental studies.

Medically oriented RIs offer extensive technology and knowledge platforms crucial for supporting and promoting diverse activities essential for clinical research. These encompass **translational research and clinical trials, biobanking of biological samples, disease models, access to high containment research services for addressing pathogens and emerging infectious diseases, and the characterisation of environmental determinants of human health.** These types of services are therefore reinforcing translational research that advances discoveries from basic research to clinical applications, accelerating the innovation process which is vital in the transition from basic to applied science. The clustering and multifaceted activities of medically oriented infrastructures facilitate translational therapeutics. They involve research from genes, proteins, cells, tissues, organs, and animals to clinical research with patient populations, all with the aim of preventing diseases and treating and curing patients. These RIs have developed an extensive range of services for biomedical scientists, including development and adaptation of assays, high-throughput screening, omics technology platforms, and medical and *in vivo* imaging of animal models. They also provide access to animal facilities that offer extensive breeding and phenotyping services to properly characterise models of diseases.

In this area, four RIs are primarily focused on biomedical services. Of these, three (**ECRIN ERIC, BBMRI-ERIC, and EATRIS ERIC**) provide clinical research and services, while the remaining one (**INFRAFRONTIER**) is devoted to developing and characterising disease models. Disease models are central also for the **ESFRI Landmark ERINHA**, which is dedicated to the study of high-risk consequence emerging

and re-emerging pathogens using *in vitro* and *in vivo* models. These activities are effectively integrated and are based on the services of Instruct-ERIC, EU-OPENSREEN ERIC and Euro-BioImaging ERIC. The former two facilitate the study of molecular structure and interactions, therefore proving useful for drug design and development; the latter provides crucial bioimaging services.

The **ESFRI Project EIRENE RI** (ENVIRONMENTAL Exposure assessment in Europe Research Infrastructure) is dedicated to assessing environmental determinants of human health, including indoor and outdoor environmental factors, lifestyle, and stressors like infection or disease. The **Human Exposome** also deals with environmental health determinants.

As a whole, the services provided by these RIs enable understanding of **disease mechanisms, personalised medicine, new treatments and therapeutic development.** These activities are effectively complemented by other services useful for biomedical research. For instance, drug design and development is facilitated by the study of molecular structure and interactions (Instruct-ERIC and EU-OPENSREEN ERIC) and by imaging tools (Euro-BioImaging ERIC).

Within this context, access to state-of-the-art technologies and approaches for therapeutic preclinical validation, especially for the innovative field of **Advanced Therapy Medicinal Products (ATMP)**, including gene therapy, cell therapy, and tissue engineering, is provided by **EATRIS ERIC**. This RI offers platforms capable to tackle several aspects of translational medicine, among which can be listed: the val-

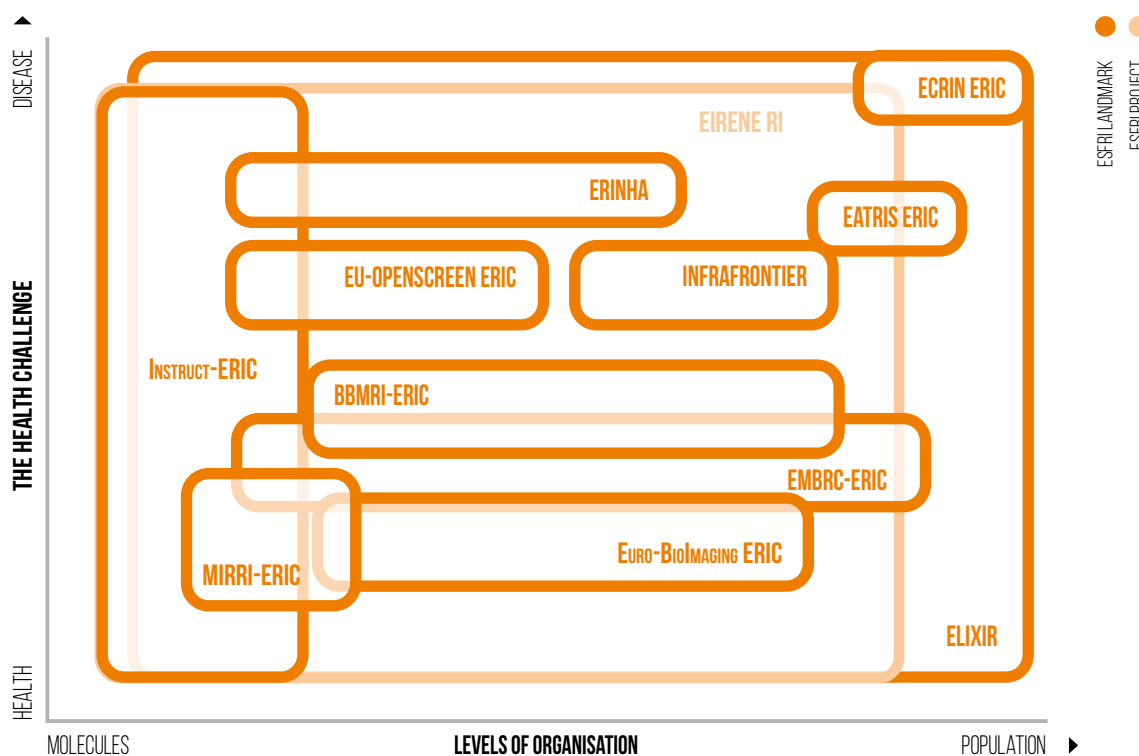


FIGURE 2.

The indicative position of ESFRI Research Infrastructures relative to the different levels of organisation in the Health domain

idation and development of biomarkers for the prevention, diagnosis and prognostic assessment of disease as well as for the prediction of therapy response; cutting-edge translational imaging facilities with a full range of high-end multimodal imaging techniques and advanced image analysis; a Small Molecules platform for the pre-clinical and clinical development of drug candidates; and lastly a Vaccines, Inflammation and Immune Monitoring (VIIM) platform which covers the entire vaccine development and production pipeline.

Access to **animal facilities and phenotyping services** to properly characterise models of diseases is the main mission of **INFRAFRONTIER**. This RI offers the generation of customised mammalian models (mice and rats) using a variety of technologies, as well as access to first-line systemic phenotypic analysis covering a wide range of physiological functions. All provided services and activities are carried out in an internationally standardised way and follow strict quality control standards to ensure data reliability and the reproducibility of results. The phenotyping data are deeply annotated and cross-linked to corresponding data sets from other model organisms and from human patients. Specialised phenotyping services in specific disease areas, such as modules for in-depth metabolic phenotyping, behavioural phenotyping or immuno-phenotyping, are also available through this RI. Finally, through the nodes of the European Mouse Mutant Archive (EMMA), mouse mutants relevant for biomedical research are made available to the scientific community.

Preparation, funding application, implementation, and management of multinational, high-quality, transparent, clinical trials in all medical domains are supported by the services and tools provided for academics and SMEs by **ECRIN ERIC**. The offered services include clinical operations, data centre certification, and infrastructure development projects. ECRIN ERIC tools allow researchers to facilitate the identification of clinical trial objects and objectives, data sharing and access to regulatory and methodological designs. Examples of ECRIN ERIC tools are the Adaptive Platform Trial Toolbox, the Paediatric Tools, and the Rare Diseases Clinical Trials Toolbox. Regulatory and ethical issues are also addressed and supported. The services and tools provided by ECRIN ERIC overcome the lack of infrastructures to support investigator-initiated clinical trials at affordable costs, and the fragmentation and poor interoperability of the national clinical research approaches, thus **contributing to creating a common approach at European level**. This is critical to promote investigator initial clinical trials that respond to health care problems that could be not of interest to companies.

Access to quality-defined biobanks and biomolecular resources in an ethical and GDPR-compliant way is assured by **BBMRI-ERIC**, which has the mission of facilitating biomedical research and improving public health through the responsible and sustainable use of **biobanking and biomolecular resources**. Its service portfolio includes findability and discovery of data and of biospecimen as well as related services of biobanks and biomolecular resources. The search of and access to biological samples and biomolecular resources is supported by effective IT common services. The BBMRI-ERIC services also contribute to standardisation of biobanks operations, towards the development of international ISO standards. Additionally, BBMRI-ERIC has played a pivotal role in originating **FAIR-Health principles**, combining FAIR principles with quality and reproducibility and privacy aspects.

The provision of the **Ethical Legal and Social Implication Services (ELSI)** is strategic for medical-oriented research. The ELSI support the community with guidance on hard and soft law (e.g., GDPR, Oviedo Convention) and provide a platform for knowledge exchange on citizen engagement, vulnerability of research participants, data protection, or incidental findings to address the particularities of research on or with humans. These types of services are implemented mainly within the BBMRI-ERIC activities.

Biotechnology plays a key strategic role at several different levels, from research to industrial applications and processes. It exploits living cells to produce or manipulate materials for specific purposes in several different socio-economic sectors including the health and the agro-food domains. Within biotechnology-oriented research, a number of RIs provide services which span from provision of microbial resources (MIRRI-ERIC), to tools and expertise for assessing environmental impact on health (EIRENE RI), to industrial biotechnology services (IBISBA).

Preservation, systematic investigation, provision and valorisation of microbial resources and biodiversity is supported by the services of **MIRRI-ERIC**. This RI covers all types of microorganisms, such as bacteria (and their cognate bacteriophages), archaea, fungi (including yeasts), eukaryotic viruses, micro-algae, and other microbiological material like microbiomes, cell lines, natural or constructs carrying plasmids, DNA libraries, and genomic DNA. The availability and supply of a very large range of microbial resources is integrated with several related services, including phylogenetic analysis; phenotypic characterisation, and Next Generation Sequencing (NGS) related services. Therefore, MIRRI-ERIC serves the bioscience and the bioindustry communities by facilitating the access, through a single point, to the broadest range of high-quality microorganisms, their derivatives, associated data and services, relevant both for the health and the food research projects.

EIRENE RI effectively supports large-scale research for the interdisciplinary assessment of **environmental determinants of human health**, including indoor and outdoor environmental factors, lifestyle, socioeconomics, and the individual's ability to cope with various stressors such as infection or disease. This RI, as already anticipated, contributes to the development of the **Human Exposure**. One of its main services consists in the determination and use of biomarkers to determine exposure, effect of exposure, disease progression, and susceptibility factors. Harmonised workflows and integrated services for data and sample collection, as well as knowledge and tools are also made accessible to researchers.

Services to the industrial biotechnology communities, mainly aimed at providing advanced multidisciplinary, integrated services for accelerating end-to-end bioprocess development, are supported by **IBISBA**, the main European RI specifically dedicated to industrial biotechnology. Its activities involve tools and expertise for studies devoted to protein discovery and engineering, production strain development, bioprocess development and optimization, and -omics analysis.

The RIs described so far are of particular relevance both for medical and biological research and for food-related research and its industrial applications.

The agro-food sector continues to tackle major challenges including sustainable food production in an increasingly variable climatic environment, and the need to both mitigate as well as adapt to climate change. Added pressures from geo-political tensions and war lead to supply issues for basic commodities and increasing costs for many of the raw materials involved in food production such as feed, fertiliser and fuel. In addition to concerns regarding food security in a global context, significant health challenges connected to poor diet, obesity, undernutrition and malnutrition significantly hamper the quality of life and/or life expectancy for those affected.

The increasing attention to **food system sustainability** represents a global issue which the H&F RIs are aiming to address through several RIs which provide services also at cross-sectoral level, by interconnecting food-related scientific research with environmental aspects.

Essential high-quality metrology services relating to food quality and food safety are provided by the **ESFRI Project METROFOOD-RI**, whose general objective is to enhance scientific excellence and scientific cooperation in the field of **food quality and safety**. The provision of reliable and harmonised metrology services in the area of food and nutrition are at the core of METROFOOD-RI. Its ambition is to promote **standardisation and harmonisation on laboratory measurements and methods development** to ensure that food is healthy and safe to eat. These services support good practice across the food chain including food production, processing, distri-

bution, retails, handling, storage and preparation. METROFOOD-RI services can be used to determine the conditions most suitable to maintain nutritional and quality properties, assess the risk of contamination and cross-contamination and ensure food safety along the food chain. Furthermore, services provided by this RI support the EU's ambition to a sustainable food system by facilitating assessment of the impact of environmental changes and related adjustments in food production and processing systems on the nutritional quality and food safety.

In the context of a changing food system, with increasing focus on novel carbon neutral production and processing technologies including new foods/ingredients from insects, algae and fungi, there is an even greater need for development and harmonisation of analytical laboratory services that can be used to assess their impact on food quality, nutritional value, and food safety. There is also a distinct possibility of the emergence of new food safety risks from pathogens, toxicants and contaminants arising from changes to production systems, the environment, novel processing methods and new ingredients. Provision of **analytical services in the areas of food nutrition and safety** including personalised nutritional characterisation, omic-based (proteomics, metabolomics, lipidomics, etc.) analyses, related method developments and trainings for assuring safety, maintaining quality and nutritional value will remain crucial for food supplies, researchers, regulators, and policy makers in addressing the challenges ahead.

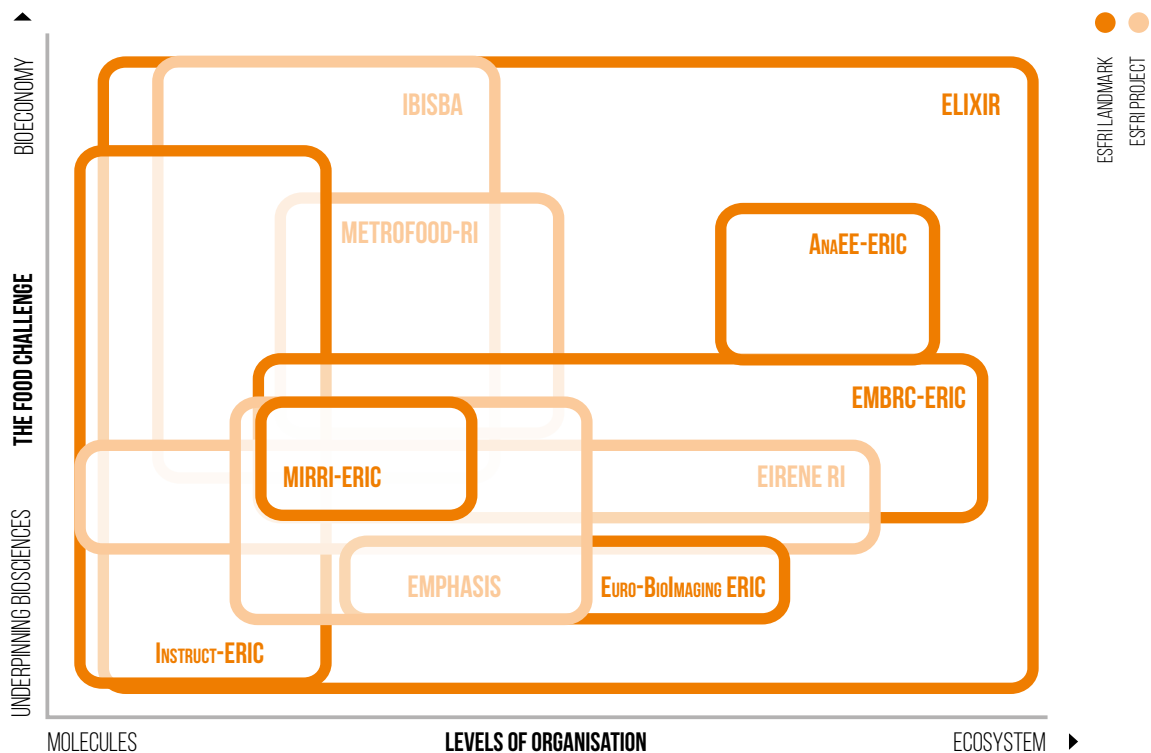


FIGURE 3.

The indicative position of ESFRI Research Infrastructures relative to the different levels of organisation in the Food domain

Additionally, in terms of protecting consumer interest, the global nature of the food system, taken together with a reported desire for more locally sourced foods with lower carbon and water footprints, would suggest an increasing likelihood of food fraud, particularly false country of origin claims. The provision of **analytical methods and services to confirm the authenticity and/or cross-check traceability records** are likely to become more of a necessity. Similarly, analysis, method development and validation, research and training for detection of food contaminants (e.g., mycotoxins and other naturally occurring toxins; organic compounds; toxic and potentially toxic elements) and food allergens available through the METROFOOD-RI network and can provide assurance to suppliers, regulators and consumers on the safety of food available on the marketplace.

In addition to services to design and develop reference methods and material, the provision of laboratories, fields and farms for animal and crop experiments are available to determine the impact of a changing environment on food production, quality and safety. By providing access to these facilities, the consortium enables interdisciplinary research, which can assess the impact of new foods, individual nutrients and/or bio-actives from varying sources on human health and investigate any linkages between nutrient deficiencies and the risk of diseases such as cancers, cardio-vascular disease, low immunity, and other adverse health issues, with a view to empowering health and strengthening immunity and vitality among citizens.

Furthermore, the services provided through METROFOOD-RI can contribute to the UN SDGs by **reducing food loss and food waste** through the assessment, validation, testing, and characterisation of sustainable food packaging solutions (such as biomaterials) and shelf-life testing.

Specific experimental, analytical and modelling facilities dedicated to assessing the **impact of climate change and land use in Europe** are available through the Analysis and Experimentation on Ecosystems (**AnaEE-ERIC**). Services provided allow for the simulation of environmental drivers ranging from land use change, pollution, biological invasion, rising atmospheric greenhouse gas concentrations to increasing extreme events such as droughts and heat waves; and for the assessment of their impact on terrestrial and aquatic eco-systems.

One of the main motivations for the provision of these services is to help determine suitable adaptation and mitigation strategies in order to maintain natural resources and facilitate a viable agro-ecological transition towards sustainable and resilient agro-food systems. The research services are provided through experimental platforms, both open-air and enclosed facilities, offering controlled environmental conditions, where experimental drivers can be applied to determine response under different types of ecosystems representative of climatic zones in Europe.

Their **experimental platforms** are complemented by **analytical platforms** featuring state-of-the-art for advanced biological, physical, and chemical instrumentation. Some of the analytical platforms are mobile and can access remote sites. The comprehensive analytical data allows for an understanding of the mechanisms of response and adaptation to different environmental factors and also

facilitates modelling that allows robust predictions of an ecosystem's responses to global changes. The modelling platforms provide users with access to numerical models and advanced software to develop models (model factories) to improve data analysis and synthesis, thereby allowing for more robust and reliable predictions to global changes.

Another RI providing services which can greatly assist agro-environmental sustainability is the European Infrastructure for Multi-scale Plant Phenomics and Simulation (**EMPHASIS**), which enables researchers to use **facilities, resources and services for plant phenotyping across Europe**. In this way, EMPHASIS helps scientists better understand plant performance under different environmental conditions and translate this knowledge into applications and improved genetic materials which will help promote future food security and sustainable agricultural production in a changing climate.

The plant phenotyping facilities provided by this RI are useful to assist crop genetic improvement programs based on biotech tools. The existing field and greenhouse facilities under controlled conditions enable the investigation of the variability of measured plant traits as a response to well-defined and monitored environmental conditions with a capacity of several hundreds to thousands of plants.

Plant phenotyping has been identified as one of the biggest challenges in the future of crop performance.¹⁰ However, it has the **potential to play a significant role in climate change mitigation and adaptation, as well as in global food security**, as it will allow crop variety phenotyping research for specific traits such as drought and salinity tolerance or yield increase, in real and specific agronomic conditions.¹¹

Across all the RIs of the H&F domain, services of data management and archiving as well tools for their analysis are provided by **ELIXIR**. This RI is devoted to **managing and safeguarding the increasing volume of data being generated by publicly funded research**. It coordinates, integrates and sustains bioinformatics resources across European countries and enables users in academia and industry to access services that are vital for their research. ELIXIR makes it easier for scientists to find and share data, exchange expertise, and agree on best practices and will help them gain new insights into how living organisms' work. Ultimately, ELIXIR helps address the Grand Challenges across Life Sciences, from food and marine research – via plants and agriculture – to health research and medical sciences.

10. Araus J.L. et al. (2018), "Translating High-Throughput Phenotyping into Genetic Gain", *Trends in Plant Science*, 23:5, pp. 451-466 <https://doi.org/10.1016/j.tplants.2018.02.001>

11. van Zelm E., Zhang Y., Testerink C. (2020), "Salt Tolerance Mechanisms of Plants", *Annual Review of Plant Biology*, 71:1, pp. 403-433

RIs are large-scale public high-technology investments and consequently there is increasing demand for RIs to demonstrate the positive contribution they make to society beyond the direct impact on research progress. This includes estimating – or even quantifying – impact on regional and national economies and the benefits they offer to our citizens through the science they deliver. However, the definition and measurement of socio-economic impact present considerable challenges. This analysis, in fact, requires the definition of clear criteria and a long-term observation of their development.

The exploitation of new knowledge and technologies places RIs at the forefront of scientific progress, with the potential to underpin breakthroughs in science and innovation while fostering a collaborative and dynamic research environment.

As providers of access to cutting-edge technology platforms for academia and industry, RIs promote the development of advanced instruments and new technologies, thus establishing themselves as **drivers of technological innovation**. This brings tremendous benefits to society through knowledge transfer and increase in expertise while driving strong economic returns at regional, national and international levels.

RIs have a crucial impact in the training of scientists, technicians and research engineers, as well as in creating opportunities for their mobility to and from science and industry or services. A great impact on innovation is also expected from the openness of well documented high-quality research data supported by reliable and effective data services.

Activities from several well established ES-FRI RIs show the significant long-term benefits of RIs to society at large. **Large-scale ESFRI RIs, and clusters of RIs, intrinsically shape the economy and society of the region** where they are located, contributing to competitiveness but also to cohesion and integration.

The RIs in the H&F domain have faced and are facing major challenges at various levels

and have demonstrated their ability to provide integrated technology and knowledge platforms to address these challenges.

During the COVID-19 pandemic, the ESFRI RIs **BBMRI-ERIC, ECRIN ERIC, Instruct-ERIC, ELIXIR, and Euro-Biolmaging ERIC** proved the importance of their services to the field of infectious disease research, as well as their institutional capacity to quickly respond to new arising challenges. Consider, for instance, the provision of fast-track access for COVID-19 research, in alignment with European needs. Patient's samples, viral proteins and RNAs were made available through open resource sharing; NMR structural characterisation and screening of fragments were conducted by Instruct-ERIC for 25 viral proteins and 20 viral RNAs. Stable variants of the spike protein were produced and utilised for advanced vaccine studies.

Successful projects were largely based on pre-existing work: serendipity plays an important role, but the experience accumulated from earlier work on rare diseases or earlier SARS and Ebola epidemics was invaluable.

TRANSFORMATIVE IMPACT OF THE H&F RIs ON EUROPEAN RESEARCH

The H&F RIs have the potential to underpin breakthroughs in science and innovation while fostering a collaborative and dynamic research environment. The H&F RIs, particularly the landmark facilities, establish European benchmarks in their respective fields, serving as the foundation for the work of RIs. For example, BBMRI-ERIC has developed the world's largest biorepository of human samples. **EATRIS ERIC** coordinates a global framework to promote good research practices, focused on quality, reproducibility, and standardisation. **INFRAFRONTIER** serves as a benchmark for designing and phenotyping animal models of human diseases. Euro-Biolmaging ERIC provides a network of state-of-the-art biological and biomedical imaging technologies. ELIXIR has established a benchmark for management of data according to the FAIR principles. In the food domain, **EMPHASIS** overcomes technological and organisational limitations of European plant phenotyping to promote future food security and agricultural resilience in a changing climate. **AnaEE-ERIC** is constructing a pan-European platform that forecasts the effects of climate and land-use changes on ecosystems, crucial for Europe's ecosystems and food sustainability. Meanwhile, **METROFOOD-RI** is developing a benchmarking metrology system for Food and Nutrition to enhance food quality and safety. Other H&F RIs also exert significant transformational impacts in their respective fields. **RIs serve as benchmarks in their respective areas, advancing research quality and reproducibility.**

H&F RIs promote and facilitate **partnerships between academic researchers and high-tech companies for mutual benefit**. Thus, medically focused research institutes contribute to the development, validation, and diagnosis of human diseases, as recently demonstrated during the COVID-19

pandemic. Additionally, they have gathered samples and data for comprehensive analysis and prediction, thus enhancing preclinical research and development by translating basic research into practical applications and offering a platform for clinical trials, bringing innovative medicines to patients. These RIs are prepared to further **strengthen translational research**.

The H&F RIs also handle **environmental factors which would impact health** as well as food production, processing, and quality, all of which are vital components of sustainability in Europe.

SCIENTIFIC IMPACT

The crucial role of H&F RIs in science rests in their giving access to **top-tier resources and services required to drive innovation, develop pioneering technologies, confront global challenges, and facilitate the green and digital revolution**. The RIs act as a pivot, facilitating and enabling researchers to achieve their goals, in an effective and efficient way. Thanks to the robustness of RIs and their cooperative efforts, they can establish large-scale projects of global importance. Examples include the world's largest biobank of human samples (**BBMRI-ERIC**), the encyclopaedia of gene function, which allows for a systematic approach to pathogenic gene variants (by **INFRAFRONTIER** within the global IMPC consortium), a complete array of imaging services (provided by **Euro-BioImaging ERIC**), and integrated tools to combine atomic characterisation with cellular context (**Instruct-ERIC**).

The collaboration of biomedical RI in translational research has the potential to develop safer and more effective therapeutics. This requires rigorous bench-to-bedside and bedside-to-bench-to-bedside research, supported by technological advancements and sophisticated analysis techniques, which drive modern data-driven discoveries and promote the advancement of personalised medicine and new therapies. **BBMRI-ERIC**, **EATRIS ERIC**, and **ECRIN ERIC** play a central role in these aspects, forming the **EU-AMRI** cluster, the European Alliance of Medical Research Infrastructures.

IMPACT ON DATA QUALITY AND USABILITY

H&F RIs have developed various solutions to address issues of data quality and usability. The rapid growth of Life Science data poses challenges for research. Each H&F RI has developed effective approaches for data management following the FAIR principles and have developed various solutions to address issues of data quality and usability. Furthermore, Life Science data resources are developed and coordinated by **ELIXIR**, a European initiative. Its expertise helps researchers manage diverse, complex data with ease. **ELIXIR's** Compute Platform is developing a network of high-performance computing services, facilitating researchers throughout Europe to conveniently access, store, transfer, and analyse large and complex datasets in the cloud. **ELIXIR's** Interoperability Platform enabled standardisation of Life Science data, streamlining comparative analyses of various datasets.

IMPACT ON EDUCATION AND TRAINING

H&F RIs enable scientists and technical staff to become **proficient users of state-of-the-art instruments and methods for conducting research**. They also facilitate distribution of research questions and opportunities facilitated by the RIs and enable clear formulation of needs and demands for continuous improvement of the technologies and services offered by the RIs. In addition, they help individuals develop specific skills required for managing RIs. Across all the RIs, **ELIXIR** offers training for the data sector. Its platform facilitates identification of necessary training and organises courses on managing massive and intricate datasets.

SOCIO-ECONOMIC IMPACT

H&F RIs socioeconomic impact encompasses all the aforementioned aspects and operates at both the European and regional levels, extending to various research areas.

For example, **EMBRC-ERIC** (the European Marine Biological Resource Centre) offers a world-class platform for both fundamental and applied research on marine ecosystems and bioresources.

In the field of Food, the socioeconomic impact is increasing alongside the challenges that must be addressed, including **environmental factors and new food resources**. As the European climate changes, food sustainability holds the utmost importance for our community.

The medically focused RIs are working together to advance **translational medicine**. The sharing of complementary expertise and concerted approaches is currently being realised in the areas of new therapies and diagnostics, personalised or stratified medicine development, new models of rare human diseases, and the emergence of new biomedical industries. These actions will enhance socio-economic competitiveness and expand opportunities for fair healthcare in Europe. This is accompanied by societal trends, such as the increasing democratisation of science and healthcare and the growth of social media, which have led to a **greater emphasis on the patient's role**. **Precompetitive collaboration and globalisation of research** also play a role.

Several important trends are gaining momentum, contributing significantly to the high impact and relevance of H&F RIs in Health and Food Research within the EU in the 2020s.

One of these is what is called the **triple planetary crisis: climate changes, pollution and loss of biodiversity**. These three challenges will impact both on health and on food production in Europe. We are already seeing spread of vector borne diseases in Southern Europe, new to the region, and drought is threatening crops in Southern Europe.

Artificial Intelligence (AI), Machine Learning (ML), Open Access and Robotics are currently seen as the means to solve some of the pressing problems in EU's health services, with the changing demographic curve and growing number of elderly and multimorbid citizens. AI and ML need big data sets to be trained on, which highlights the need to keep the focus on FAIR data, open data and the **European Health Data Space**. Furthermore, we need a focus on **ethical Open Access, AI, ML and Robotics** in order to keep the EU population's trust intact.

Working with big data is a growing trend among both health and technical researchers. This makes it necessary to implement **experimental studies for generation of trustworthy data**. Clinical intervention data need to be connected with observational studies and register data of all sorts. Furthermore, data protection needs more harmonisation across the EU in order to handle the issue of data owner versus data user.

There is a trend towards providing open access and developing open data policies. Despite being an increasingly accepted approach, it also raises a few questions which need to be addressed:

- How do users view open data? To whom is/should the data be open? Considering the **user perspective** is important.
- What approach should companies take regarding data? **Industry scientists** should be considered as users and not as owners of the data.
- Is there a need to reconsider the **business model of RIs**? The current model seems ineffective for the private sector's needs.

Indeed, the services provided by RIs can be useful also for private companies. There is increasing pressure to provide more services to the industries. This is a trend and also a gap in the case of governments not keen to support infrastructures towards this type of users. In these conditions, a **business model for services to the private sector** needs to be implemented.

The trends described above call for a cross-disciplinary, integrated and multiple level way of addressing scientific problems and questions. Indeed, while a more reductionist approach used to dominate in the past - one technique, one problem at a time - we are now moving towards a more complete, **integrated, multiple level way of addressing scientific problems** and questions.

More and more expertise is required for providing a complete range of services. All RIs started as equipment-based services, offering specialised access to instrumentation. Now they have evolved offering a **broad spectrum of services and expertise**, thus providing complete solutions to different problems. This is relevant to broaden the range of potential users to researchers who are not experts in a single technique. This is more and more relevant against fragmentation of research but requires extensive support.

A growing trend in healthcare and health research focuses on patient and citizen perspectives and involvement. **Citizen Science research** is a growing trend, alongside the development of research together with patients and users. The RIs in the EU may be increasingly prompted to develop these kinds of programmes by establishing focus groups, citizen advisory boards, and similar initiatives in the future.

Gaps and needs in the H&F domain are related to the governance and business models currently in place, as well as to the type of services that will have to be updated considering the challenges to be faced in the near future.

There are significant gaps to be filled and connections to be enabled. Those gaps and needs can be identified at various levels. To complete the landscape, it is important to connect efforts and build a natural link between the two complex medical and agriculture fields.

IMPROVE AND STRENGTHEN ALREADY ESTABLISHED ESFRI LANDMARK RIs

ESFRI Landmark RIs are at the crossroads of diverse demands. As they increase in size and importance, they face challenges in their organisation, management, and financing. Such hurdles threaten the RIs capabilities in expanding their innovation and service portfolios and meeting demands against rising societal challenges. The need to address these challenges has been identified by Landmarks themselves, requesting support from central and regional funding organisations. These challenges fall into the following themes:

- **Long-Term Sustainability.** Currently, the sustainability of RIs is not secured since it relies on stochastic income from various non-profit and profit organisations. On the other hand, the invaluable services that RIs offer have not been fully capitalised upon. Selective EU projects use RI services (e.g., via INFRA-SERV, INFRA-DEV, or more focused schemes). However, instruments that will **actively integrate RIs in large EU Projects and EU Missions** are needed to enhance the sustainability of the RIs and **balance income from profit vs. non-profit organisations**. An additional issue relates to differences in **national investments in support of the regional nodes** of the RIs. Despite the contribution of regional nodes in implementing policy and creating national growth and jobs, their support at the national level varies considerably across EU countries, yielding differences in capacities and capabilities.
- **Harmonisation of activities.** The distributive nature of most RIs depends upon the central coordination of complementary activities provided by different regional nodes. **Centrally coordinated instruments** are needed to (a) align all efforts in innovation and (b) harmonise services and activities (e.g., acquisition of common SOPs, costly service and protocol exchanges, position documents) for the provision of solid and efficient services. There has also been a tendency to develop and offer what can be seen as overlapping services. Rationalisation is therefore required, besides consolidation of services of the existing RIs.

- **Training of RI managers.** The successful long-term operations of RIs require a diversity of management skills that scientists cannot provide. RI managers need to acquire a **'service culture'**. To be effective, they should possess skill sets in scientific and organisational administration, personnel management, finance, policy and communication with stakeholders and policymakers. Moreover, they should be able to support inter-relationships between RIs in the same science domain and across domains. A strategic investment in training for RI management is needed to handle precious RI portfolios successfully.
- **Career paths for technical experts in biological, medical, and food research.** Careers in Research Infrastructures would be an alternative to the classical academic career. The latter is based on a fairly narrow definition of merit accumulation and therefore makes it very difficult for technical experts to forge an academic career. However, career paths for technical experts need to be developed (the issue is on the rise in several countries).

NEW SERVICES AND NEW RIs

As the research landscape has dynamically evolved in recent years, bringing new technologies and opening new fields in Health and Food, there is a growing need for new types of expertise and services to be provided by the existing RIs. Integrated RI services, or clustering research efforts among domain-oriented infrastructures, bring decisive advantages in the efficiency of services and translational research, creating a vital element of a functioning research and innovation system. This emerged from analysis of the landscape and should mainly result in recommendations to expand or consolidate the existing Landmarks but also on the possibilities of establishing new RIs.

In the Health domain, the COVID-19 pandemic underlined the role of several Landmark Life Science RIs and the importance of effective collaboration among RIs, relevant stakeholders, and user groups. It also revealed the need to identify synergies and build networks before crises, as it is very hard to set up new international collaborations during an emergency. In the case of Life Science and Health RIs, the issue is not if, but when the next health crisis will occur. Therefore, preparedness is essential, particularly for **communicable diseases**. There has been global progress in reducing disease burden due to several communicable diseases¹². However, additional emerging health threats such as acute threats to life deserve attention, highlighting health-system deficiencies wherever they occur.

Besides the emergence of new communicable threats, societal threats from **non-communicable diseases persist**. RIs have invested in genomic and proteomic profiling, single-cell analyses, ad-

¹² Institute for Health Metrics and Evaluation, Global Burden of Disease (2019). Processed by Our World in Data <https://ourworldindata.org/burden-of-disease>

vanced tissue imaging, exploring them both in models and in the clinical environment. Together with EU-projects which facilitate multivariate data gathering, these efforts already provide genetic, molecular, expression profiling, cellular underpinnings and specific biological mechanisms relevant to human disease. Similarly, RIs explore various innovations for developing genetic, cellular, and pharmacological therapeutics. However, as in the case of COVID-19, a more coordinated and targeted approach is needed to align the efforts towards effective therapies for non-communicable diseases in terms of development, preclinical testing and clinical application. An additional gap pertains to the relatively low level of investment in preclinical analysis of appropriate **non-animal models to complement animal models**.

An efficient, equitable, and sustainable approach to **Rare Disease research** is also needed to establish an integrated RI platform focused on developing links between rare disease researchers and efforts to replace or correct defective genes. Gene therapy approaches are still technically challenging and risky. However, several recent developments have made it more likely for gene therapy to become a clinical option for many rare diseases in the foreseeable future.

Overarching all these aspects is the need for further strengthening the possibility of performing **multinational clinical trials** in Europe, overcoming the **regulatory and legal barriers** among the European countries¹³. This would be particularly relevant for setting up and conducting clinical trials in Europe during crisis times. To this end it would be relevant to set up an ever-warm clinical trial network to ensure a baseline of continuous clinical trial activity across a wide and diverse range of trial sites, which allows for the rapid adaptation of the trial in case of an epidemic/pandemic¹⁴.

The exponential growth of **Artificial Intelligence, Deep Machine Learning** and similar methodologies, such as neural networks specifically applied to health research, requires expertise other than mathematics and digital. It should be taken into consideration how to include these emerging needs in the frame of the H&F RIs.

There is a need for a pan-EU approach on food and nutrition as well as in sustainable agriculture and bio-economy building. **In the H&F domain**, gaps exist in evaluating the **effect of nutrition and diets on animal and human health** to ensure more personalised safety approaches. Recommendations on food patterns related with healthy lifestyles, including in the elderly, require high quality population and interventional studies. Application of precision medicine strategies to adapt diets and nutrition to individuals also require a better effort of existing H&F RIs to improve the necessary tools to produce adequate evidence. These tools encompass, for instance, expertise in clinical studies design in nutrition, improvement in metabolomics standardisation and metabolite libraries, and microbiota subproducts. The increasing production and consumption of food supplements, along with natural products affected by climate changes, necessitate the

availability of more and improved analytical facilities. These facilities are crucial not only for quality control purposes but particularly for analysing biological samples. Presently, in the H&F domain, it is not clear which RI can expand by repositioning analytical services to accommodate nutrition and environmental sciences. For example, **Instruct-ERIC** possesses the expertise of applicable targeted and non-targeted metabolomics. **EU-OPENSREEN ERIC** has high capacities in the screening and chemical optimization of biomedical compounds and could consider expanding in providing similar services in environmental sciences. Similarly, **ECRIN ERIC** could provide expertise and tools for design and implement clinical studies in nutrition. The projects **EMPHASIS** and **METROFOOD-RI** could also be venues for combining nutrition and environmental studies.

In addition, an important gap identified is related to the **phenotyping of biotechnological improvements for animal farming systems** (livestock and fish), whose characterisation is not included within the EMPHASIS portfolio. EMPHASIS does not have the required infrastructure to develop phenotyping studies in animals. So, there is a need to further develop and enhance EMPHASIS capabilities for animal phenotyping studies, including fish species used in aquaculture. Alternatively, this need may be covered by a **new RI dedicated to animal farming studies**.

Considering the entire agro-food-value chain and its dependencies on the natural resources availability, there is a need to appraise **water cycle studies in ecosystems including agro-ecosystems**. Considering the increasing frequency of extreme climatic events, particularly drought and heat-waves, it is essential to focus more on water management studies to better determine the main components of water balance using state-of-the-art technologies in a coordinated effort¹⁵. In this sense, there is a need to develop a network for water studies infrastructures, including lysimeters, micro-meteorological instruments, and informatics facilities for modelling efforts using big data analysis and AI¹⁶. This could also allow better exploitation of the existing satellite data availability provided by the European Copernicus Earth Observation program.

CROSS-DOMAIN INTERACTIONS

Cross-domain aspects have already been identified. As such, they represent gaps and needs, which may justify specific expertise and further expansion of what is already available within the ESFRI context.

For example, a particular RI may be needed to facilitate response to emerging crises in both the Health and the Food domains. This could align efforts towards applying stable and efficient platforms (e.g., the Vaccelerate covering all the steps in vaccine development).

13. Accelerating Clinical Trials in the EU (ACT EU)
<https://www.ema.europa.eu/en/human-regulatory-overview/research-and-development/clinical-trials-human-medicines/accelerating-clinical-trials-eu-act-eu>

14. Report of the EMA/ETF workshop on Lessons Learned on Clinical Trials in Public Health Emergencies
https://www.ema.europa.eu/en/documents/report/report-emaetf-workshop-lessons-learned-clinical-trials-public-health-emergencies_en.pdf

15. Hering J.G. and Ingold K.M. (2012). "Water Resources Management: What Should Be Integrated?", Science, 336, pp. 1234-1235

16. Liang S. et al. (2010). "Review on Estimation of Land Surface Radiation and Energy Budgets From Ground Measurement, Remote Sensing and Model Simulation", IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 3:3, pp. 225-240. Doi: 10.1109/JSTARS.2010.2048556

*Global challenges require interdisciplinary approaches. Also, the EU's priorities call for cross-domain collaborations. The green and digital transition as well as resilient, inclusive and democratic societies require joint efforts from different fields. The recent crises – climate, geopolitical, pandemic – have stressed how intertwined different domains are. Climate change affects Health and Food production, while the agro-food domain has a strong impact on the environment, climate and energy supply. **Figure 4** shows the landscape of the H&F domain, including crucial RIs from other domains.*

DIGIT

The digital transition calls for the integration of digital technologies by researchers, companies and the public sector while taking their impact on society into account. Many sectors are directly affected by the digital transformation including health care and the agro-food sector. Therefore, the EC has initiated the European Health Data Space (EDHS)¹⁷, which responds to the need for further digitisation making health data accessible for citizens and research. Therefore, almost all ESFRI Landmarks from the Health and Food domain have strong connections to the DIGIT domain, building on new digital technologies, open data management, modelling and high-performance computing. **BBMRI-ERIC** and **ELIXIR**, along with the Project **EBRAINS**, are involved in the EDHS HealthData@EU Pilot¹⁸. **EMPHASIS** requires digital tools for the data analysis obtained in the phenotyping studies. Another example is the Horizon Europe project EOSC4Cancer¹⁹ in which **Instruct-ERIC**, **EU-OPENSOURCE ERIC**, **Euro-BioImaging ERIC**, **BBMRI-ERIC**, **EMBRC-ERIC**, **ECRIN ERIC**, **INFRAFRONTIER**, and **EATRIS ERIC** together contribute to the EOSC.

17. Regulation of the European Parliament and of the Council on the European Health Data Space 20220407-EHDS for Decide (003) (europa.eu)

18. EDHS HealthData@EU Pilot <https://ehds2pilot.eu/>

19. EOSC4Cancer <https://eosc4cancer.eu/>

PSE

Modern Life Sciences have been changed considerably by the development of novel technologies. High throughput and big data approaches are applied in many areas. Therefore, most H&F Landmarks are strongly related to Physical Science and Engineering, as they rely on new technological developments, for instance in the field of imaging, NMR, protein crystallisation and X-ray approaches, sensors, drones and satellites. Examples are **Euro-BioImaging ERIC**, **Instruct-ERIC**, **EMPHASIS** and **AnaEE-ERIC**, with the latter strongly relying on experimental modelling systems to better predict the impact of changing climatic conditions and related challenges on food systems, agricultural outputs and ecosystems.

ENV

Strong links exist between the H&F and the Environment domain. As climate change becomes increasingly apparent, the focus on the environmental impact on human health intensifies, as does the scrutiny of the effects of the health system on the environment. The effects of environmental and other factors on human health are the main focus of the recently established **EIRENE RI**. This RI supports interdisciplinary human exposome research bridging expertise across various

fields including environmental and analytical chemistry, biology and toxicology, environmental and human exposure and risk assessment, epidemiology, biostatistics, bioinformatics, pharmacokinetics, and geospatial modelling. Other examples showcasing cross-domain activities are **ELIXIR** and **EU-OPENSOURCE ERIC**. The former provides integrated bioinformatic resources not only for H&F, but also for environmental research; while the latter helps identify pharmaceuticals that are environmentally friendly. However, strongest synergies exist between the Food and ENV domain. **AnaEE-ERIC** and **EMPHASIS** intensively interact with infrastructures from the ENV domain such as **eLTER RI**, providing services for the identification of drivers for ecosystem change. They also interface with **ICOS ERIC**, providing high precision measurement on carbon cycle in agricultural systems and support for climate-smart agriculture; and, lastly, with **ACTRIS ERIC**, offering measurements of air quality parameters and extreme weather events and impact on agriculture. **MIRRI-ERIC** and **EMBRC-ERIC** closely collaborate with **DiSSCo**, all providing biological resources that can be used in health, food and environmental research.

ENE

Landmarks especially from the Food domain also exhibit synergies with the Energy domain. Bioenergy from crops and other plants but also from microbial and aquatic resources is addressed by **AnaEE-ERIC**, **EMBRC-ERIC** and **EMPHASIS**. Energy itself is also a primary resource for the agro-food-value chain where the Water-Energy-Food-Ecosystem Nexus (WEFE Nexus) approach needs to be considered and reinforced²⁰.

20. Mohtar R.H. et al. (2022). "Opportunities and Challenges for Establishing a Resource Nexus Community of Science and Practice". *Frontiers in Environmental Science*, 880754 Doi: 10.3389/fenvs.2022.880754

SSH

Health and nutrition are strongly influenced by social factors. To yield meaningful results, health parameters as well as nutrition, social and lifestyle factors have to be considered. Therefore, many RIs from the H&F domain synergize with SSH, for instance in the field of longitudinal studies and cohorts. Collaboration between RIs from both domains can be exemplified in the project BY COVID, aiming to provide comprehensive open data on SARS-CoV-2, and other infectious diseases across scientific, medical, public health and policy domains. BY COVID²¹ is benefitting from collaboration between **Instruct-ERIC**, **INFRAFRONTIER**, **ERINHA**, **ECRIN ERIC**, **EATRIS ERIC**, **EU-OPENSREEN ERIC**, **Euro-Biolmaging ERIC**, **BBMRI-ERIC** and **CESSDA ERIC**. Cross-domain effects are also visible when it comes to ethical, legal and social aspects with regards to sample and data management. Land use, including agriculture used for food- and non-food production as well as ecosystem services, has a strong influ-

²¹ BY COVID
<https://by-covid.org/>

ence on social aspects in rural areas. **MET-ROFOOD-RI**'s aim to promote metrology in food and nutrition has an important role to play in changing dietary behaviours, reformulating and addressing the impact of obesity and other diet related diseases on public health, as food is being recognised as one of the leading causes of ill-health and death.

Horizon Europe has funded several initiatives such as InfraServ, InfraEOSC, InfraDev to strengthen RIs and promote cross-RI and cross-domain actions. Further funding for such cross-domain RIs could encourage further collaboration, mirroring efforts like AgroServ, also funded under the Horizon Europe programme. This transdisciplinary project (2022-2027) aims to support the agroecology research community by encouraging the cross-fertilisation and inte-

gration of knowledge and services in a variety of fields such as agricultural sciences, natural sciences, biological sciences, ecology, forestry, fisheries, agronomy, etc.

However, there may be further scope to enhance the interaction and engagement of RIs from different domains. This collaboration is pivotal in effectively tackling grand challenges related to climate, environment, food and health, alongside those related to societal changes and digitalisation of human interactions. These challenges require input and collaboration from a diverse array of societal stakeholders, combining different sources of knowledge in new and useful ways. Particularly as various long-term challenges such as globalisation, pressure on natural resources, and an ageing population are intensifying.

Co-ordinated access to several services and technologies accelerates scientific progress and will enable Europe to be at the forefront of science advances, helping to implement EU strategies to address global challenges such as Corona Global Response, EU Green Deal, as well as the Sustainable Development Goals.

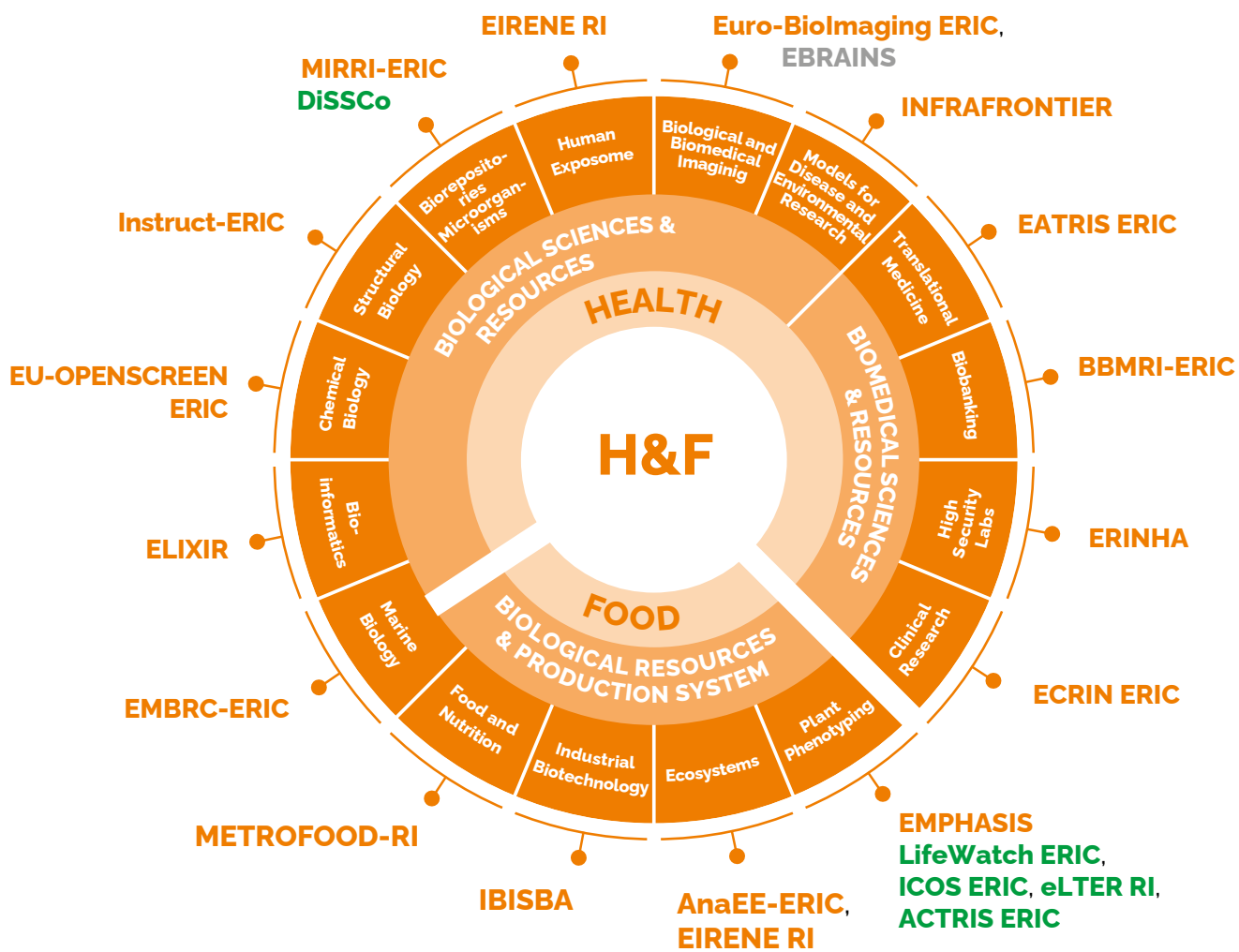


FIGURE 4.
The Landscape of the Health & Food domain



ESFRI LANDSCAPE ANALYSIS 2024 - SECTION 1

PHYSICAL SCIENCES AND ENGINEERING



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PHYSICAL SCIENCES & ENGINEERING

CURRENT STATUS IN THE DOMAIN 00

ASTRONOMY, ASTROPARTICLE PHYSICS AND SPACE SCIENCES

European Astronomy, Astroparticle Physics and Space Sciences continue to occupy a world-leading status as a result of a strong portfolio of intergovernmental, multi-national and national Research Infrastructures (RIs) available to the community. The community is strongly organised at the European and national levels, with two bodies dealing respectively with the Astronomy and Astrophysics and the Astroparticle Physics strategy, [ASTRONET](https://www.astronet-eu.org/)¹ and [APPEC](https://www.appec.org/)², which both started as an ERA-NET and are now self-sustained groups of funding agencies and associated bodies. Their main mission is encouraging a common science vision for all of European Astronomy, delivering a strategic plan and an infrastructure roadmap. In 2023, ASTRONET released The Science Vision and Infrastructure Roadmap 2022-2035³. The APPEC Consortium, which was created in 2012 following the preparatory work of the ASPERA ERA-NET, launched in January 2018 its European Astroparticle Physics Strategy

1. [ASTRONET](https://www.astronet-eu.org/), a planning and advisory network for European Astronomy <https://www.astronet-eu.org/>

2. APPEC, the Astroparticle Physics European Consortium <https://www.appec.org/>

3. A strategic plan for European Astronomy, Roadmap 2022-2035 https://www.astronet-eu.org/?page_id=521

2017-2026⁴ that was updated in September 2023. These European-level community-driven roadmaps, coupled with the planning processes convened by ESO and ESA, have provided strategic coherence and are still being implemented.

Ground-based telescopes continue to deliver new science. ESO's [Very Large Telescope/Interferometer](#) (VLT/I) is the world-standard, recently contributing to the 2020 Nobel Prize in Physics (research work on the Milky Way supermassive black hole Sgr A'), while the construction of the 39 m diameter Extremely Large Telescope ([ESFRI Landmark ELT](#)), is being pursued with first light expected in 2028. The [ALMA millimetre/sub millimetre array](#) in the Atacama Desert (Chile), the largest such facility in the world, is in full operation. The international [LOw Frequency ARray telescope](#) (LOFAR ERIC) and the [Joint Institute for](#)

4. European Astroparticle Physics Strategy 2017-2026 <https://www.appec.org/roadmap> and <https://www.appec.org/mid-term-review>

[VLBI ERIC](#) (JIVE) in the European Very Long Baseline Interferometry (VLBI) Network, are pathfinders for the [ESFRI Landmark SKAO](#) (Square Kilometre Array Observatory) and international infrastructures on their own. High-energy gamma-ray Cherenkov telescopes [HESS](#) and [MAGIC](#) developed the observation of TeV scale photon sources into a full-fledged Astronomy and are pathfinders for the [ESFRI Landmark CTAO](#) (Cherenkov Telescope Array). [EGO-Virgo](#), located near Pisa (Italy), is the present European contribution to the global network for gravitational waves observation, together with [LIGO](#) in US and [KAGRA](#) in Japan. In this field, the next generation ground-based infrastructure in Europe will be the Einstein Telescope ([ESFRI Project ET](#)) while, following the success of the LISA pathfinder ESA mission, the [Laser Interferometer Space Antenna](#) (LISA) will be the first space-based gravitational wave observatory. These facilities need to be complemented by a wider network of infrastructures that are aligned to future priorities.

Over the last decade, extraordinary progress has been achieved across all areas of Astronomy and Space Sciences research, drawing huge interest from the public and media as well as from the wider scientific community. Most Astronomy breakthroughs are actually triggered by technological advancements, improvements in computing methods and capabilities, and new theoretical ideas. This is especially true now, in this era of 'Big Science, Big Data'.

For example, our recent ability to use gravitational waves and high energy particles to probe the Universe, in combination with the full coverage of the electromagnetic spectrum, is enabling fundamental new

discoveries in areas from stellar Physics to Cosmology.

Fundamental questions in today's Astrophysics are:

- What is the nature of dark matter and dark energy?
- How to explain cosmic inflation in the very early Universe?
- Are there deviations from the standard theories and models (general relativity, cosmological model, standard model of Particle Physics)?
- What are the properties of the first stars, galaxies and black holes in the Universe?
- How do galaxies form and evolve, and how does the Milky Way fit in this context?
- What are the progenitors of astronomical transients?
- What physical and chemical processes control stellar evolution at all stages, from formation to death, and how?
- What are the necessary conditions for life to emerge and thrive? Are we alone?
- How do planets and planetary systems form and evolve?

- What is the impact of the Sun on the heliosphere and on planetary environments?
- What are/were the characteristics and habitability of various sites in the solar system, such as Mars or Jupiter's icy moons?
- What is the origin of cosmic rays of all energies?
- How can extreme astrophysical objects and processes probe new fundamental Physics?

The ESFRI infrastructures cover many of the required capabilities for the desired discoveries. [see Figure 1]

The **ESFRI Landmark ELT** (Extremely Large Telescope) is under construction by ESO in Chile with an expected technical 'first light' in 2028. This ~€1.5 billion project is funded by the ESO Member States and will deliver the **world's largest ground-based telescope operating in the optical and infrared wavelengths**. ESO's headquarters is in Germany. Most of the construction is led by European commercial contractors, together with significant academic leadership in the design and delivery of its scientific instruments. The ELT remains one of the highest priorities in European and national strategies for As-

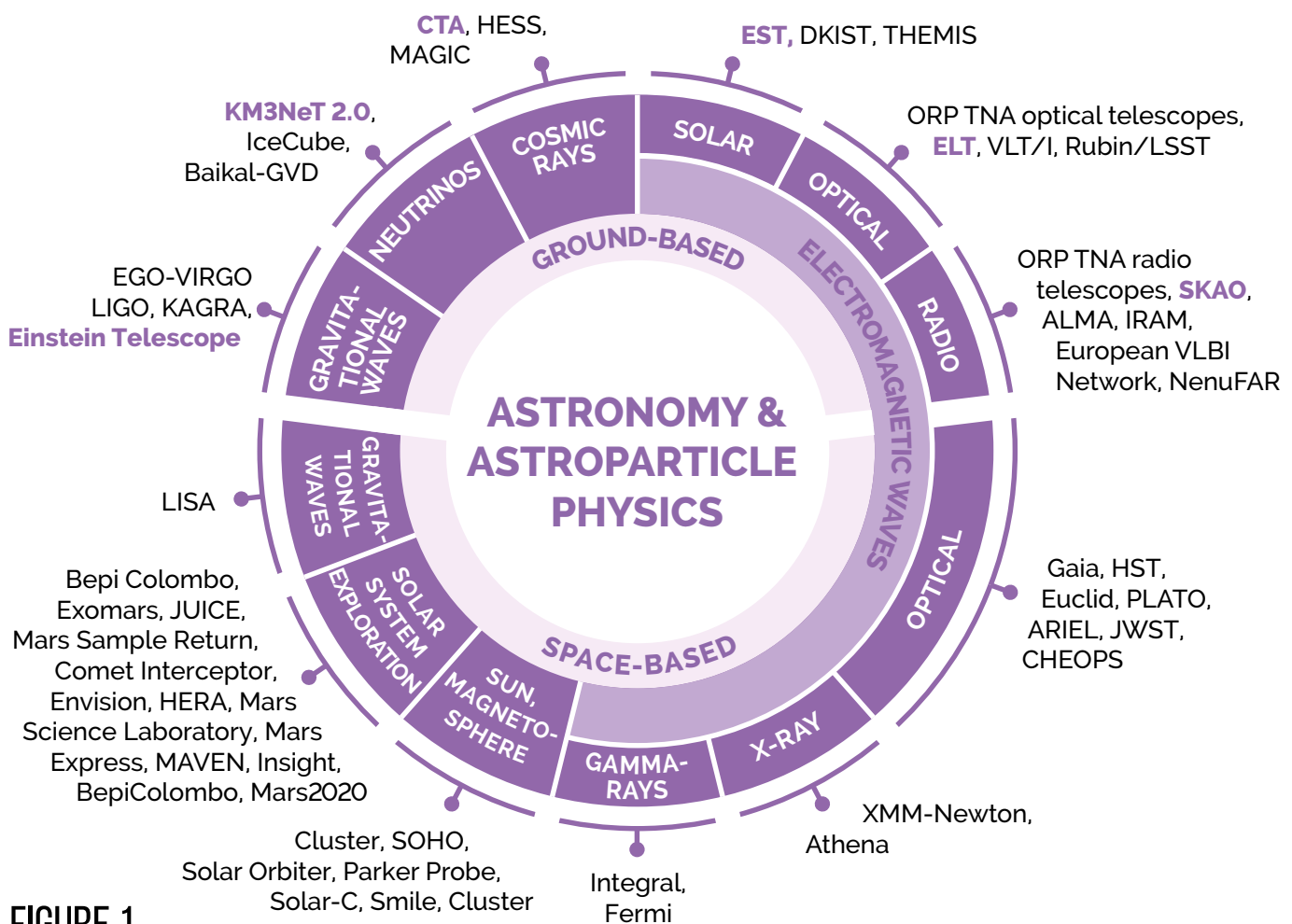


FIGURE 1.

The landscape of the Astronomy & Astroparticle Physics sub-domain

tronomy and will be delivering world-leading science into at least the 2050s. ELT science will benefit considerably from support and integration with facilities focusing on other wavelengths (radio, x-ray, gamma ray, etc.) and in space (JWST, Euclid, etc.).

The **ESFRI Landmark SKAO** (Square Kilometre Array Observatory) will deliver the **worlds' largest radioastronomy arrays** sited in South Africa and Australia later this decade, with a headquarters at Jodrell Bank in the UK. This new intergovernmental organisation has a global partnership which is still growing and includes significant financial and in-kind contributions from partners both within and outside Europe. Like the ELT, construction relies on a mix of commercial contractors and academic groups to deliver the mix of antennae and the computing capability. The total cost of the facility is currently around €2 billion, funded by its Member States. The science from the SKAO will also benefit considerably from integration with other wavelengths (optical, IR, x-ray, etc.) and other radio capabilities (for example the European VLBI network, JIVE ERIC, and LOFAR ERIC that is on-going its LOFAR 2.0 upgrades).

The **ESFRI Landmark CTAO** (Cherenkov Telescope Array Observatory, soon CTAO ERIC) is commencing construction in the Canary Islands and Chile and is expected to start operation in the next few years. It will **observe gamma-rays with energies from a few 10s of GeV to a few 100 TeV for the exploration of the extreme Universe**. The project expects to operate as an ERIC and has the support of a broad European partnership but includes some non-European interests. The CTAO is expected to open up new pathways in gamma ray science, with strong links to the programmes of both Astronomy and Astroparticle Physics.

The **ESFRI Project EST** (European Solar Telescope) is **expected to become a world-leading solar physics capability**, sited in the Canary Islands. Most of the development work to realise this 4m-diameter, adaptive optics controlled telescope has been completed, in part supported by EC funds. The partnership has recently formed a Canarian Foundation to progress towards an expected ERIC status for the construction phase. Its capabilities will complement those of the US-led DKIST facility in Hawaii and current and proposed space-missions targeting solar physics (Solar Orbiter, Solar-C, etc.).

The **ESFRI Project KM3Net 2.0** (KM3 Neutrino Telescope) underwater facility will hugely **advance our understanding of neutrino physics** and is currently taking data while completing construction. The large-volume telescope optimised for high-energy neutrino Astronomy (ARCA), and the dedicated detector to resolve the neutrino mass hierarchy (ORCA) have broad community support and are another example of a common interest between Astroparticle Physics and Astronomy.

The confirmation of the existence of gravitational waves and their sustained detection by facilities such as LIGO, EGO-Virgo and KAGRA has opened up this new field of Physics around understanding high energy events. Linked to this is the need for a **multi-messenger approach**, to combine information from a range of facilities to fully understand the physics behind observed events. The ESFRI Project ET (Einstein Telescope, ESFRI Project since 2021) is expected to be the next-generation European ground-based infrastruc-

ture, vital for progress in the **observation of gravitational waves**. Development and building partnerships are underway, and operation is expected starting by 2040. Gravitational wave science is a further example of a cross-over area with Astroparticle Physics and Particle and Nuclear Physics.

These new facilities under construction are fully aligned and complementary with the major upcoming missions in space (such as the study of dark energy via Euclid, launched in 2023, the study of exoplanets via PLATO and ARIEL, the study of gravitational waves via LISA, space exploration such as the proposed missions to the Moon and Mars). **Space-based observatories will require significant investment by European partners to secure leadership in missions led by ESA or in partnership with NASA, JAXA and other international space agencies**. Experimental facilities should be **completed by e-infrastructures** to cope with the rapidly developing Big Data capabilities of Machine Learning and Artificial Intelligence. Such networks of Research Infrastructures have been established (e.g. Opticon, Radionet, Europlanet) and are an essential part of the European Research Area. There is a long and successful European heritage here, and huge future potential across all areas of Astronomy, to include commercial return, computing and technology, training and outreach.

The last update of the ASTRONET Science Vision and Infrastructure Roadmap 2022-2035 prioritised facilities currently preparing for construction (CTAO, EST) and the development of a general purpose, wide-field, high multiplex, spectroscopic facility for a telescope of 8-10 metre class. One vision for this is the MSE (MaunaKea Spectroscopic Explorer), though at this time other concepts are being explored, at sites better aligned with European interests. This capability will help capitalise investments in JWST and Euclid in space but also the ELT and US-led, Vera Rubin Observatory (VRO) ground-based facilities. Continued support and development of the 4m-scale wide-field high multiplex spectroscopic facilities, including Weave and 4Most is also essential to ensure critical mass in this new capability.

On the Astroparticle Physics side, the last APPEC strategy 2023 update prioritised the ESFRI infrastructures CTAO, Einstein Telescope and KM3Net together with the Euclid mission, the upgrade of the Auger observatory and the continuation of double-beta decay and dark matter search experiments. APPEC also encourages the development of next-generation experiments to explore the Cosmic Microwave Background (CMB). Current projects with significant European involvement (such as the Simons Observatory in Chile) are seen to be the precursors to the next big facility, CMB-S4, to explore large-scale polarisation in parallel with space-based approaches (such as LiteBIRD, led by Japan but with ESA engagement).

Whilst inclusion within the ESFRI Roadmap is undoubtedly an advantage for many facilities, **Astronomy and Space Sciences also require a range of intermediary-scale capabilities to provide test beds, vital follow-up, broad community access** (where access to the largest capabilities is sometimes focused upon those who have contributed to their construction or operation, e.g. for SKAO) **and training**. Laboratory facilities and high performance and high throughput computing are also essential.

NUCLEAR AND PARTICLE PHYSICS

Today's research in Nuclear and Particle Physics requires infrastructures of a size and cost that can only be built and exploited through international cooperation and cost sharing. The main research directions and programs are designed and developed at the international level with very strong interactions within and among Europe, North America and Japan. But also, China, Korea and Russia are developing new complementary or competing facilities.

In Particle Physics, the discovery of the Brout-Englert-Higgs (BEH) boson in 2012 has opened a new research field. The BEH mechanism is of central importance to the Standard Model (SM) providing an explanation for the mass of the elementary particles and is at the same time its least understood ingredient. Many of the open questions of Particle Physics are related to this mechanism. The precise measurement of the properties of the BEH boson is of utmost importance to lead the way to a more complete understanding of nature. The exploration of the rich neutrino sector and the search for new particles and interactions, for example those thought to be responsible for dark matter, remains one of the priorities of Particle Physics. Other major areas of activity relate to the intensive and precise determination of the processes already observed, in particular in the 'electroweak' and 'flavour' sectors, in order to discover any deviations from the predictions of the standard model, which would signal 'new Physics'.

CERN is the European laboratory for Particle Physics with a recognized worldwide leading role in the field. CERN operates the Large Hadron Collider (LHC) as well as fixed target experiments and installations for developing and testing new detectors and accelerators. The LHC restarted in 2022 for a period of 4 years (Run3) after its second long technical shutdown (LS2) which lasted an additional year due to the COVID crisis. The successful completion of the LHC high-luminosity upgrade (ESFRI Landmark HL-LHC) remains the focal point of European Particle Physics. The installation of the accelerator equipment and the major upgrade of the ATLAS and CMS experiments will take place during the next long technical shutdown (LS3, 2026 to 2028). The HL-

LHC will then be in operation until 2041 and will continue to be the reference infrastructure for the discipline worldwide, including for the study of flavour physics (with LHCb) and the quark-gluon plasma (with ALICE). It will increase the amount of data collected tenfold, offering increased sensitivity to the tests of the Standard Model and the possible discovery of new Physics.

The European Strategy for Particle Physics (ESPP)⁵ was updated in 2020 and recommended an electron-positron Higgs factory as the highest-priority next collider. For the longer term, the European Particle Physics community has the ambition to operate a proton-proton collider at the highest achievable energy. On this basis, a feasibility study for a new flagship accelerator at CERN has been launched and is currently converging towards a new collider (called FCC, Future Circular Collider) located in a 91 km tunnel extending from CERN near Geneva and south towards Annecy in France. Such a machine would, if realised, start out as a Higgs factory (FCC-ee) around 2048. It could later be upgraded in the same tunnel to proton and heavy-ion collisions (FCC-hh) covering the energy frontier from around 2070 until the end of the century. A concrete recommendation on FCC is expected for the next upgrade of the European Strategy for Particle Physics by 2027. In parallel, studies of alternative scenarios based on linear electron-positron colliders (CLIC, ILC) or on the promising but technically highly challenging muon collider continue to be explored. The realisation of at least one of these colliders at CERN is required to secure Europe's continued leading role in Particle Physics, to elucidate the role of

5. 2020 Update of the European Strategy for Particle Physics
<https://cds.cern.ch/record/2721370>

the Higgs boson and the BEH mechanism beyond the capabilities of the HL-LHC, and to continue the exploration of nature at the energy frontier. It should be noted that China is working on a competing program similar to that of the FCC (an electron-positron collider, CEPC, possibly also followed by a proton-proton collider, SPPC).

In the field of particle accelerators, the challenge is to achieve higher energies and higher intensities that allow access to new or rare physical phenomena, but also improved energy efficiency. Research focuses, in particular, on the improvement of high-current sources and injectors, on the design of high-field superconducting magnets (whose development is crucial for FCC-hh), on the improvement of accelerator gradients (e.g. through better control of the surface states of superconducting radio frequency cavities) and on the development of the ERL (Energy Recovery Linacs) technology. To achieve very high field gradients (> 1 GV/m), new techniques exploiting plasma wakefield acceleration are being explored. The ESFRI Project EuPRAXIA aims at the construction of the worldwide first multi-GeV plasma-based accelerators (laser-driven and beam-driven) with industrial beam quality and user areas. Beam-driven wakefield acceleration is also explored at CERN in the AWAKE project. An Accelerator R&D Roadmap⁶ gathering all these topics has been developed and released in 2022 to focus and coordinate the effort at the European level.

Future Particle Physics will require new detector technologies with higher spatial resolution, ultra-precise timing measurements, and more on-detector intelligence. Novel detectors such as quantum sensors will improve the capabilities and open up new opportunities for applications such as medical imaging or photon science. ECFA, the European Committee for Future Accelerators, is an important forum for exchange on these detector technologies developments and has published in 2021 a dedicated R&D Roadmap⁷. Large-scale da-

6. European Strategy for Particle Physics, Accelerator R&D Roadmap
<https://arxiv.org/abs/2201.07895>

7. The 2021 ECFA detector R&D Roadmap

ta-intensive software and computing infrastructures are also an essential ingredient to the Particle Physics research programme, with major challenges ahead in view of the exploitation of the HL-LHC which will require coordinated R&D efforts.

After more than six decades of experimental and theoretical studies, neutrinos remain enigmatic particles. Their non-vanishing mass not only challenges the completeness of the Standard Model but also has a measurable effect, due to the relic Big Bang neutrinos, on the evolution of the largest structures of the Universe. Unlike the other fermions, their mass might not be generated through interactions with the Higgs boson. Moreover, neutrinos offer a potential solution to the problem of the lack of antimatter in the universe, and sterile neutrinos are a potential candidate for dark matter.

The exploration of neutrinos' fundamental properties requires dedicated infrastructures and experiments, which either produce them using accelerators (long-baseline experiments like T2K and the future Hyper-Kamiokande in Japan, or LBNF-DUNE in the US), nuclear reactors (like JUNO in China), or through their observation from nuclear double-beta decays in underground facilities (e.g. SuperNEMO at the LSM in France, or CUPID at the LNGS in Italy) or as atmospheric and cosmic radiation (like in KM3NeT 2.0, cf. Astrophysics section). Europe's main strategy in the field is to continue to support long baseline experiments in Japan and the United States. Accelerator-based study of neutrinos is one of the present priorities of the US⁸, which is developing the DUNE experiment (based on neutrino beams produced in FNAL, Chicago, and sent to an underground detection facility in a mine in South Dakota) to study the phenomenon of neutrino oscillations. There is a strong collaboration between Europe (including CERN through the Neutrino Platform) and the US around this project, both around the DUNE detectors (e.g. liquid-Ar TPCs) and on the Fermilab PIP-II accelerator upgrade.

Searching for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new Physics. This can be done in many ways, for example through precision measurements of flavour physics (like at LHCb at CERN, for which an upgrade is under discussion, or at the Belle-II experiment in Japan, as well as charged-lepton flavour experiments at PSI, FNAL and in Japan), of electric or magnetic dipole moments (e.g. the muon program at PSI), and searches for axions, dark sector candidates and feebly interacting particles. There are striking similarities between the search for neutrinos properties and the search for the nature of dark matter, with theoretical motivations for unresolved questions spanning from Particle Physics through Nuclear Physics. The range of probed masses and possible (very weak) interaction types of cosmic dark matter with ground-based detectors is extremely wide, but some scenarios are being aggressively pursued globally. Chief among them currently is the search for the signature of a massive \geq GeV but weakly interacting particle (WIMP) of cosmic origin, observed directly in large detectors located deeply underground like at the LNGS with the XENON experiment, or indirectly through self-annihilating in cosmic dark matter clusters) or

<https://cds.cern.ch/record/2784893>

8. See Report of the 2023 Particle Physics Project Prioritization Panel, "Pathways to Innovation and Discovery in Particle Physics" (draft) <https://www.usparticlephysics.org/2023-p5-report/>

produced directly at colliders such as the LHC. Theorised particles as light as 10^{-9} eV, such as axions, have however gained attraction over the past decade, requiring very different detection techniques. The identification of the nature of dark matter and getting a better grasp of the physics associated with the neutrino, are major science drivers for the coming decade.

The strategy for the development of Nuclear Physics in Europe is provided by the Nuclear Physics European Collaboration Committee (NuPECC) in its 2017 Long Range Plan (LRP)⁹ and in the ongoing LRP update to be published in 2024. Nuclear Physics is composed of a broad spectrum of sub-fields including hadron physics, strongly interacting matter at extreme conditions, nuclear structure and reactions, nuclear astrophysics, fundamental interactions and symmetries as well as applications of nuclear science. All these sub-fields extensively exploit several large-scale and more than 15 smaller-scale infrastructures in Europe. The main science drivers are as follows:

- To understand the structure and the origin of the properties of hadrons;
- To pursue the exploration of the nuclear matter phase diagram;
- To explore the limits of stability of nuclear systems and evolution of nuclear structure across the nuclear landscape;
- To understand the origin of elements and how nuclear processes shape the Universe;
- To contribute to the development of new nuclear science technologies for societal applications.

High-energy Nuclear Physics, i.e. relativistic heavy-ion physics at the energy frontier (up to 5 A.TeV centre of mass energy), has progressed towards unprecedented precision understanding of the Quark Gluon Plasma (QGP), based on the dedicated ALICE detector operating at CERN-LHC, but also with significant programs at the other LHC detectors (ATLAS, CMS and recently also LHCb) and at RHIC in the US (sPHENIX and STAR detectors). The ALICE detector has recently (2020-2022) undergone a major upgrade enabling continuous data readout and thus data collection and readout increased by about a factor of 100. An extensive proposal for a new ALICE-3 detector based on large extent on monolithic ultra-thin Si inside a new superconducting magnet (to be eventually deployed around 2034) and a new forward calorimeter (FOCAL) focused on searching for experimental evidence for the Colour Glass Condensate (CGC) from 2029.

At lower beam energies, the ESFRI Landmark FAIR (Facility for Antiproton and Ion Research), in construction in Germany, is developing a dedicated heavy-ion detector (CBM, Compressed Baryonic Matter) targeting the search for the critical point of nuclear matter at energies between 8 and 45 A.GeV, using beams from the future SIS100 synchrotron.

9. NuPECC LRP 2017 – Perspectives in Nuclear Physics <https://www.nupecc.org/pub/lrp17/lrp2017.pdf>

The diverse field of hadron physics requires a multitude of experimental facilities, either dedicated hadron physics experiments or multi-purpose experiments in neighbouring research fields. The most important from the existing facilities and experiments in Europe are AMBER at CERN, and MESA in Mainz, Germany. The future flagship experiment in Europe is expected to be PANDA at FAIR. The European hadron physics community is also involved in the experimental programs at Jefferson Laboratory in USA, Belle II in Japan, BES III in China as well as in the design and construction of the new EIC (Electron-Ion Collider) project in Brookhaven, USA.

The field of low-energy nuclear physics is undergoing an important transformation based on results obtained at existing facilities such as GANIL in France, GSI-FAIR in Germany, ISOLDE at CERN, JYFL in Finland and LNL & LNS in Italy. These results have motivated very ambitious efforts worldwide to produce and study exotic nuclei using Radioactive Nuclear Beams (RIB). Without forgetting the worldwide RIB facilities in Japan, USA, Canada, China and Korea, the European roadmap is mainly based on FAIR and **ESFRI Landmark SPIRAL2**. FAIR and GANIL-SPIRAL2 exploit **two different and complementary methods to produce radioactive beams**.

FAIR will deliver high-energy beams of heavy-ions and will have an unrivalled potential to produce exotic nuclei far from stability lighter than uranium (NUclear STructure, Astrophysics and Reactions – NUSTAR programme). GANIL-SPIRAL2 directly produces exotic nuclei, which can then be re-accelerated into high optical quality, high intensity, and lower energy beams for precision measurements as well as very heavy nuclei heavier than uranium. The GANIL-SPIRAL2, ISOLDE and JYFL today, SPES at LNL and ISOL@MYRRHA in the future, will provide precision measurements complementary to those performed with energetic FAIR beams.

While the first experiments with the FAIR detectors available at existing GSI accelerators have been successfully recording data since 2018 as part of the FAIR 'Phase-0' program, the actual beginning of operation of the 'First Science' phase of the FAIR infrastructure is scheduled for 2028. It will include the start of the NUSTAR and APPA (Atomic, Plasma Physics & Applications) programmes plus possibly the CBM experiment. GANIL, which started the operation of its new superconducting linear accelerator in 2019, will see the full deployment of the phase 1 of its upgrade project, SPIRAL2, by 2030. Phase 1 of SPIRAL2 includes experimental areas with three

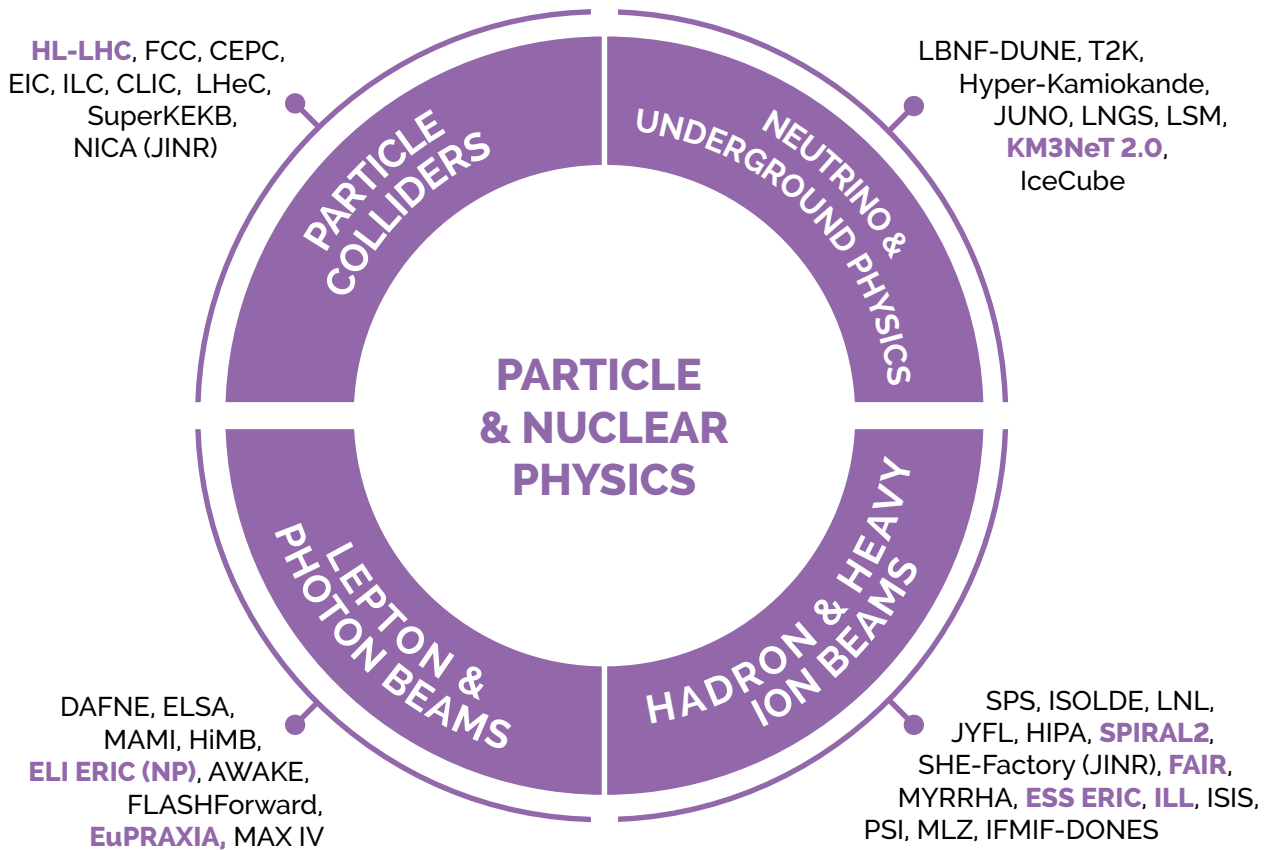


FIGURE 2.
The landscape of the Particle & Nuclear Physics sub-domain

halls for experiments, respectively with a high flux of fast neutrons (Neutrons for Science, NFS), with very high intensity beams of heavy ions (Super Separator Spectrometer, S3) and with low energy exotic nuclei (DESIR) produced at S3 and with the existing SPIRAL1 facility. While NFS is operational, S3 is scheduled to begin exploitation in 2025. DESIR started its construction in 2023 and the first experiments are planned from 2027. The construction of a new injector for the SPIRAL2 linear accelerator, called NEWGAIN, is planned to extend the range of available high intensity beams to uranium by 2028.

One of the three pillars of the **Extreme Light Infrastructure**¹⁰, namely ELI-Nuclear Physics (ELI-NP) in Romania, is the most advanced research facility in the field of photonuclear physics, a new interdisciplinary research field which brings together **high-power lasers and nuclear physics**. The facility includes the highest power (10 PW) operational laser system in the world and begun its broad scientific program in 2020 while continuing the construction of its gamma beam facility.

10. See Analytical Physics section.

AGATA (Advanced GAMMA Tracking Array) is a new and original mobile RI for nuclear structure Physics and Astrophysics. AGATA is a European collaborative project to build and operate a new type of ultra-pure Germanium gamma ray multi-detector, based on the concept of gamma ray tracking. It reveals the **structure of the nucleus under extreme experimental conditions**, whether with relativistic beams at FAIR or with the lower energy exotic beams of GANIL and SPES-LNL. AGATA will be used in these European infrastructures, illustrating their complementary nature.

The range of neutron facilities operating concurrently also supports distinct Nuclear Physics and Astrophysics user groups with their unique needs and objectives. Nuclear Physics research using 'slow' neutrons and the production of radionuclides for research and cancer treatment is concentrated on the **ESFRI Landmark ILL** (Laue Langevin Institute), a European flagship facility, located in Grenoble. The capacity of high flux neutron time-of-flight measurements will be augmented over the longer term by complementing the present flagship facilities **n_TOF** at CERN and **NFS** at GANIL with the new facility, **ESFRI Project IFMIF-DO-NES** planned in Spain. In Lund, Sweden, the

ESFRI Landmark ESS (European Spallation Source) is being constructed (see section on Analytical Facilities).

The Gran Sasso National Laboratory (**LNGS**), the largest underground laboratory in the world devoted to neutrino and astroparticle physics, is also of particular importance for nuclear astrophysics. It offers the most advanced underground infrastructure in terms of dimensions, complexity and completeness. For the last 30 years, research in nuclear astrophysics has been carried out by the LUNA Collaboration at LNGS. The collaboration plans to install a new **LUNA 400-kV accelerator** at LNGS.

Finally, the European Centre for Theoretical Studies in Nuclear Physics and Related Areas (**ECT***) in Trento, Italy, is a globally recognised international research infrastructure in theoretical Nuclear Physics and related areas. Since its inception in 1993, ECT* attracts participants from around the world and is supported by numerous European countries and European framework programs.

For an overview of ESFRI and non-ESFRI RIs in the Particle and Nuclear Physics sub-domain, see **Figure 2**.

ANALYTICAL PHYSICS

Analytical Physics (AP) infrastructures [see Figure 3] enable the research on the quantum properties of atomic matter by exploiting the interaction of particle and photon beams with material samples in standard or extreme conditions of pressure, temperature and external fields. By definition, this field is transverse and multidisciplinary; it thus concerns most fields of fundamental or applied scientific research (Materials Science, Biology, Chemistry, Physics, Geology, Health, Heritage Science...).

Through AP exploitation, key questions like understanding the relationships between the functionality and properties of matter and its atomic structure and dynamics down to attosecond and quantum scale, studying proteins to unravel the complex mechanisms of living organisms or engineering new materials with unprecedented properties can be addressed. The long-term vision shared by the network of AP in-

frastructures is to contribute to solving the grand societal challenges (digital and green transition, healthy society, climate change...) by exploring frontiers of fundamental and applied scientific research.

A non-exhaustive list of research fields driven by science and applications in the field of Analytical Physics and corresponding examples is:

- Inventing new, more targeted medicines by determining three-dimensional structures of biological molecules;
- Finding effective treatments for cancer based on studies using neutron rich isotopes;
- Creating new functional and optimised materials including topological materials (2016 Nobel prize);
- Novel devices for quantum information processing for future microelectronics;
- Improving energy management and generation through improving fuel cells, batteries and laser fusion processes;
- Contributing to the production of healthier food through detailed understanding of interaction with soils;

- Addressing environment and climate challenges through developing better catalysts for chemical processes and study of aging of building materials;
- Temporal analysis of processes down to the attosecond scale for understanding better enzyme catalysed reactions in cells;
- Preserving cultural heritage by analysing artefacts like historical paintings and scrolls;
- Understanding the physics inside of planets and exploring fundamental symmetries in fundamental Particle Physics.

To maintain the scientific excellence of the AP infrastructures over their wide range of applications, continuous upgrade by developing innovative solutions and pushing the boundaries of the current technologies is mandatory. This is especially true to successfully tackle the challenges of the AP field, that is achieving higher brilliance, higher temporal and spatial resolution, routinely running *in situ* and *in operando* experiments and making available the most advanced detector technology.

The extremely wide portfolio of matter probes available at the European AP infrastructures, coupled to continuous upgrading plans, represents a formidable asset for the positioning of European research. In order to more efficiently pursue scientific

ically focused goals by exploitation of the wide range of services available at the AP RIs, the Analytical Research Infrastructures in Europe (ARIE¹¹) consortium has been established, which collects seven European Research Infrastructure (RI) consortia representing about 120 national and international research facilities, including all the thematic ESFRI Projects and Landmarks. The seven networks are: (1) the League for European Accelerator based Photon Sources (LEAPS¹²), which brings together the European accelerator based light sources; (2) the European Distributed REsearch In-

11. ARIE consortium
<https://arie-eu.org/>

12. LEAPS
<https://leaps-initiative.eu/>

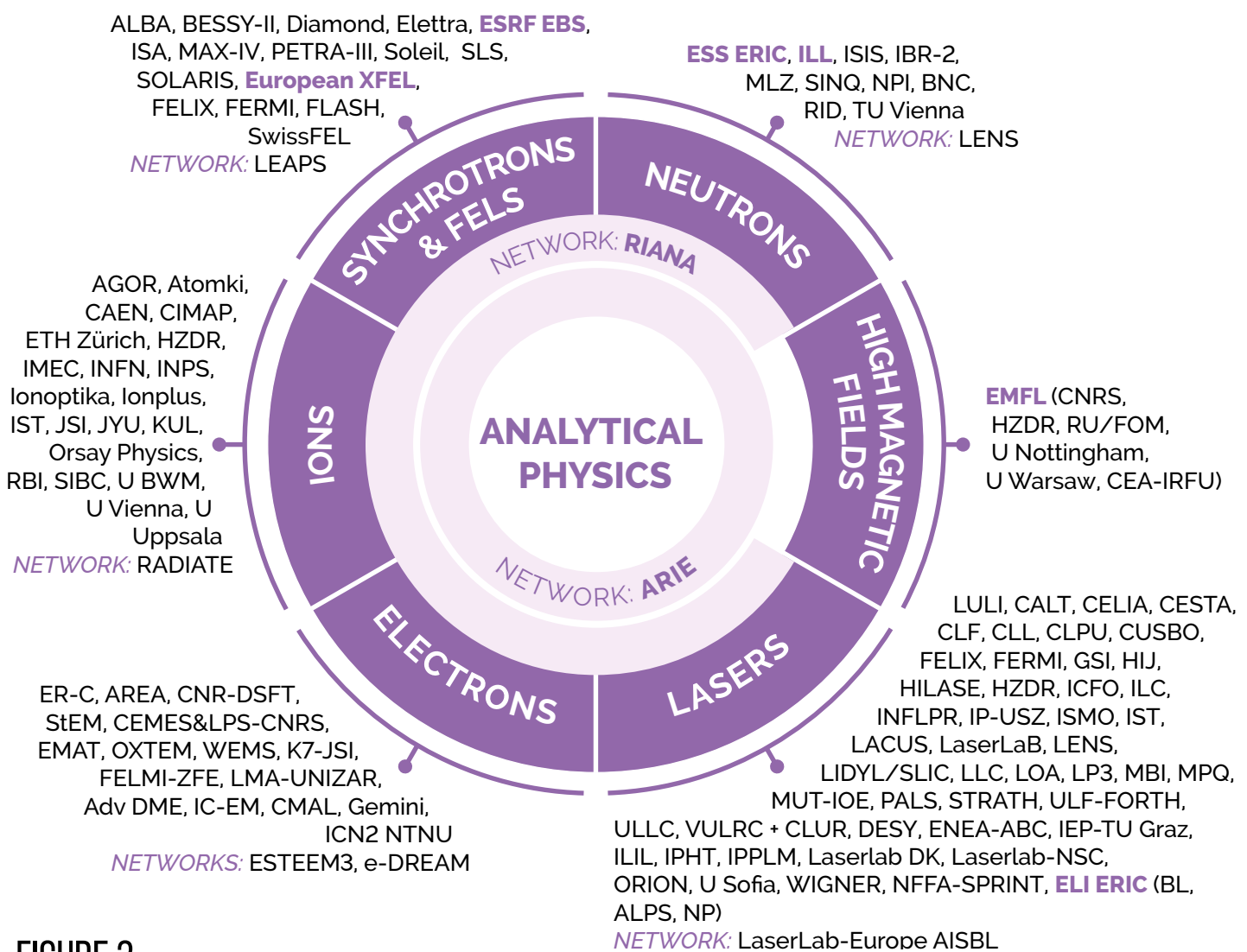


FIGURE 3.

The landscape of the Analytical Physics sub-domain

frastructure for Advanced Electron Microscopy (e-DREAM¹³), which collects the major actors in electron microscopy; (3) Laser-Lab-Europe¹⁴, which coordinates the laser infrastructures; (4) the League of advanced European Neutron Sources (LENS¹⁵), which includes the neutron facilities; (5) the **ESFRI Landmark EMFL**, encompassing the high magnetic field facilities; (6) INSPIRE for the proton facilities; and (7) RADIATE for the ion facilities. As a joint effort, the networks thrive to **create common tools for data, expand user communities, advance the technologies, and access models including industrial use.**

Photon beams are generated by the globally widest array of electron storage rings and linear accelerator-based free electron lasers. These light sources are gathered at the European level in the LEAPS consortium, which comprises 16 organisations representing 19 light source facilities across Europe. LEAPS has produced **strategy roadmaps** that encourage the development of new technologies and should keep the European RIs at the highest level of competitiveness. These LEAPS strategic roadmaps are executed as part of a coupled open innovation effort with industry stakeholders who will be able to expand their product portfolios and markets.

The global landscape of synchrotron sources consists of some fifty synchrotron radiation centres worldwide, only three of which being 'high-energy': ESRF (European Synchrotron Radiation Facility, Grenoble, France) at 6 GeV, APS (Argonne, USA) at 7 GeV and SPring8 (Japan) at 8 GeV. In Europe, the **user community**, estimated to around **30.000 researchers**, can access to **12 synchrotrons in operation** (including UK and Switzerland), all being national facilities except ESRF which is an international infrastructure gathering 13 member states, broadly acknowledged as the best performing facility.

High brilliance from the soft to the hard X-rays has expanded the impact of analyt-

ical facilities by enabling high resolution, chemical contrast, imaging in domains from the nanostructured materials to the Life Sciences and to the natural and cultural heritage. The major technological evolution of synchrotron light sources today consists in **integrating the Multi-Bend Achromats (MBA) technology**, initiated at MAX-IV in Sweden, **into the storage ring**. A reduction of a factor of 10 to 100 in the horizontal emittance of the electron beam is then obtained (down to the diffraction limit), which is accompanied by a gain in the brightness of the light produced by the same factor, as well as an improvement in its coherence. These new performances, in addition to reducing the duration of experiments and therefore increasing access possibilities, open up **new fields of application with previously unattainable spatial resolutions and acquisition times**, particularly for experiments carried out in situ or in operando.

ESRF, which was the first 3rd generation synchrotron to arise in 1994, successfully implemented such an upgrade in the recent years (**ESFRI Landmark ESRF-EBS**, Extremely Brilliant Source, ESFRI Landmark since 2018) has become, since the restart of beam operation in 2020, the **first 4th generation high-energy synchrotron**. In the near future, all excellent European synchrotron radiation centres will be upgrading their accelerators using this MBA technology. Such upgrade programs are already starting in several of them (e.g. SLS in Switzerland, ELETTRA in Italy, DIAMOND in UK, SOLEIL in France).

Femto-second (fs) time resolution is obtained at advanced academic laser laboratories, offering Research Infrastructure services as well as at dedicated facilities like the **free electron lasers (FEL)** across the electromagnetic spectrum with Seeded or SASE (Self Amplified Stimulated Emission) amplification mode. FELs offer unprecedented performance for studying the **electronic, structural and dynamic properties of matter at the atomic scale**, addressing fs dynamics of molecules, proteins, clusters and solids by means of advanced pump-probe scattering and spectroscopy experiments. The **ESFRI Landmark European XFEL**, inaugurated in September 2017, has 7 instruments in full operation. It is one of the most intense coherent X-ray sources in the world along with the LCLS and forthcoming MHz facilities such as the LCLS II

at Stanford (US) and the SHINE at Shanghai (China). The FLASH facility in DESY (Hamburg), which served as a pilot facility for the European XFEL, also provides ultrashort pulses in soft X-rays. All those facilities are based on SASE amplification of radiation pulses and use superconducting accelerator technology. FEL sources based on normal-conducting accelerator technology are also available for European users, such as the Swiss-FEL (SASE) for hard X-rays or the world-unique seeded-source facility FERMI@Elettra operating in the soft-X-rays region. Since 2012, this facility enables ultrafast spectroscopy and imaging experiments for a broad international community.

FEL science will expand in the next decade as the availability of specialised, engineered, light pulses will be exploited in many domains of science, beyond the experimental demonstration phase of recent years. **New scientific instrumentation, upgrades and experimental setups will further enable experiments in emerging fields by exploiting non-linear spectroscopy methods and approaching attosecond science.** European users will be in an excellent position to exploit FEL sources also thanks to the synergy with advanced laser facilities and their networks as well as with nanoscale-matter characterisation facilities that support the design of ultrafast time domain experiments.

Laser Research Infrastructures in Europe are coordinated through the Laserlab-Europe AISBL network, which comprises 47 leading laser Research Infrastructures in 22 European countries. The majority of the members provide open access to their facilities, through a centralised access-managing system. They enable experiments in a large variety of inter-disciplinary research, covering advanced laser science and applications in most domains of research and technology. The **ESFRI Landmark ELI ERIC** (Extreme Light Infrastructure) has entered the operation phase. ELI ERIC and ELI-NP¹⁶ are jointly launching users calls since 2022, for the three sites with complementary capabilities: (i) ELI-Beamlines, for new laser-plasma accelerators delivering particles and photon sources at extremely high energies; (ii) ELI-ALPS, for the generation of ultrashort light pulses down to the

13. e-DREAM
<https://e-dream-eu.org/>

14. LaserLab
<https://www.laserlab-europe.eu/>

15. LENS
<https://lens-initiative.org/>

16. Negotiations for the accession of Romania, which is hosting ELI-NP, as member of ELI ERIC are ongoing.

attosecond time domain with applications in atomic and molecular Physics; (iii) ELI-NP, for nuclear photonics applications with petawatt-class laser systems and a brilliant gamma-ray source. The ELI ERIC infrastructure combines cutting-edge technologies, installation size, and project costs that are unthinkable at the scale of a laboratory. ELI ERIC should then be the gateway to new regimes in fundamental research and foster new laser technologies (technology transfer and innovation). With plasma physics, generation of radiation sources or particle beams and light-matter interaction, the laser facilities make it possible to address major scientific questions in Physics today either in the **high-energy-density regime (HDE)** or at **ultra-high intensities in the relativistic regime (UHI)**. Recently the European Laser Science and Technology Landscape and Roadmap has been published as a joint report of Laserlab-Europe and ELI.

Neutron radiation is used to study and characterise the **properties and behaviour of condensed matter, from the atomic to the macroscopic scale, on time scales ranging from 10-12 to 1 s**. Based on the specificities of the neutron-matter interaction (high penetration in matter, magnetic interaction, sensitivity to light atoms in particular to hydrogen and its isotopes, energy and wavelength close to those of the excitations and relaxations encountered in matter...), it is a powerful and unique tool in a wide range of fundamental research fields, in particular in condensed matter and chemistry. The most intense neutron beams are produced either in a **nuclear research reactor** or by the **spallation reaction**, the principle of which is based on the interaction of a very high-energy proton beam with a metal target, the neutrons being produced during the decay of the target atoms. Nuclear reactors produce continuous thermalized neutron fluxes ($1 \text{ meV} < E < 150 \text{ meV}$) while spallation sources produce pulsed beams over a very wide energy range, and with high peak intensity (while the time-integrated intensity is generally lower than in a reactor).

Europe has enjoyed a world leading position in neutron radiation, with nearly 6000 regular users of neutron sources in all disciplines, representing **more than half of the world's users**. However, since the last decade, the European neutron facilities landscape shows a clear decrease in the overall supply due to the progressive shutdown of

nuclear reactors, most of them dating from the 1970s. This will only be partially offset by the **ESFRI Landmark European Spallation Source (ESS)**, currently under construction in Lund (Sweden). ESS is now based on a 2 MW proton accelerator and will install 15 instruments in its initial phase (the original baseline was 5 MW and 22 instruments). It is expected to start up in 2027 and, after some years of ramp-up and possible upgrades, should become the world's most powerful neutron source. By the end of the 2020s, Europe's main other neutron sources are expected to be the **ESFRI Landmark Laue-Langevin Institute (ILL, Grenoble)** and **FRM2 (MLZ, Munich)** reactors, as well as the **ISIS (STFC Rutherford Appleton Laboratory, UK)** and the **SINQ (Paul Scherrer Institute, Switzerland)** spallation sources. The operation of the international ILL facility, whose 58 MW high-flux reactor started up in 1971 and produces the **most intense continuous beams of neutrons in the world**, is meant to be **phased with the ramping-up and full operation of the ESS**.

In 2022, the **LENS** consortium, gathering the ten European-level research facilities in the field, published *Neutron Science in Europe*, an analysis of the current landscape and future opportunities for neutron facilities. The priority for LENS, in the hypothesis where the ILL reactor stops operation in the 2030s, is therefore to fully develop the full capabilities of the ESS (up to 35 instruments) while ensuring funding for the optimal exploitation of the large national facilities FRM2 (Germany), ISIS (UK) and SINQ (Switzerland), including upgrades (like ISIS II) or extension of their instrument suites. It would be also important to provide an overall joint strategy to match the operation schedule of the ILL with the ramping up to full 5 MW operation of the ESS, and to further develop the new **High-Current Accelerator-driven Neutron Source compact concept (HiCANS)** which needs a demonstrator soon. An interesting and structuring initiative of LENS is to study the possibilities of optimisation by further integration of their activities in a more formal consortium, 'European Laboratory for Neutron Scattering'.

In the AP RIs landscape, **transmission electron microscopy (TEM)** provides advanced characterisation techniques to investigate **structural and chemical properties of materials with sub-Angstrom lateral resolution and meV energy resolution**, which finds

application in a wide range of disciplines from Physics to Materials Technology, Engineering, Chemistry and Life Sciences. Europe's expertise in electron microscopy is distributed across different scientific sectors, with often regional funding, and a limited international structuring. There are over 100 high-end Electron Microscopy (EM) instruments in Europe with 15 leading laboratories and some SMEs that had formed the networked infrastructure **ESTEEM3** to provide access to state-of-the-art TEM instrumentation and methods for industry and academy. The current state of the technique shows rapid technological developments and an increased access demand to advanced TEM instrumentation, beyond what is sustainable at laboratory scale. Also, there is a clear **user request for fully interoperable experimental approaches** that have the potential to couple correlative, multi-modal and multi-scale experiments with complementary techniques like X-rays, ion beams and optical techniques-based experiments, as is currently explored in the **IMPRESS** project. Within the ARIE network, the **e-DREAM** consortium was formed in 2021 to promote cooperation between European advanced electron microscopy laboratories, collaborative research and transnational user programmes. It supports the European electron microscopy and works closely alongside the ESTEEM3 project, the **European Microscopy Society**, and other RIs like **ESFRI Landmark Instruct-ERIC** supporting the use of **cryo-EM for structural biology applications**.

Ion beam analysis techniques provide unique information on the depth-dependent chemical composition, defects and impurities. Ion beams also provide information about the age and origin of geological, archaeological, and cultural heritage samples. Other applications are in the atomic scale modification of materials. Implantation of radioactive ion beams (e.g. at **ISOLDE, CERN**) into a sample, followed by the detection of the emitted radioactive decay products, provides unique information about the structural and functional properties of the host lattice and form a bridge to Nuclear Physics research.

Infrastructures that develop and operate **very high magnetic field facilities** are also more and more essential for research in Materials, Engineering and Life Sciences. These distributed infrastructures usually

gather diverse analytical scientific instrumentation dedicated to physical measurements under intense fields (like NMR typically), often performed in combination with very low temperatures. The **ESFRI Landmark Instruct-ERIC** is an emblematic example in the Life Science domain. In the field of extremely high magnetic fields research, activities in Europe are organised under EMFL (European infrastructure European Magnetic Field Laboratory), with a common user access program, outreach, training, and technical developments. The EMFL, based on three laboratories, has the objective of **exploring exceptional magnetic fields** with, in particular, very **high stability and spatial homogeneity**. All EMFL facilities have recently been fully renewed or upgraded, are internationally competitive and have complementary specificities.

The optimal usage of the ESFRI and national portfolio of analytical facilities is also crucially supported by distributed resources which provide irradiation facilities, nanoscience laboratories, atomic resolution imaging facilities, high energy and time resolution fine-analysis methods, and advanced computation codes with HPC support.

The integrated/distributed AP Research Infrastructures enable European scientists to perform state-of-the-art research directly exploiting the synergy between the large-scale AP RIs and the highly specialised resources from academic research laboratories of national dimension. In the last decade the European Commission has also favoured consolidating distributed infrastructures like **NFFA-Europe** in the field of nanoscience and nano-microtechnology (a pan-European consortium of 22 international partners) or the **RADIATE** project (a consortium of 26 ion beam centres). These Research Infrastructures are in the process of evolving towards established legal entities to warrant long-term operation. The European landscape of research in Matter Physics is made unique also by established **agreements among the major national Research Performing Organisations** to enforce open access for integrated research proposals that merge with the advanced usage of the large radiation sources, to develop **complex metadata schemes for expanding the FAIR-data productivity across complementary methods and techniques**.

SERVICES IN THE DOMAIN

In the domain of Physical Sciences & Engineering (PSE), the time to develop a new project is in the order of 5-10 years for operation typically lasting several decades. It should be noted that the roadmaps of the different fields address goals and priorities reaching well into the 2030s and often much longer. Since the last Landscape Analysis in 2021, there has been little evolution in the services and trends, especially as the Research Infrastructures have had to recover from the COVID years, have been confronted with inflation (soaring energy prices) as well as the consequences of the Russian invasion of Ukraine, which unfortunately also limits scientific exchange and cooperation. Nevertheless the AP facilities have shown a high degree of resilience developing alternative remote access protocols and virtual access services that feed into the EOSC technology.

ESFRI Research Infrastructure services in PSE encompass a wide range of capabilities and resources that support fundamental and applied research and experimentation. The main common services offered by the Research Infrastructures in the PSE domain are as follows.

- **Access to the facilities** – Open access to state-of-the-art research facilities by all researchers (e.g. through Transnational Access (TA) including Virtual Access (VA) funding from the EU's framework programmes) is a unique strength of the current European ecosystem of RIs, yielding excellent scientific results. The number of TA users in PSE fields stays at a high level and the demand for services is significant. However, due to cuts in funding for TA in fundamental research in Horizon Europe, a significant decrease is to be expected. The EU should again provide adequate support and match the demand, as TA funding is unique and cannot be substituted through national programmes.
- **Experimental support** – Research Infrastructures provide expert support and advice in the planning, execution and analysis of experiments, including training of users in these services. In addition to the facilities and platforms for experimentation, they usually provide the experimental setup, calibration and data acquisition. Experienced staff and technicians are available to ensure smooth operation and meet technical challenges. This is especially the case for analytical Research Infrastructures with a high percentage of unexperienced users from other scientific areas or from the industry.
- **Data management and analysis** – Research Infrastructures provide services and tools for data management, storage and analysis. Given the large volumes of data generated by modern PSE experiments, which often challenge the limits of existing e-infrastructures, infrastructures provide more and more data processing solutions, data repositories and computing resources to facilitate data analysis and access to the users. The increasingly important role of the **European Open Science Cloud** (EOSC) for Research Infrastructures, providing services for open research data, is also worth noting. The EOSC will indeed establish as a federation of the most advanced FAIR data and FAIR service solutions already operational, among which those of the ESFRI RIs and other advanced RIs will play a key role. The development and adoption of common standards, protocols, and best practices to enable the integration of data and services, is ongoing in projects like **ESCAPE** and **PANOSC**, increasingly allowing users to combine and analyse data from different sources. The HE project **OSCARS** is meant to reach out all scientific clusters and community in developing elements of the EOSC and pursuing a coherent effort in open data and FAIR data services.

- **Networking and collaboration** – Research Infrastructures promote networking and collaboration between users and institutes. Examples are RadioNet, ARIE, LEAPS, LENS or Laserlab among many others. This often entails offering common services, such as Very Long Baseline Interferometry in radioastronomy, common access points for users and common developments. Cooperation often goes beyond Physical Sciences & Engineering alone (e.g. with the fields of **Energy**, **Environment**, **Health & Food**...), increasing the impact of the facilities. As an example, ARIE represents more than 100 different RIs that support the work of more than 40,000 researchers from academia and industry in a wide range of fields including medicine, health, food and cultural heritage (**Social Sciences & Humanities**). Another example is the recent innovation platform HI-ACTS (Helmholtz Innovation Platform for Accelerator-Based Technologies & Solutions) which aims at making accelerator-based technologies specifically accessible for industrial and medical applications. Moreover, Research Infrastructures organise conferences, workshops and user meetings to bring scientists together and promote the exchange of ideas, expertise and knowledge. Collaboration tools and platforms are often provided to facilitate remote collaboration between users.
- **Open access and dissemination** – ESFRI infrastructures promote open access to research results and encourage the dissemination of scientific knowledge (open data and science). They can provide platforms for publishing research results, hosting scientific databases and sharing experimental data with

the wider scientific community. SCOAP3 is a successful example of how open access publication has been realised in the field of Particle Physics. Research Infrastructures have a key role to play in engaging the general public and inspiring the next generation of scientists, with subjects such as Astronomy and Cosmology recognised as a draw for STEM (Science, Technology, Engineering and Mathematics) subjects. Public and schools' access to facilities is offered through open days, 'researchers' night' and festivals and many RIs have very successful schools and teacher training programmes. Promoting results through media and social media channels can lead to worldwide attention. Consider, as an example, the image of the shadow of the black hole in M87 (made using a global network of telescopes).

- **Innovation and technology transfer** – More and more Research Infrastructures in the PSE domain offer Knowledge Transfer (KT) and Technology Transfer (TT) services, CERN and **ESRF** being emblematic examples. Through these services, they increasingly collaborate with industrial partners, promoting technology transfer and enabling the development of spin-off companies based on the research results.
- **Proprietary access and support for industry** – Analytical infrastructures, such as **ILL** and **ESRF**, generally offer specific support for users from industry, advising them on proprietary access, collaborations, technology transfer as well as on available EU or national funding.

The impact of Research Infrastructures is fundamental for the knowledge triangle, i.e. research, education and innovation. Overall, ESFRI Research Infrastructures in PSE play a vital role in pushing the frontiers of knowledge, fostering collaborations, stimulating technological advances and contributing to societal and economic development. They remain essential pillars of scientific research and innovation in Europe and beyond. In order to find solutions to current crises and anticipate future ones,

it will clearly be important to learn from existing or recent crises, such as the COVID-19-pandemic, Russia's war of aggression against Ukraine and the severe impact of the energy supply and cost, in order to secure and further reinforce the European research infrastructure landscape. Under these circumstances, it is remarkable how resilient European Research Infrastructures have been.

In spite of the three aforementioned crises, European Research Infrastructures have been able to broaden their accessibility, increase their sustainability, and thus help boost their impact in addressing local and global challenges.

IMPACT ON SCIENCE AND EDUCATION

By providing access to state-of-the-art facilities, equipment and technologies, Research Infrastructures enable scientists to conduct ground-breaking research. They facilitate experiments and investigations that contribute to exploring new frontiers of knowledge and advancing our understanding of the Universe. Key questions that the PSE Research Infrastructures help to answer for the progress of human knowledge are as follows.

- What is the origin of the Universe and its constituents from smallest to the largest and how did they evolve to their present form? Is there a unified theory of the forces of nature?
- What are the conditions that enable life and is there life outside Earth?
- What is the nature of dark matter and dark energy and what is their connection to Physics beyond the Standard Model of Particle Physics?
- What are the relationships between the functionality and properties of materials and their atomic structure and dynamics?
- How to engineer new materials with unprecedented properties?

Answering these questions underpins the vision of scientific research in the PSE domain and defines the basic mission of the PSE Research Infrastructures. Moreover, many Research Infrastructures, and particularly those in the field of Analytical Physics, are multidisciplinary by nature, attracting users from a variety of scientific fields. Collaboration between physicists, chemists, biologists, materials scientists and other disciplines is increasingly encouraged and even incentivised in the approval of equipment usage times. Encouraging this **interdisciplinary and transnational approach**, including through funding in the EU's framework programme, is gen-

erating innovations in the priority areas of green and digital transitions as well as Horizon Europe missions.

Research Infrastructures also offer **training programmes, workshops and schools** to improve the skills and knowledge of scientists and researchers. They ensure training to PhD students in science, developing thus a specific skill set for students coming from different domain and shareholder countries. These students are able to bring this knowledge and skill set back to their communities and use them as well as pass these on to others and acting as multipliers. **Research Infrastructures should also take care of training research managers** and incorporate them to the RI strategy and operations.

SOCIETAL AND ECONOMIC IMPACTS

The societal and economic impact of discovering and understanding the laws of nature and thus of frontier research has been always immense. This is evident throughout history of science and has impacted all fields of technology, such as micro-electronics, electromagnetic waves, nuclear medicine or nuclear fission and fusion among others. To generate more research results translating into direct applications and societal impact, Research Infrastructures of the ESFRI landscape are increasingly open to **collaborations between academia and industry**. For example, research in Materials Science is stronger directed towards development of new materials with improved properties, while research in Astronomy and Particle and Nuclear Physics contributes to medical instrumentation and advances in cancer and other diagnostics and treatments. Fundamental and applied research in Physics are also playing an important role in the development of carbon free sources of energy.

Most of the PSE Research Infrastructures contribute scientific outputs to address the main societal challenges defined through priority areas (such as Europe fit for the Digital Age) and through the five missions of Horizon Europe. These include Adaptation to Cli-

mate Change, Cancer, and 100 Climate-Neutral and Smart Cities. They are also aligned with the UN Sustainable Development Goals (SDGs), such as: Good Health and Well-being (SDG 3), search and use of Affordable and Clean Energy (SDG 7), Decent Work and Economic Growth (SDG 8), Industry, Innovation and Infrastructure (SDG 9), Climate Action (SDG 13) and Partnership for the Goals (SDG 17). A small selection of examples for the contribution of PSE Research Infrastructures to these societal challenges are:

- Material Science and Engineering for batteries, solar energy, spaceflight applications, power lasers for laser fusion, hydrogen systems;
- Materials for low power electronic, processing of big data volumes and data compression;
- Optical and radar technologies for atmospheric sensing;
- Imaging technologies, sensors, diagnostics, radio-isotopes, radio and ion therapy in medicine;
- Enhanced international access to RIs particularly through the TA programme in Horizon Europe.

In order to speed up the contributions made with regard to this goal, increasing efforts take place to support technology development and innovation within Research Infrastructures and in their ecosystems, including the development of **common test protocols and industrial standards**. The constant development of accelerators, detectors, data acquisition and analysis push the limits of technology, the technologies developed by RIs being often shared and transferred to other RIs. These innovations are of course mainly targeted and benefiting fundamental research, but also find applications in other fields, such as **Health, Energy**, Materials Science, etc. The European Commission has defined **Key Enabling Technologies** (KETs), which provide the basis for innovation in a range of products across all industrial sectors. Technology development in Research Infrastructures overlaps with KETs like photonics, advanced materials, nanotechnology, micro and nanoelectronics, and advanced manufacturing technologies. Many Research Infrastructures are technological leaders in their field and in order to maintain this leadership role, they need to actively develop new technologies often in collaboration with industry. This innovating R&D can result

in attracting business and creating spin-offs based on the key technologies for relevant high tech, sciences and life & health sectors.

DEVELOPMENT OF THE EUROPEAN RESEARCH AREA

PSE Research Infrastructures contribute to the actions proposed by **European Research Area (ERA) Policy Agenda** for the period 2022-2024, including:

- ERA Action 1: Enabling open sharing of knowledge and the re-use of research outputs, including through the development of the **European Open Science Cloud** (EOSC);
- ERA Action 4: Promoting attractive and sustainable research careers, balanced talent circulation and international, transdisciplinary and inter-sectoral mobility across the ERA;
- ERA Action 5: Promoting gender equality and fostering inclusiveness, taking note of the Ljubljana Declaration;
- ERA Action 8: Strengthening sustainability, accessibility and resilience of Research Infrastructures in the ERA;
- ERA Action 9: Promoting a positive environment and level playing for international cooperation based on reciprocity;
- ERA Action 12: Making EU R&I missions and partnerships key contributors to ERA;
- ERA Action 12: Accelerate the green/digital transition of Europe's key industrial ecosystems;
- ERA Action 13: Empowering higher education institutions to develop in line with the ERA, and in synergy with the European Education Area;
- ERA Action 14: Bringing science closer to citizens;
- ERA Action 16: Improve EU-wide access to excellence.

In the last two years, sustainability has become an even more central concern in Research Infrastructures, especially with the explosion in energy costs, inflation and procurement costs. There is an increasing emphasis on **minimising environmental impact, reducing carbon footprint and energy consumption, and adopting green technologies**. Efforts are being made; CERN, for instance, has been publishing a yearly Environment Report since 2020, outlining the organisation's commitment to becoming a role model for environmentally responsible research and setting out concrete objectives for environmental stewardship. The on-going efforts will need to be intensified to develop energy efficient designs, use decarbonized energy sources and implement environmental footprint practices throughout the RI life cycle of infrastructure (sober use of materials, recycling, reuse and waste management). It is also worth noting the tendency of RIs to transfer the technologies developed in the design of their facilities to society in the broad field of energy and environment.

Another major recent evolution has occurred for the PSE Research Infrastructures since the COVID period: the development of **novel remote access, virtual access methodologies and technologies, and distributed data analysis**. Similarly, for operations that take place outside normal working hours, systems have been developed to allow staff to access instruments and data remotely. Consideration is being given in many infrastructures to extending remote access to users. This will require a significant change in facility staffing levels. The risk of impact on training, expertise and user engagement will also need to be carefully assessed. The trend is towards technical systems that allow more users to participate, some in person and some remotely.

Physics research is increasingly generating huge amounts of data, requiring advanced data management, storage and analysis capabilities. PSE Research Infrastructures are in the process of adapting to **meet the challenges of Big Data and provide efficient data management plans, including data processing systems, high-performance computing resources, data analysis tools** but also **FAIRness of data, curation and archiving capabilities**. The role of the **European Open Science Cloud (EOSC)** in centralised data management will be crucial in the future, as EOSC's central objective is to facilitate the access, sharing and re-use of scientific data on a European scale.

As highlighted in the previous section, all PSE Research Infrastructures are increasingly committed to contribute, through their scientific outputs and associated applications, to addressing emerging societal challenges. They contribute massively to this effort, with a focus on environmental and climate challenges, innovative materials and sustainable economy, clean energy transition or health innovation. In this latter field, they have been deeply engaged, in a coordinated way, in effectively studying, understanding and contributing solutions to the **COVID-19 pandemic**, including new drugs, therapeutic strategies and medical equipment developments. Emblematic examples in this health innovation field are the

CERN-MEDICIS, which produces innovative radioisotopes since 2017 for **cancer treatment research**, and the recent contribution of the **ESRF** to the 'Human Organ Atlas'.

Naturally, Research Infrastructures are constantly **improving their instrumentation capabilities** to enable more accurate measurements, higher sensitivities, and new techniques. This includes the development of advanced detectors, ultrafast lasers, high-resolution imaging technologies and new particle and radiation sources.

In the **Astrophysics** area, astronomers continuously attempt to expand the knowledge and search beyond the limits. **New instruments are needed to enhance their sensitivity and allow the detection of fainter cosmic objects**, with more angular and spectral resolution and rapid response to study the transient Universe. Bigger telescopes (e.g. **ELT, CTAO**), interferometers (e.g. **SKAO**), gravitational wave observatories (e.g. **Einstein Telescope, LISA**) and neutrino detectors (e.g. **KM3Net**) will fulfill these ambitions. They will provide improved capabilities in a wide variety of cosmic signals, opening the path to the full development of multi-messenger and multi-wavelength Astrophysics. In this respect, the coordination between the different Research Infrastructures will become more and more important for the benefit of a complete solution of astrophysical problems.

In the **Particle and Nuclear Physics** area, the trend is to push towards **next-generation detectors** but also towards **more powerful particle accelerators**, requiring higher energy, intensity and efficiency. The technologies under consideration encompass high-field magnets including high-temperature superconductors, but also plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, Energy Recovery Linacs. These innovative accelerator technologies are also a powerful driver for the many accelerator-based fields of science and industry. Leading technologies based on superconducting radio-frequency cavities for example are today being used in the latest generation light sources (e.g. **European XFEL**) and neutron sources (e.g. **ESS**). Continued R&D for future accelerators in Particle and Nuclear Physics is essential for the development of techniques and technologies for future Research Infrastructures, as illustrated by the on-going present dissemination of the **ESRF's Extremely Brilliant Source** technology, which is willing to be applied in 19 synchrotrons worldwide (7 in Europe). The structured development of general R&D on accelerators is well coordinated and promoted by the **Test Infrastructure and Accelerator Research Area (TIARA)** European consortium, who acts in close connection with **CERN** and the two leagues **LEAPS** and **LENS**.

In the **Analytical Physics** area, the complexity of research on quantum materials and the living matter does impose the **large-scale analytical facilities** to optimise their offer and to actively interface with the most advanced sample synthesis and control methods available at the medium scale facilities, supported by the EC, which are often unique and state of the art installations. Efforts to develop

complementarity and synergy between electron microscopy, ultra-fast lasers, *in situ* synthesis with growth of samples in controlled conditions (materials engineering) and theoretical work that exploits advanced open codes and HPC resources, are pursued by established **distributed infrastructures** and by schemes of **combined access** to the large-scale infrastructures represented by EU-wide consortia. These developments enable transdisciplinary and interdisciplinary research to be carried out with the most specialised methods and techniques built for fundamental science.

The trend to **strengthen collaboration between Research Infrastructures in Europe** is well illustrated by the recent formation of the **ARIE** consortium for analytical research (see section A), the **ORP** (Opticon RadioNet Pilot) project for ground-based Astronomy and **Space Neons**, a recent network of RIs dedicated to Astronomy and Space Science, which facilitate transnational access to infrastructures. This trend is further supported by several collaborative projects to also **develop common technologies and best practices** for various infrastructures. The **EURO-LABS** (European Laboratories for Accelerator Based Science) project aims to bring together, for the first time, the research communities of Nuclear Physics, accelerator and detector technologies for high-energy Physics, in a pioneering

super-community of subatomic scientists (network of 47 Research Infrastructures, including 3 virtual-access RIs). Another example is the **I-FAST** project that has been instrumental in recent years in strengthening Europe's competitiveness in accelerator technologies by fostering innovation, cutting-edge research and technology transfer to industry. Another interesting case is the **ATTRACT** (A Technology TRansfer pilot for European Advanced Technology) initiative, which aims to support the transformation of breakthrough ideas in the wide fields of sensing and imaging into innovative technologies with societal and economic impact, with the aim to promote their transfer to the market. The ATTRACT consortium gathers several large European Research Infrastructures like CERN, EMBL, ESO, ESRF, European XFEL and **ILL**. Smaller thematic infrastructures, inherently distributed and multidimensional (including highly specialised academic laboratories, large clean room facilities, and large fine-analysis installations), have the potential to evolve into more structured and integrated organisations. An example is the **CERIC ERIC** model in Material and Life Science, where 8 EU countries share their multidisciplinary analytical facilities in open access. Such models have the potential to extend PSE resources and methods to other fields of research, such as Life Sciences.

GAPS AND NEEDS IN THE DOMAIN

In the PSE domain, Europe is presently at the forefront of research with world-leading Research Infrastructures like **CERN**, **ESO**, **ESRF**, **ILL**, **European XFEL** or **ELI**, and soon **ESS**, **FAIR**, **CTAO**, **SKAO** and hopefully **Einstein Telescope**, as well as with human exploration and permanent bases on the Moon and Mars. Nevertheless, Europe must remain vigilant to ensure that it has the means to maintain this leadership. In this perspective, some principal gaps and needs are identified below.

Over the last few decades, with the commissioning of the LHC in 2008 and the concomitant shutdown of the Fermilab Tevatron in the United States in 2011, CERN has consolidated its position as the undisputed world leader in the field of high-energy Physics. Since then, there is a worldwide tacit understanding that the **global effort in Particle Physics at the energy frontier should focus on CERN facilities** while **America and Asia** should deal with the main experiments at the **intensity frontier**, in particular the long baseline neutrino facilities. Some long-term initiatives are nevertheless explored in Europe in this field, e.g. in the **ESSnuSB** project. In order to keep this leadership in the future, Europe and CERN need to schedule as soon as possible the future machine to be hosted at CERN after the completion of the **HL-LHC** programme, which is supposed to end in the early 2040s. On the basis of the priorities identified by the Particle Physics community (see section A), the proposed reference scenario is the **Future Circular Collider**, with an electron-positron Higgs and electroweak factory as a first stage (FCC-ee) followed by a discovery hadron collider with a centre-of-mass energy of at least 100 TeV (FCC-hh). This scenario, which arose from Japan's in-

decision since 2013 to embark on its ILC Higgs-factory project, will be scrutinised in the coming years for a possible decision in 2028.

Further theoretical research covering the full spectrum of Particle Physics should also be intensified, fostering links with Cosmology, Astroparticle Physics, and Nuclear Physics. This might open alternative pathways to **new approaches towards revealing the nature of dark energy and dark matter**. On this respect, another gap to be addressed is a ton-scale neutrinoless double beta decay experiment, which might be located in Europe and/or in Canada and is among the priorities of the US and European neutrino communities.

Another potential future gap to be underlined concerns the **neutron scattering landscape**. As underlined by the **LENS** consortium in its Neutron Science in Europe 2022 document, the world-leading ecosystem of neutron facilities in Europe has been created by decades of investment, but the landscape is now undergoing major changes. Many of the national reactor-based sources have closed, reducing European experimental capacity in the 2030s (when ILL is likely to reach the end of its operation) to around 60% of that available in 2019. At the same time, the world's most innovative countries beyond Europe are planning to bolster their capacity and capability in this sphere. Some of these losses will be mitigated by the European Spallation Source and by the further development of existing sources. However, although ESS will be the most powerful neutron source in the world once fully operational, it will initially provide less than half the current capacity of ILL. The only route for entirely new facilities with significant capacity are **High Current Ac-**

accelerator-driven Neutron Sources (Hi-CANS), which could occupy the role played by national reactor-based sources in the past. Designs need to be demonstrated in practice through the realisation of an operational facility of this type.

More generally, to keep its world-leading position in the PSE domain, **Europe needs to secure adequate and sustainable funding for the proper operation, maintenance and development of Research Infrastructures**. Many PSE RIs require significant financial resources, with construction costs sometimes at the multi-billion-euro level (e.g. ESS and FAIR presently), and it is essential to secure funding of the whole PSE portfolio in the long run. Ensuring the **education and training of new generations of technical and scientific staff** is also crucial, as well as providing incentives for increased staff mobility between Research Infrastructures to allow the exchange of skills and foster collaborations between teams, institutions, and countries, which is a great tool for diplomacy. **Administrative and legal procedures** especially for the establishment of ERICs need to be streamlined and better adapted to the accession of international members and organisations.

The **on-going war in Ukraine** represents an additional risk and a source of concern, which could possibly lead to additional gaps and needs. Besides the generic side effects like the rise of inflation, the volatility of energy prices or the difficulties in the supply of some scientific equipment or fluids (e.g. semiconductors, helium), several PSE research domains have been particularly impacted by the **freeze of the scientific collaborations with Russia**. This is the case for Nuclear Physics, for which the **JINR** in Dubna was a major partner, providing enriched rare stable isotopes for many European Research Infrastructures in the field. The war has also led to the sudden loss of European access to Russian space launch capacity, adding on already existing restrictions on Europe's independent launch capacity. The impact on CERN, whose Council decided to conclude cooperation with Russia and Belarus in 2024, is also severe with multiple impacts being mitigated on budgets, human resources and available expertise. In 2024, **Russia is still a funding shareholder of ESRF, European XFEL** (through the Kurchatov Institute) and FAIR (through ROSATOM), but **without Russian scientists and experts benefiting of proper access to these facilities**. Even if contingency plans are being put in place, this unstable situation is

likely to jeopardise the operation model of these infrastructures in the upcoming years.

In most of the PSE Research Infrastructures, the original science case often evolves in substantial ways during the long life-time of the facility, requiring significant updates towards next-generation instruments. Preparing for such upgrades necessitates the implementation of continuous and lively dedicated R&D programmes. In this area, even if Horizon Europe is supporting rather well such programmes in a transverse way, there is presently a **lack of funding opportunities to support specific high-budget R&D projects** (from several million euros to several tens of millions of euros) specifically targeting the development of large-scale pioneering technological demonstrators or innovative scientific instruments (e.g. high efficiency, high repetition rate, high-power lasers, high-temperature superconducting magnets, energy recovery linac technology, next-generation optics for telescopes, beyond state-of-the-art detectors...). This gap should be addressed.

To encourage the establishment of **public-private partnerships** for innovative developments, it would be opportune to make European industry more aware of the opportunities and synergies offered by the PSE Research Infrastructures. The **BSBF** (Big Science Business Forum) events, which aim to promote collaboration between large scientific Research Infrastructures and industry, are a step in this direction. Another possible route for innovation would be to further **promote the exchange of staff** between universities, national research institutes, Research Infrastructures and industry to increase cross-fertilisation and foster mutual trust and effective engagement.

Finally, sustainability, including environmental impact and energy consumption, has become a central and crucial issue for all Research Infrastructures, especially in field of PSE and **Energy**. Each RI develops its own approach and contribution to the subject of sustainability. There is currently a **lack of a forum for global information on the sustainability of RIs** to measure and compare approaches and share good practices. The 'Energy for Sustainable Science at Research Infrastructures' (ESSRI) Workshop is an embryo of such a forum which could be more formalised and serve as a basis for a collective platform.

CROSS-DOMAIN ASPECTS

As highlighted in the previous sections, PSE Research Infrastructures have numerous links and synergies across the different ESFRI domains. In short:

- All PSE RIs are closely linked with the **DIGIT** domain due to their character and the large amount of data that need to be processed, analysed and distributed. Most of these Research Infrastructures are actually active drivers of the European Open Science Cloud. The CERN World LHC Computing Grid (WLCG) also connects up to 200 computing clusters and offers near real-time access to LHC data.
- Analytical infrastructures play a particularly important role in answering the societal challenges of today, especially in the areas of **Energy**, **Environment** and **Health & Food**. Bridging information from X-ray, neutron and other analytical facilities is vital to understand and predict the behaviour of matter and to guide the development of improved sources of renewable energy or the design of new functional materials for a climate neutral and circular economy in Europe. Applications of analytical RIs also include deep understanding of underlying molecular mechanisms of a large variety of microbial diseases, viruses (such as COVID-19) and cancer. Synergies with the **Social Sciences & Humanities** domain are also present, as illustrated by the set of analytic tools used by the European Research Infrastructure for Heritage Science (**ESFRI Project E-RIHS**).
- Astronomy & Astroparticle Physics RIs are strongly connected with the **Environment** domain, e.g. to monitor the Earth's subsurface with seismic-vibration sensors, to access data on sea currents and temperature or to monitor the properties of the atmosphere.
- Nuclear & Particle Physics RIs have outstanding applications in the **Health & Food** domain, participating in research programs in biophysics, radio-biology, innovative radio-isotopes development for diagnostics and therapy, optimisation of hadron-therapy protocols and new, less invasive cancer treatments. Strong interactions exist also with the **Energy** domain around the development of nuclear fission and fusion energy; in these fields, many technological developments are made in synergy with the PSE domain, as for infrastructures like MYRRHA, IFMIF-DONES, ELI ERIC or ITER.
- ESFRI PSE RIs and other major European RIs in this domain are also among the main drivers of global collaboration discussed and fostered by the GSO Global Research Infrastructure (GRI) that evaluates the full breath of possible internationalisation of efforts.



ESFRI LANDSCAPE ANALYSIS 2024 - SECTION 1

SOCIAL SCIENCES AND HUMANITIES





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SOCIAL SCIENCES AND HUMANITIES


CURRENT STATUS IN THE DOMAIN

The Social Sciences & Humanities (SSH) landscape covers a wide range of academic disciplines, which help us to understand ourselves, others, and the human societies around us. These disciplines can be grouped in the following main areas¹: Individuals, Markets and Organisations, Institutions, Governance and Legal Systems, the Social World and its Interactions, the Human Mind and its Complexity, Texts and Concepts, the Study of the Human Past, Human Mobility, Environment, and Space, Studies of Cultures and Arts.

¹ ERC panel structure (2024)
https://erc.europa.eu/sites/default/files/2023-03/ERC_panel_structure_2024_calls.pdf

Moreover, SSH contributes to multidisciplinary research, inter alia in the field of Health, Security, Urban Studies, Science and Technology Studies.

The Domain of Social and Cultural Innovation (SCI) in the ESFRI Landscape includes all those infrastructures projects and European Research Infrastructures legal entities (ERICs) that support our understanding of people and society and the research in the disciplines under the acronym of SSH. Given this acronym is used outside of ESFRI, it should again be used instead of SCI.



SSH disciplines address the **digitalisation paradigm** by exploiting and adopting new methods, data types, and tools. Human behaviour and its consequences are complex, and affect how culture is generated and shared, how society is organised, and how technology and policies should be developed and implemented. Understanding the mechanisms behind these

processes requires Research Infrastructures (RIs) that enable the cross-disciplinary study of development over time, locations, and interlinkages. It requires facilities capable of dealing with the growing amounts of complex, multi-layered data, which needs proper contextualisation and evaluation. The recent diffusion of systems, which generate information on the basis of Large Language Models (LLM), has added the need for evaluating the generated 'knowledge' and account for the impact of these systems on societies.

SSH is at the forefront of establishing RIs that efficiently implement **sharing of FAIR data resources**² as a core driver for research development. At the same time this data driven SSH research creates a vital platform **for development of fair social policies in Europe** to advance citizens' well-being, welfare, and cultural dialogue. Moreover, SSH researchers address the various societal challenges in the forms of transformations, crises, and divides. In this line, the

² FAIR data principles are a central concept of Open Science. Their implementation means making the data Findable, Accessible, Interoperable and Reusable. See, e.g., GO-FAIR initiative <https://www.go-fair.org/>

SSH provide underpinning research for the European pillar of social rights and European policies enabling an understanding of local, national, and supra national realities. Even though most of the SSH RIs primarily address researchers supporting the highest standards of research quality, they also serve policy makers and the public at large.

RIs are long-term enterprises and represent strategic investments, which are indispensable for enabling and developing research. In addition to fostering scientific knowledge for the benefit of SSH researchers, they also impact the research environment socially and economically. The Council's conclusions on RIs in December 2022 recognised RIs' central role in the development of the European Research Area (ERA)³.

Data analysis on social transformation provides crucial insight into people's capacity to adapt to fast environmental and technological changes. The Council's 2022 conclusions affirm that RIs "provide knowledge-based solutions to societal challenges and help to deliver the EU's green and digital transitions". Finally, SSH RIs support the preservation and reuse of cultural data which are essential to understand the development and variety of cultures, and consequently to the resilience of Europe as a project of Member States (MS), alongside the creation of economic value in multiple industries, spanning from the creative arts to tourism.

Providing an in-depth understanding of the social and human dimension, the contribution of SSH RIs to different challenges, including the Sustainable Development Goals (SDGs) and policy making in general, is more visible than ever before. At the core

³ Council of the European Union (2022), Council Conclusions on Research Infrastructures <https://data.consilium.europa.eu/doc/document/ST-15429-2022-INIT/en/pdf>

of these research domains lies the **understanding of societal upheavals and changes and cultural transitions**; it involves **engaging citizens** to modify behaviour to help alleviate the consequences of climate, societal and technological changes, **exploring political debates** in different languages, and **understanding the impact of events such as wars, migration, and pandemics on people's well-being and health**. Complementary to the approaches of the natural and physical sciences, SSH research provides methods, pre-requisites, sources, tools, and evidence to improve our societies' well-being and resilience. This research does not solely focus on behavioural change or social acceptance of the future; it also yields hard data and solutions that support policies and programmes, catering to the needs and desires of citizens.

SSH RIs support research that significantly contributes to **European scientific excellence**. A recent EC publication claims that Humanities is a focus of expertise in Europe⁴ and SSH research plays a crucial role in scientific competitiveness. Focusing on Europe, the US National Science Foundation's report on publications (2022) claims that the European authored Social Sciences publications are 17% of

4. EC (2022), "Science, Research and Innovation Performance of the EU 2022. Building A Sustainable Future in Uncertain Times", pp. 7 & 54.

world share versus the 8.4% in the US⁵. Furthermore, the most recent report by the International Association of Scientific, Technical, and Medical Publishers (STM) shows that the global share of SSH publishing in 2020 was \$4.5 billion, and Europe benefits by 32% of total value (US 40%, Asia 20%)⁶.

SSH RIs identify important themes for European research, contributing towards scientific excellence in these domains. They support the creation, collection, and curation of essential data to support disciplinary areas in exploring new approaches to fundamental questions. SSH RIs also play a key role in the innovation of methods and research processes both at disciplinary and interdisciplinary levels. RIs in this domain also draw in non-academic actors who accelerate the realisation of the benefits of research for society. These RIs are **ideally positioned to support current research and nurture the next generation of scientists** across Europe using resources from SSH data archives to cross-national surveys along with new methods and processes. In some areas, SSH RIs are at the forefront of current developments, as relevant practices have been established for a long time; for instance, sharing data for the purpose of historical

5. NSF Science and Engineering indicators 2022
<https://nces.nsf.gov/pubs/nsb20214/publication-output-by-country-region-or-economy-and-scientific-field#>; Gingras Y. and Mosbah-Natanso S. (2010), "Where are Social Sciences produced?", World Social Science Report, Chapter 4, p. 150.

6. STM Global Brief 2021 – Economics and Market Size
https://www.stmassoc.org/2022_08_24_STM_White_Report_a4_v15.pdf, pp. 10-12

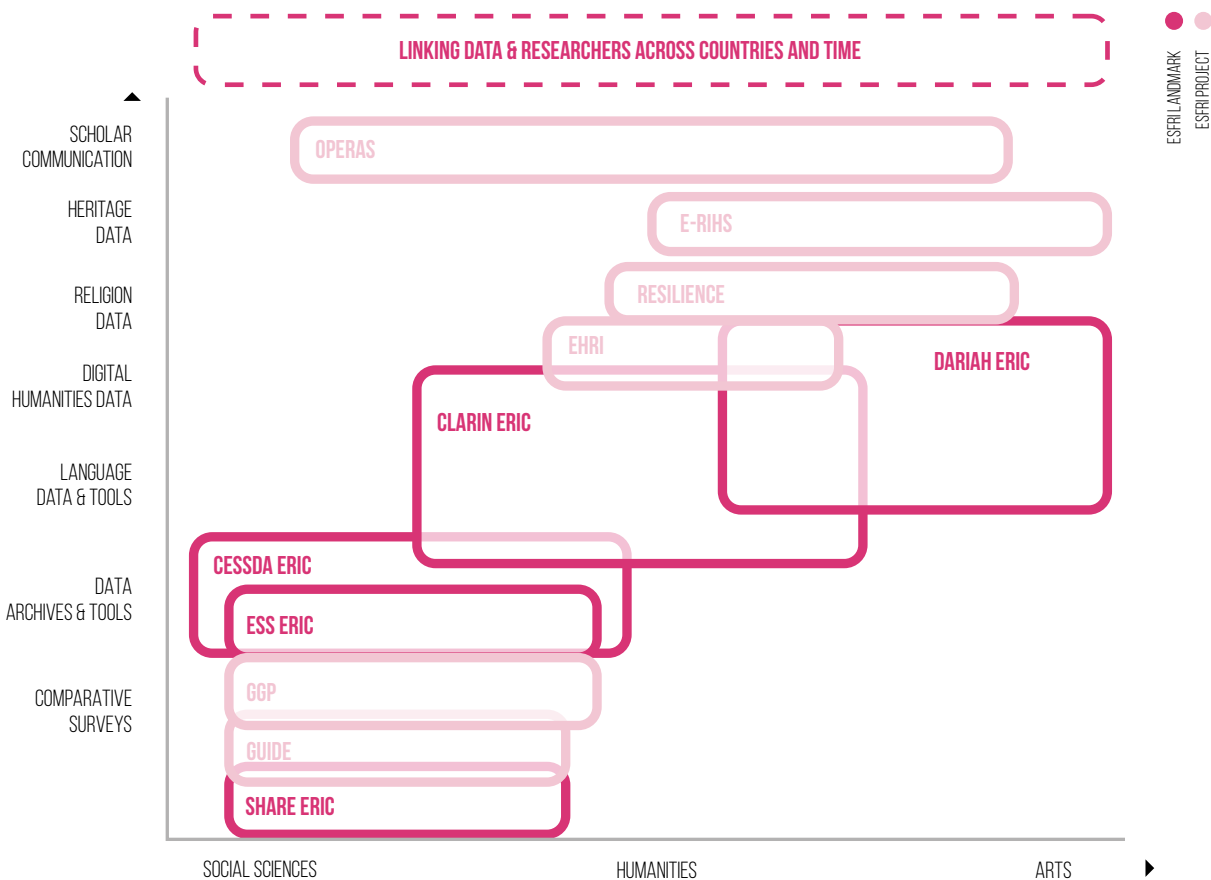


FIGURE 1.
 The indicative position of ESFRI RIs in relation to the types of data and tools employed in the Social Sciences & Humanities domain

comparison between cultures and countries and study of trends in social developments.

Furthermore, working with experts from other domains encourages collaboration and exchanging best practices. RIs may also assist the coordination within or between disciplines and support research with provision of tools. More importantly, they consider the FAIR principles and encourage the use of standards in data collections. Namely, RIs can help ensure that researchers have the options for re-use of existing data before creating new datasets; where possible, new data are designed to be interoperable with existing high-quality, comparable data, creating new knowledge. RIs deliver more than access to data, they facilitate shared data collection on a grand scale and provide access to expertise and guidance to researchers early in the design phase of new research.

The first five large SSH ERICs (**CESSDA ERIC**, **CLARIN ERIC**, **DARIAH ERIC**, **ESS ERIC** and **SHARE ERIC**) were included in the ESFRI roadmap in 2006 and awarded Landmark status in 2016; some of them built upon collaborations started decades earlier. Two more (**E-RIHS**, **EHRI**) were added in 2018, followed by another four that joined in 2021 (**GGP**, **GUIDE**, **OPERAS** and **RESILIENCE**).

The current SSH RIs are displayed in **Figure 1** and **Figure 2** and are summarised below, following a thematic division and with the Landmarks (ERICs) first, followed by the Projects (in alphabetical order).

SOCIAL SCIENCES – SURVEYS, DATA TOOLS AND SERVICES

The **ESFRI Landmark ESS ERIC** (European Social Survey)⁷ is an academically driven long-term cross-national survey in Social Sciences that has been conducted across Europe since 2001. It **assesses the attitudes, beliefs, and behaviour patterns** of diverse populations in more than 30 nations, measuring change over time within and between European countries in their living

7. <https://www.europeansocialsurvey.org/>

conditions, social structure, public opinion, and attitudes.

The **ESFRI Landmark SHARE ERIC** (Survey of Health, Ageing and Retirement in Europe)⁸ is a Research Infrastructure for studying health, social, economic, and environmental questions over the life-course of European citizens and beyond. SHARE collects multidisciplinary and cross-national survey panel data on **health, socio-economic status and social and family networks of individuals aged 50 or older** (biennial survey waves).

The **ESFRI Project GUIDE** (Growing Up in Digital Europe)⁹ is a pan-European comparative birth cohort survey including a sample of newborn infants and a sample of school age children. Both cohorts are surveyed using a common questionnaire and data collection methodology at regular intervals until the age of 24. The Research Infrastructure is a source of high quality longitudinal statistical evidence to support the development of social policies to enhance the **well-being of children, young people, and their families** across Europe.

The **ESFRI Project GGP** (Generations and Gender Programme)¹⁰ provides scientists and policy makers with high-quality and timely data about families and life course trajectories of individuals to enable researchers to contribute insights and answers to current societal and public policy challenges. GGP survey focuses on **inter-generational and gender relations** between people, expressed in care arrangements and the organisation of paid and unpaid work.

The **ESFRI Landmark CESSDA ERIC** (Consortium of European Social Science Data Archives)¹¹ provides large-scale, integrated, and sustainable data services to the Social Sciences. It **brings together Social Sciences data archives across Europe**, aiming at promoting the results of Social Science

8. <https://share-eric.eu/>

9. <https://www.guidecohort.eu/>

10. <https://www.ggp-i.org/>

11. <https://www.cessda.eu/>

research and supporting national and international research and cooperation. CESSDA provides a central data catalogue and a platform to jointly develop user-friendly tools and services.

HUMANITIES – SURVEYS, DATA TOOLS AND SERVICES

The **ESFRI Landmark CLARIN ERIC** (Common Language Resources and Technology Infrastructure)¹² provides data, tools, and services to support research based on language resources, and it is available to all disciplines and not exclusively to SSH. CLARIN's Virtual Language Observatory (VLO) provides easy and sustainable access to **digital language data and advanced tools** to discover, explore, exploit, annotate, analyse, or combine them, wherever they are located.

The **ESFRI Landmark DARIAH ERIC** (Digital Research Infrastructure for the Arts and Humanities)¹³ provides **support to digitally enabled research and teaching across the Arts and Humanities**. DARIAH is a network of people, expertise, information, content, methods, tools, and technologies. It develops, maintains, and operates an infrastructure in support of digital research practices and sustains researchers in using them to build, analyse and interpret digital resources.

CLARIN ERIC and DARIAH ERIC jointly manage the **Digital Humanities Course Registry**¹⁴ and in some countries, they have joined their efforts.

The **ESFRI Project EHRI** (European Holocaust Research Infrastructure)¹⁵ enables online and physical access to Holocaust sources and expertise dispersed across many institutions in Europe and beyond. EHRI provides innovative tools and training

12. <https://www.clarin.eu/>

13. <https://www.dariah.eu/>

14. <https://dhcr.clarin-dariah.eu/>

15. <https://www.ehri-project.eu/>

that advance the digital transformation of Holocaust research, remembrance, and education. The vision of EHRI is to secure seamless access to all sources and expertise that are relevant to the study of the Holocaust.

The **ESFRI Project E-RIHS** (European Research Infrastructure for Heritage Science)¹⁶ is dedicated to heritage science, an interdisciplinary domain merging STEM and SSH to enhance knowledge, conservation, and appreciation of cultural heritage. E-RIHS aims to preserve heritage's accessibility and significance in a changing world by unravelling its cultural and historical layers, understanding material change, and utilising it for socioeconomic and environmental sustainability.

The **ESFRI Project RESILIENCE** (REligious Studies Infrastructure: tooLs, Innovation, Experts, conNections and Centres in Europe)¹⁷

16. E-RIHS
<https://www.e-rihs.eu/>

17. RESILIENCE
<https://www.resilience-ri.eu/>

focuses on Religious Studies, building a high-performance platform, supplying tools and access to physical and digital data to scholars from all scientific disciplines. RESILIENCE primarily serves the academic community, but its impact extends to the non-academic community. It gives physical and digital access to major relevant data archives for Religious Studies.

Open scholarly communication of Social Sciences & Humanities in the ERA is supported by the **ESFRI Project OPERAS** (OPen scholarly communication in the European Research Area for Social Sciences and Humanities)¹⁸. Its mission is to coordinate and federate resources in Europe to efficiently address the scholarly communication needs of European researchers in the field of SSH. OPERAS fills a gap in the European landscape, between generic e-infrastructures and RIs dedicated to research data in specific disciplines or topics.

18. OPERAS
<https://operas-eu.org/>

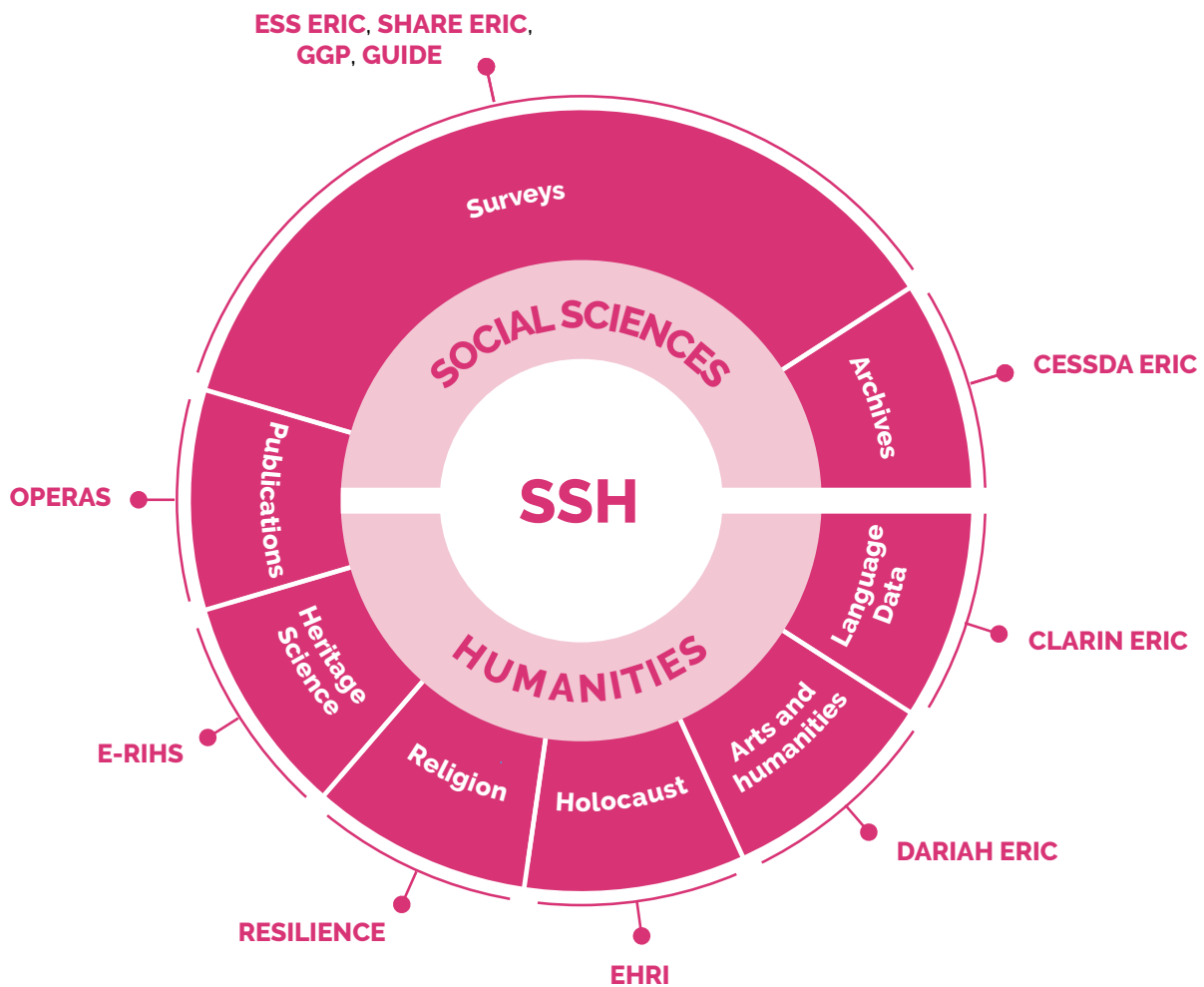


FIGURE 2.

The Landscape of the Social Sciences & Humanities domain

The main user group for the SSH RIs are **researchers, both individuals as well as institutions** at the world, European, and national level. Furthermore, a growing number of organisations are using data provided in the SSH domain. **DARIAH ERIC, EHRI and CLARIN ERIC**, for instance, collaborate with **non-academic organisations, in particular in the cultural heritage sector of galleries, libraries, archives, and museums** (GLAM). Similarly, non-governmental organisations focusing on migration and population studies utilise **SHARE ERIC** data; Holocaust memorialisation, anti-discrimination, and Human Rights organisations are supported by EHRI governmental organisations use data from **ESS ERIC** and SHARE to inform public policies¹⁹, while CLARIN and DARIAH help address societal awareness of the ethical issues related to the use of Artificial Intelligence and large language models. More importantly, the number of civil servants and industry users is growing. National governments' research units and social enterprises, publishers and the health industry seek access to datasets for their business planning and implementation. The conservation industry, for example, is targeted in the innovative approaches developed via **E-RIHS** for the preservation of cultural heritage. User statistics have been tracked, sometimes using ESFRI KPI for scientific excellence.

Many SSH RIs are **distributed** and provide access to large volumes of **complimentary digital resources** and offer **federated services**. Many of the large datasets being distributed by SSH RIs are open and free at the point of use, being based on Open Science and FAIR principles. Most of the shared datasets have not been created and annotated automatically, but they have been collected and/or curated by surveys or by human work and expertise in many countries worldwide. RIs' coordinating offices ensure support for the development of standards as well as of common metadata, implement shared platforms to make resources and federated services available, and blend user training and support. Heritage sciences also require instruments and techniques to study tangible heritage objects. Some RIs, like EHRI, **RESILIENCE**, DARIAH and E-RIHS, deploy instruments for **Transnational Access (TNA) that facilitate physical access** to their resources. For instance, results of surveys provide a wide range of information on societies and European citizens offering key insights on the impact of different social policies, while standardised datasets allow for the analysis of phenomena across languages, time periods and cultures, testing of methods and tools, reusability, and extension.

Data archives respond to the current demand of large data and research resource availability. Scattered resources and scarce accessibility of original collections, especially those that require preservation, are just two of the obstacles that researchers can overcome with RIs. Studying languages, religions or heritage, financial data or historical phenomena, and public opinion via social media still heavily rely on the capacity of individual researchers to identify and access specific original resources. **Many types of socially related**

data have different owners and their use implies a series of ethical issues. Here the **CARE principles**²⁰ can complement the FAIR principles. RIs' activities therefore also encourage the development of tools, methodologies and standards for their harmonious collection and set up pathways for collaboration among different entities responsible for such data.

Some RIs offer observatories, blogs, spin-off projects and fellowships and in-person services for face-to-face **training** across different facilities, both for researchers and practitioners. EHRI, for instance, offers in-person access to distributed facilities, CLARIN and E-RIHS provide **state-of-the-art tools and services** to cross-disciplinary users and communities. Some RIs, like ESS, provide data analysis tools with visualisation.

All infrastructures in the Social Sciences & Humanities domain offer critical services with different characteristics. Among these services are data consultation, and opportunity to contribute to the datasets.

Some SSH data-driven projects need independently collected datasets. In these cases, RIs provide **standards for data collection and annotation**. Users are also encouraged to deposit their original datasets and to compile new datasets according to existing criteria and standards for metadata or according to new research questions. Users then become creators and contributors to the RI and can benefit from RI resources. Notable examples are CLARIN resources, enabling researchers to reinforce their area of expertise and develop novel methodological frameworks for the exploration of multilingual data; and E-RIHS, which encourages the user-provider co-creation process.

Working with common standards also informs and supports researchers from other domains, like computer scientists for example, and reinforces their contribution in all aspects of data management and curation.

Yet, the number and involvement of researchers at national level varies greatly for each infrastructure, which hampers the possibilities for scholars to understand mutual methods and resources. Infrastructures will need to continue to develop their 'service provision' capability.

Services provided by all SSH RIs have proven particularly relevant in times of crises or societal upheavals. For example, the SHARE Corona Survey allowed the in-depth examination of how individuals were coping with the health-related and socio-economic impact of COVID-19. DARIAH launched a theme call dedicated to artistic responses to the pandemic²¹. At the same time, CLARIN was collecting parliamentary debates across Member States supporting the

19. Reports on happiness, well-being and economic challenges by France Stratégie, part of the French Prime Minister's Department, have used ESS and SHARE data.

20. CARE Principles
<https://www.gida-global.org/care>

21. DARIAH Theme Call: Arts Research during Covid-19
<https://www.dariah.eu/activities/impact-case-studies/arts-research-during-covid-19/>

comparison of how the pandemic has been addressed. Micro-data analysis of society makes researchers and policy makers far more aware of unintended consequences of certain policies and functions as an indicator for social and psychological behaviour, which can be utilised to adapt future political interventions.

More recently, some ESFRI SSH RIs started or renewed **activities with Ukraine** and/or are exploring ways to cooperate with the country. The ESS ERIC is preparing a data collection in Ukraine as part of the coming 11th wave of data collection in Europe; Ukraine has also participated in earlier rounds. SHARE ERIC and **GGP** work on collaborations with researchers and organisations in Ukraine to organise future data collections. **CESSDA ERIC** supports Ukrainian data experts. They work on saving data assets in Ukraine as well as on developing tools and services to provide better access to data, especially from researchers outside of the country. CLARIN ERIC collaborates with researchers from Ukraine in different ways, for instance establishing an expertise centre (K-Centre) for Ukrainian and helping to develop language and text corpora or translation systems. Some of these services are already exploited for investigations in war crimes. EHRI has an active presence in Ukraine since 2010 and is currently facilitating a permanent association of the country to the RI. In the case of Ukraine, as well as of other countries of the Eastern Partnership of the European Union, it is not only important to reconstruct RIs, but also to allow participation and access of the produced data for the present and future of a country's identity and sovereignty.

The RIs also offer the possibility to **raise the visibility of data and services** they provide. For example, the **Social Sciences & Humanities Open Cluster (SSHOC)** is the thematic cluster²² for the SSH infrastructures and has developed the **SSH Open Marketplace**²³, a central hub to find detailed information about software tools, pub-

22. Overview of the thematic Science Clusters
<https://science-clusters.eu/>

23. SSH Open Marketplace
<https://marketplace.sshopencloud.eu>

lications, datasets, training materials, and workflows supporting research across the many facets within the SSH domain.

The emergence of citizen science is encouraging a fast-growing audience of citizens that for varied reasons demand access to SSH data facilities. Therefore, some infrastructures made various resources available, including books, policy reports, summary materials, data dictionaries, data collection, data analysis and visualisation tools, often supported by the Zenodo community²⁴. Services like **VERA** offered by **OPERAS** allow researchers to collaborate on citizen science projects and provide support throughout the preparation of the project²⁵.

While the RIs present a significant opportunity for SSH research across Europe, there is potential for further development, both at European headquarter level and at national level. One of the issues is **interoperability**, but there are also issues of **visibility, training, and access**. More effort could be dedicated to train students, scholars at all levels, data stewards, and research managers so that they could harvest the full benefits of data offered by the RIs. Even though some RIs already adopt these instruments, more efforts can be made to disseminate best practice for researchers and support the endeavours that RIs are doing in terms of training and education. Such efforts could build further on existing training materials such as those developed in the context of the SSH Open Marketplace²⁶ and **DARIAH Campus**²⁷.

24. Zenodo
<https://about.zenodo.org/>

25. VERA Service by OPERAS
<https://operas-eu.org/?s=VERA>

26. Training Material – SSH Open Marketplace
<https://marketplace.sshopencloud.eu/search?categories=training-material>

27. DARIAH Campus
<https://campus.dariah.eu>

This section outlines the progress in measuring the scientific, economic and societal impact of SSH RIs, as well as the challenges in determining the diverse types of impact

in the Social Sciences & Humanities domains. Several best practices and SSH impact case studies are provided.

RIs represent an increasingly large share of research investment, and both national and European funders are expected to develop systematic and transparent procedures underlying their investment choices. Consequently, there's a growing consensus regarding the importance of assessing the value of RIs beyond research itself and for society at large. This should not be difficult for SSH RIs given that they are the most proper candidates among RIs to have an effect on the wellbeing and future of society.

Indeed, there are outstanding examples of SSH RIs undertaking ground-breaking work in analysing their scientific, economic and societal impact. **ESS ERIC** stands out among RIs in all domains regarding study, analysis, and reflection of the various categories of impact of RIs and use of assessment methodologies. Soon after becoming an ERIC in 2013, ESS has started with impact studies, tracking its academic and non-academic impact. A recent impact case study noted a set of common general types of non-academic ESS impacts, including general intelligence and insights for NGOs or government ministries, agencies, or advisory bodies. Such impact drives agenda setting, where ESS data highlights a particular problem or challenge, triggering various types of policy action. ESS data or ESS-based findings can also influence public debate when presented in the news media. Using ESS data as indicators enables the tracking of certain aspects of societal progress, for instance aiding in the assessment of policy effectiveness according to desired outcomes. This includes instances where ESS methodology or questions have been integrated into other surveys run for such monitoring processes. In addition, in 2022, ESS has contracted a study to map ESS topics to European Commission policy priorities. This will help to identify future opportunities for ESS data to be more visible at the European Commission level.

At the same time, several studies, policy

papers and statements note that assessing impact of RIs beyond the scientific impact is challenging and that a unified framework for impact assessment of investment in RIs is questionable. This was underlined again recently, by OECD in 2019 and by ESFRI in 2023.

In a recent policy paper, the OECD noted that assessing the impact of RIs remains a challenging endeavour.²⁸ The main reasons lie in the fact that, although RIs deliver quality services that facilitate excellent science, outcomes are indirect and not produced by the RIs themselves but rather by its users. In many cases, RIs do not know the users, given also that the data are freely obtainable for non-commercial purposes.

These findings have also been supported by a recent Policy Brief (June 2023) by ESFRI, **Assessment of Impact of RIs**²⁹, which underlines that impact measurement of RIs is feasible and necessary but should be undergone with a relative amount of caution. The report emphasises the importance of scientific impact while recognising the so-

28. https://read.oecd-ilibrary.org/science-and-technology/reference-framework-for-assessing-the-scientific-and-socio-economic-impact-of-research-infrastructures_3f1ee43b-en#page1

29. <https://www.esfri.eu/latest-esfri-news/esfri-publishes-policy-brief-impact>

cio-economic impacts of RIs. **Quality over quantity** of impact assessment should be the guiding principle. Soft evidence such as impact cases and anecdotal evidence as opposed to hard evidence is the recommended way forward for showcasing impact.

Most of these findings and frameworks address all RI domains and do not concentrate on Social Sciences & Humanities specifically. The specificity of SSH Research Infrastructures stems from their **influence on the vision of decision makers and social actors**.

SSH RIs have all individually started to monitor and assess their scientific, societal and economic impact with the KPIs developed centrally by ESFRI. However, for this to remain a scientifically grounded and recognised assessment, more depth and time will need to be invested at all levels. The individual uniqueness of RIs also means that their impact can have many different forms.

As regards scientific impact, SSH RIs score high because they have revolutionised the way in which SSH research in Europe is conducted, as explained above. A push to **more data-intensive SSH research** has brought about a shift in European SSH research, slowly moving it away from nationally focused and context-dependent approaches. Not only has this shift made SSH research more international (through the availability of cross-country data), but it has also encouraged a fruitful exchange and further development of research methods.

In terms of societal impact, Humanities RIs contribute significantly to cultural impact: **digitalisation of cultural artefacts** (e.g., archival records, books, newspapers, manuscripts, museum collections) makes them more accessible and appreciated, boosting community integration and identity. Benefits for society include contributions to art, movies, and books that may ultimately lead to more **societal awareness about the benefits of science**. Other examples for societal impacts include providing **open access publications, data and software for societal use and contributing to social inclusion**, for example by hiring people from under-represented groups or by adopting practices

promoting gender equality. There are also broader societal impacts on national research systems in the European Research Area (ERA): European RIs are a cornerstone of the ERA and impact directly on national governance in its structuring of the national research and funding systems.

Moreover, several of the SSH RIs contribute fundamental facts about the current state of European societies and policies, which is particularly important in order to **fight disinformation** and organised campaigns aimed to undermine public trust and legitimacy threatening European democracies.

Assessing **economic impacts** is more difficult, as they are solely indirect: they are to be seen as a **long-term outcome of policies adopted on the basis of information and insight provided by data generated at the level of SSH RIs**.

For example, in 2020, **DARIAH ERIC** launched an initiative of producing impact case studies to showcase the depth and richness of the impact achieved over the year into research communities, national consortia, and the practices and knowledge base of individual researchers in the area of (Digital) Arts and Humanities. This collection of case studies is enriched annually. The DARIAH Impact Case Studies are inspired by the UK's Research Excellence Framework³⁰ which included more narrative and qualitative Impact assessment approaches, more suited to the Humanities & Social Sciences. Furthermore, some RIs have a truly global reach: **SHARE ERIC** does not only cover all EU Member States in a harmonised way, but is also embedded in a network of sister studies all over the world, from the Americas to Eastern Asia.

30. UK's Research Excellence Framework
<https://www.ref.ac.uk/about-the-ref/what-is-the-ref/>

This has to do with the comparability of its data with other international ageing surveys such as **HRS** in US and **ELSA** in UK. Such comparability has allowed for a worldwide understanding of how health care policies have coped with the COVID-19 pandemic, prompting important lessons for the future. In the same vein, during the COVID-19 pandemic, ESFRI showcased many stories on its website where SSH RIs directly contributed to addressing the crisis³¹.

In summary, it can be noted that societal and economic impacts can be assessed, in addition to scientific impacts. However, especially in the SSH domain, societal and economic impacts are indirect, very long-term and dispersed due to the large variety of user groups.

31. ESFRI RIs against COVID-19 pandemic
<https://www.esfri.eu/covid-19>

TRENDS IN THE DOMAIN

RIs in the SSH domain are evolving in a fast-changing context, where the impact of technology has major effects. Europe is a knowledge society. Within a generation, more than half of the European population will have completed a tertiary level education, and the number will continue growing. Knowledge is no longer the driver of the economy alone; it will also shape social and political processes in Europe and allow citizens to be more informed. Digital technologies change the way research is done across all scientific fields, and the greatest change might be seen in SSH.

Increasingly, **data relevant for research comes from multiple sources**, such as administrative documents, statistical collections, businesses, electronic devices, online transactions, social media. The competitiveness of the ERA might hinge upon the ability to **harness and integrate this data** alongside data generated by researchers more than ever before. However, these types of data present many challenges. They often align less with FAIR principles than traditional research data. The existence of specific collections might be obscured, accessibility issues arise due to commercial interests,

data protection or copyright concerns. Data is often not well-documented, and there might be a lack of standards facilitating its interoperability.

While it might be impossible to freely disseminate all data types, it is still important to **secure their access to researchers**. This holds not only for data from public organisations, like statistical offices or public administrations, but also for data from the private sector including publishers, especially when there is a significant public interest at stake. In these cases, making data available

may be an obligation, as outlined in the **European Data Act**. Unlike industrial data, data within SSH RIs is in most cases free and open, with some exceptions regarding access to cultural heritage data.

The **evolution of AI**, with for instance its generative systems based on Large Language Models (LLM) like ChatGPT, is determining a paradigm change, and access to high performance computing is required to researchers and students. Moreover, the **evaluation of the results generated by LLM, including ethical aspects**, is an important future task to be addressed by SSH RIs. Not only digitalisations have changed the scale of the results, but they have also transformed methodologies and training of all scholars. Among the actors of this transformations are new forms of data and data analytics, the use of MRI for behavioural studies, satellites used

to map and measure economic growth, laser scanner data from archaeology and art. Just like any field, researchers in the Social Sciences & Humanities domain find innovative tools to conduct research, of which many are new and expensive.

RIs like **CLARIN ERIC** and **DARIAH ERIC** must reflect on their distinctive role in this process. They must engage further showing their capacities, distinctiveness, and unique role under the light of these new developments.

Developing and enhancing the usage and impact of data about societies in Europe from various sources should be a priority. Vast amounts of scientific data about our European societies are being archived and distributed in data repositories within the network of **CESSDA ERIC** and have a large potential. Legislative reforms like the **Data Governance Act (DGA)** and the **Digital Services Act (DSA)**, enabling better data access for research, should be brought to their full potential by supporting research endeavours that build on analysing large data sets. The DGA invites Member States to establish safe and secure platforms to give researchers access to data that originally stems from administrative acts. Legal and administrative obstacles that still hinder sharing of, for instance, administrative data for research should be removed also at the national level. The technological means for storing and sharing such data in an ethically responsible way are already in place.

More and more MS are using these new possibilities. The DSA enables access to large commercial platforms, giving access to social media data for research from **Very Large Online Platforms (VLOPs)** and **Very Large Online Search Engines (VLOSEs)**.

More established data assets are produced and distributed by **National Statistical Institutes** and **Eurostat** within the framework of the **European Statistical System (ESS)**. There is large capacity to enhance their impact for research. The interplay between academic research and NSIs has untapped potential that could be brought to use to gain new knowledge about climate behaviour, mobility and economic questions. Furthermore, the major innovation in public policy over the next 10 years will be the **personalisation of public services**, from health to education. People will rely on new knowledge to help guide and inform their decisions and choices throughout their life from birth, through their working life and on into retirement. The issues that concern and challenge EU citizens the most are largely 'social'.

Green and Digital transitions are strong European priorities and they have become the lens to look at European policies for the future. SSH RIs are moving towards focusing on the twin transition. In relation to federated and connected databases, it will be possible to understand the impact of the twin transition in a **more geographically focused way** – local and regional – in addition to national and European. Large cities and small communities are impacted differently and respond in dissimilar ways to the transformation implied by the digital and green transitions. Locally held social data can offer key insights about how to adapt to European diversity, especially in crucial areas such as labour relations and labour markets, market behaviour and social standards. Social policy could benefit greatly from a better understanding of a diverse European society with locally sourced data augmenting the larger national and pan-European datasets.

It is therefore key to explore trends for this domain in the significant investments made in large-scale Research and Innovation (R&I) projects through the EU Framework programmes and with attention to multidisciplinary approaches.

SSH research started to be funded under the 4th Framework Programme with a limited amount and a small number of projects. In Horizon Europe, the cluster dedicated to SSH research became far more relevant. For instance, Horizon 2020 funded projects around Migration and Democracy (under the Governance topics), many of which had significant data collections and analysis components. A summary report on **migration studies**³² identified that the resources collected could lead to an important cluster of data for emerging infrastructures in support of population studies, mobility and, above all, migration flows.

Similarly, Horizon Europe devotes special attention to the intervention area of **democracy**. One important field of application will be research on our European democracies, which are the cornerstones upon which the European Union is built. Since their establishment, European democracies have faced challenges due to societal developments, and they will most likely continue to do so in the future, being confronted with

climate change, energy supply, novel technologies, and the like. Thus, to strengthen the resilience of European democracies and render them fit for the future, it will be crucial and inevitable to monitor how they navigate these challenges.

Democracy research is, as of now, very fragmented. It is in fact characterised by many separate data collections spread across prominent research institutions all over Europe, each one employing different data collection methods, coding practices, and archival standards. This currently impedes a comprehensive and efficient analysis of democracy research data. The role of SSH RIs in the **standardisation and harmonisation of different data objects in order to make them interoperable and linkable, and to a greater extent reusable**, is therefore central to ERA.

Evolving RIs like **Monitoring Electoral Democracy (MEDem)** or projects like **Reconstructing Democracy in Times of Crisis, A Voter-Centred Perspective (REDEM)** provide data that will enable better, more comprehensive, and highly innovative comparative research on electoral democracies and electoral systems.

The research community encouraged participation in **large consortia** and **inter- and multidisciplinary approaches in large-scale projects**. Over time, cross national collaboration has also increased the presence and, only to some extent, funding for SSH and a better visibility of its research results at both European and National levels. Horizon Europe surpasses Horizon 2020 as for Cluster 2, a dedicated SSH research-driven cluster focusing on three intervention areas: democracy, cultural heritage, and social transformation. The programme also includes Humanities and Social Sciences as a cross item element, and a collaboration to be taken into account in a number of flagged topics across different clusters. The Missions launched in Horizon Europe are another example of how crucial it is to align national and European efforts for wider and more ambitious achievements in science. SSH sector data could be particularly important for addressing these missions as they can lead to **Data Spaces combining academic, governmental, administrative and company data**. SSH RIs are actively participating in data space initiatives including cultural heritage, language and skills. Furthermore,

³² WP10 – Deliverable 10.2 Strategic Research Agenda on Migration. Proposal number: GA 7701121. Horizon 2020. Call: H2020-SC6-REV-INEQUAL-2016-2017

a strong collaboration between SSH RIs and the emerging European Collaborative Cloud for Cultural Heritage (ECCCH) will be crucial.

More trends can be identified in other areas of development. In the area of **language**, both spoken and written, commercial actors are developing platforms and services at an unprecedented speed. Translation tools such as dictionaries (e.g., [dict.leo.org](https://www.dict.leo.org/)), or translation machines like Google Translate or DeepL have become common tools for citizens as well as researchers. Spoken language tools and voice translations are developing at a similar pace, already offering or poised to offer spoken interpretation and translation services for many languages.

The interest of creating new infrastructures or extending the scope of existing ones lies in the fact that infrastructures, which could be created out of the Europe wide collection of smaller facilities, can easily become 'greater than the sum of the parts' for researchers if brought together under the coordination of a RI. For example, the number and spread of **'behavioural labs'** (rather than living labs) which exist across Europe, if coordinated under a RI, could provide a significant resource to European Social and Behavioural Sciences. Research subject availability, research subject diversity, and ethics standards are all critical in appropriate subject sampling for

research design innovation; at present, these and other resources remain fragmented. Structural support of such 'core facilities' could provide a significant boost to their sustainability.

Social and behavioural sciences miss a single point of observation about emerging large consortia and initiatives. They also miss a representation within the EIROforum³³, an entity that plays a crucial role in simplifying and facilitating interactions with the European Commission, the organs of the European Union, national governments, industry and so on.

All RIs in this domain offer critical services but with different characteristics. **A concentrated effort should be made to see whether services can be 'unified'** at least up to a certain extent, or whether connectedness in this respect can be achieved between certain RIs. It should be noted that some efforts are being tested in this regard.

An emerging generation of RIs is the one which combines physical labs with data analysis of tangible outputs; an exemplary case being **E-RIHS**.

33. EIROforum
<https://www.eiroforum.org/about-eiroforum/>

GAPS AND NEEDS IN THE DOMAIN

The **levels of funding and support in research programmes is low** for the SSH domain across most Member States and Associated Countries, given the great number of disciplines it covers. This has two consequences: SSH research, especially at national level, is often characterised by small size projects, which can generate scattered data collections, and a variety of methods and scientific approaches. In some cases, scientific collections – but usually not basic research – are funded and supported by donations, small local authorities, and foundations. In the field of SSH, researchers have often been trained as individual single scholars rather than team scientists, although the impact of technology and the opportunities offered by large datasets are profoundly changing the methods and practice of these disciplines, especially in the last 15-20 years. However, this trend mainly focuses on the employment of those technologies rather than on genuine collaboration. The importance of RIs to contribute to these changes, for instance through harmonisation and support of the creation and sharing of FAIR resources and the development of new methodologies and tools, is evident; but support to RIs from the various national funding policies is not always adequate. This is true especially if considering the **new technological requirements imposed by very large data and models**. This includes **access to high performance computing** to researchers and students.

There is then a fundamental hurdle about **how to finance such efforts if they lack large national investment**. A separate analysis of existing datasets with such characteristics could indicate how pressing this issue may be. The aim will be to make timely provi-

sions to support the emergence of scattered, local, and differently funded infrastructures.

EU level programmes, in particular **Framework Programmes**, and **COST actions** have had a significant influence on shaping some areas of research within the European SSH research domain. Even so, the current R&I landscape is rather fragmented and incoherent across the different countries, and this will remain a significant barrier to finding a place for RIs in the research ecosystems. Such alignment is required both thematically – within specific scientific domains such as SSH – as well as at the level of optimising national and European R&I priorities. Many RIs tend to feature in national strategies, but their founding focus is often as a national resource; the task to make them aligned to European aims and purpose comes with high costs in time and effort. In 2021, the European Research Area launched action 8, which aims to share more information to **align better national and European funding policies** to foster common approaches across Member States. This action, bringing together all MS interested in joining the dialogue, tries to tackle a variety of problems: sustainability of funding, equal access to RIs throughout MS, the economic and societal impact of RIs in Europe, and priority setting with regard to the focus on specific scientific and political needs³⁴.

Within the emergence of the European Open Science Cloud (EOSC)

34. WP10 – Deliverable 10.2 Strategic Research Agenda on Migration. Proposal number: GA 7701121 Horizon 2020. Call: H2020-SC6-REV-INEQUAL-2016-2017

in the R&I ecosystem, this positioning becomes even more urgent as Member States and Associated Countries should also report on their EOSC contribution; the EOSC partnership assumes in fact that the €500 million of EC budget will be matched by the countries. The SSH Thematic Science Cluster SSHOC, which brings together the SSH RIs with other key research organisations in the domain, will facilitate a stronger SSH voice within the EOSC.

However, the integration or collaboration of SSH research with other domains to address European priorities is still very weak. For instance, at the European Mission level – as the E-RIHS report highlights – none of the five Missions identified has properly focused or included Humanities and Social Sciences effectively, making it harder for these RIs to leverage the data that could be particularly valuable for the Missions' objectives. This situation can be exemplified by a case from the cultural heritage perspective: in the Ocean

Mission, opportunities can be found to connect coastal and maritime communities with their cultural heritage and the adaptation to Climate Change to increase awareness of the value of preserving cultural landscape. In the Soil Mission, art, culture, and creative industries have been used to stimulate citizens' consensus. As for Climate-Neutral and Smart Cities Mission, there is unexplored potential for data from **E-RIHS, GUIDE** and **SHARE ERIC**, which can substantially contribute to new social policies on cultural heritage, ageing societies and children wellbeing.

Even more cooperation between existing RIs should be pursued along with a tentative expansion of their activities to cover fields related to the thematic areas they already serve. This also includes cooperation with RIs in other domains, which requires establishing stronger, sufficient, and stable financial support to the RIs.

CROSS-DOMAIN ASPECTS

The SSH RIs sector is a particularly versatile area: social, linguistic, and cultural data serve large demands across all science domains. Some SSH infrastructures have already demonstrated high levels of interdisciplinarity. As an example, **SHARE**'s future development will be driven by interdisciplinary studies on the interaction of health and socio-economic living conditions. Over the life course of European citizens, health and socio-economic policies determine individuals' standards and demand for their social and health care. Similarly, **E-RIHS** will enable the provision of state-of-the-art tools and services to cross-disciplinary users and communities. Among these are STEM and SSH researchers, curators and cultural heritage professionals, PhD students and technical staff: this variety encourages applications from user teams with a strong interdisciplinary character. So far, 90 successful user group leaders belonging to main academic backgrounds in the disciplines of Chemistry (20%), Humanities (50%) and Conservation Science (25%), have already been involved in working with E-RIHS data; the remaining figure includes users with a background in Engineering Physics, Earth and Life Sciences.

Metadata schemes and classification criteria either have been already advanced (as is the case for **CLARIN ERIC**), or they are gradually being established. The best practices developed can be shared with other domains. Besides metadata and standards, **CESSDA ERIC**, as an example, also promotes the need for data to be more interoperable within and beyond disciplines. Developments in the data space shall focus on the easier (machine-readable) processing of data from different disciplines to tackle societal challenges. A special focus is given to restricted and sensitive data.

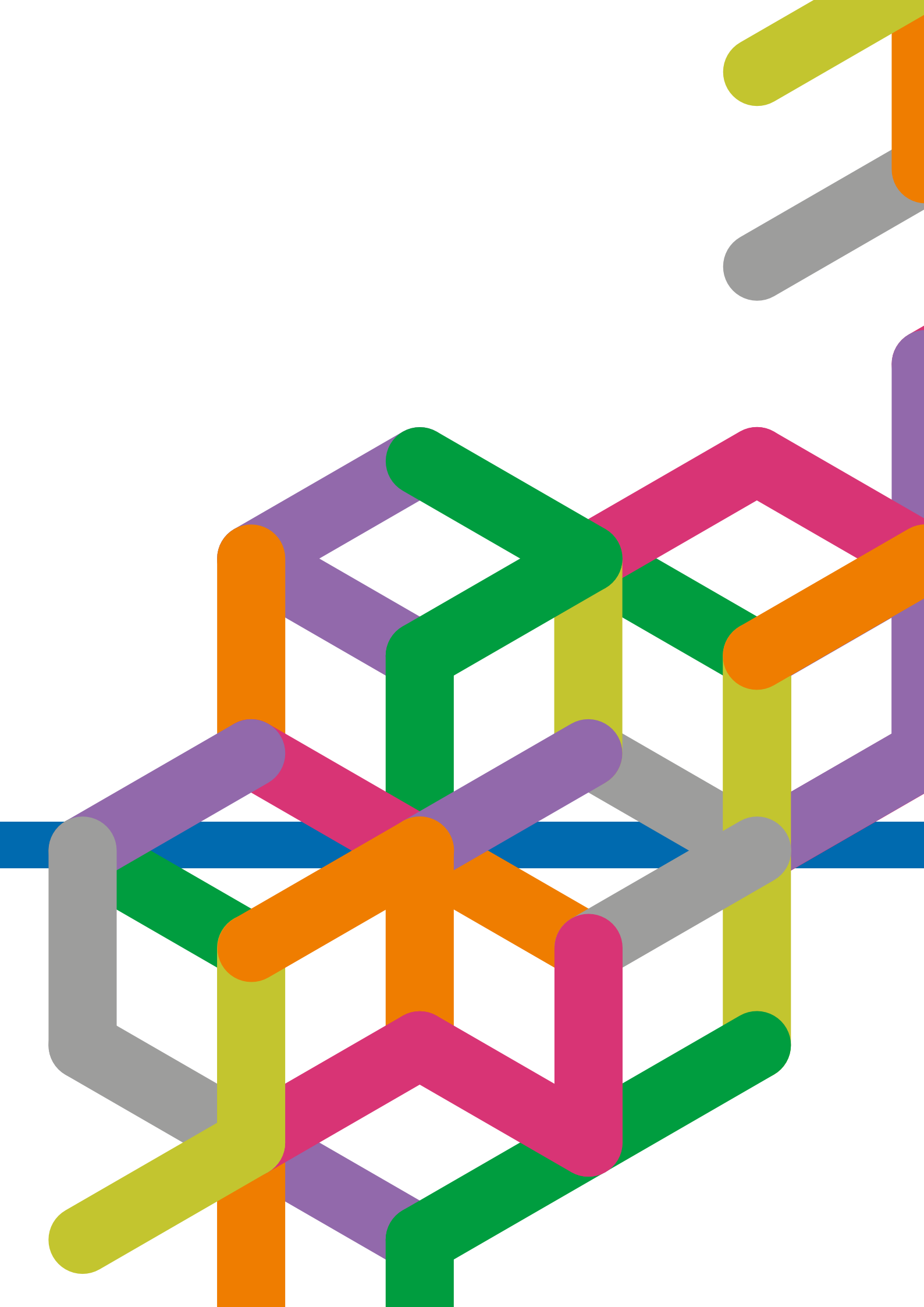
SSH can also make important contributions to Destination Earth, the new digital twin of the Earth, which will help tackle climate change and protect nature³⁵.

RIs have already achieved great results. Now the challenge is to ensure they become front-line resources in research to contribute to the major research challenges prioritised in a programme like Horizon Europe. Recently, **ESS ERIC** has been collaborating with **ICOS ERIC** on a H2020 project to improve carbon emission monitoring at the city level and collect data from residents in those cities in the same period, with the aim to create a more complete picture and help address the Green Deal. ESS has also been linking its data to data coming from the **Environment** domain in the context of the EOSC Future project, again underlining the power of cross-domain collaboration to address the Missions and other key areas. Collaboration between the various Science Clusters including SSHOC will become increasingly important, but this should not imply duplication of work, including metadata and tools.

Advanced studies to join information about health and socio-economic conditions are well developed. Understanding the impacts of environmental changes on communities and new industrial and biological threats are all part of what future science scholars will explore and where big data approaches will be dominant. A demand for more priority focused data sets, understood through the lens of Sustainable Development Goals or science advancements in specific fields, could pave the way to faster breakthroughs.

Moreover, more comparative data focused on special groups (e.g., societal elites or vulnerable groups) along with a number of challenges coming out of them would be welcomed and useful for understanding how European societies and democracy evolve as well as for future developments.

35. Destination Earth (EC)
<https://digital-strategy.ec.europa.eu/en/policies/destination-earth>





SECTION 2

ESFRI LANDSCAPE ANALYSIS 2024

CROSS-DOMAIN TRENDS AND CHALLENGES



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INTRODUCTION: SHAPING THE HORIZON: NAVIGATING RIs FUTURE

Building upon the foundational insights presented in Section 1 of the Landscape Analysis, Section 2 goes deeper into the evolving dynamics of European Research Infrastructures (RIs). This section amplifies the dialogue on the transformative role of RIs in fostering scientific excellence, technological innovation, and societal impact. It further explores the intricate interplay between RIs and European Research and Innovation, underscoring the critical contributions of RIs in addressing global challenges through interdisciplinary collaborations and digital transformation.

This section highlights the pioneering trends that are shaping the future of research, from the integration of Artificial Intelligence (AI) with the corresponding complements of quantum computing to the emphasis on sustainability and ethical responsibility. It also addresses the pressing challenges of sustainable funding, governance evolution, and the necessity for enhanced collaboration across domains. By presenting a comprehensive analysis of current states, future trends, and strategic recommendations, this section aims to guide stakeholders, policymakers, and the scientific community towards a robust, responsive, and innovative European RI ecosystem.

HORIZON SHIFTS: PIONEERING TRENDS IN RIs

The landscape of scientifically excellent RIs is evolving at a rapid pace, influenced by a confluence of trends in scientific and technological advancements, funding mechanisms, collaborative approaches, governance and human resources, and ecosystem

integration. Central to these transformations is the role of Artificial Intelligence, digitalisation, and the increasing emphasis on addressing societal challenges. This chapter synthesises these trends, offering a comprehensive view of the changing landscape of RIs.

SCIENTIFIC AND TECHNOLOGICAL ADVANCES

AI REVOLUTION: TRANSFORMING RESEARCH ACROSS DOMAINS

AI has the potential of revolutionising research methodologies, enabling more sophisticated data analysis and predictive capabilities. AI is a new driver for quality FAIR data productivity and FAIR data integration, and the AI assisted or automated workflows have potential to become a new tool for data handling. AI can support data curation and categorisation of large datasets, for consistency and coherence tests and for generation of synthetic data.

In domains like the Social Sciences & Humanities (SSH), it is facilitating new understandings of social dynamics, while in the Envi-

ronmental domain (ENV), AI models are predicting climate patterns with unprecedented accuracy. AI's role in Health & Food (H&F) RIs is transformative, driving innovations in disease prediction and treatment, drug and diagnostic developments, food security and safety, and in sustainable practices. In Physical Sciences & Engineering (PSE) and Energy (ENE) Infrastructures, AI may become an important tool supporting complex data processing, enhancing energy optimisation and basic and applied science research efficacy.

AI is not merely a technological tool: it represents a fundamental shift in how we approach research across various domains. By analysing patterns in vast datasets, AI is uncovering insights that were previously inaccessible, pushing the boundaries of human knowledge. Each domain, from SSH to ENE, is harnessing AI's power to address its unique challenges while contributing to a collective understanding of complex global issues. The integration of AI is a unifying trend across RIs, driving a new era of innovation, efficiency, and discovery. This trend aligns with the overarching progress in digitalisation and the need for interdisciplinary collaboration, as **AI can bridge the gap between diverse research areas and foster a more holistic approach to solving critical societal challenges.** However, before the promises of AI can be fully realised, it is crucial to address issues related to **data privacy, bias in algorithms, interpretability of AI models, and the wider societal impact.**

DATA TRANSFER AND ANALYSIS

- **Life sciences:** digitalisation has enabled projects like the 1000 Genomes Project to analyse vast genomic data, leading to breakthroughs in personalised medicine

- **Environmental sciences:** digital technologies applied to satellite, airborne and ground-based observations provide essential data for climate modelling and understanding global environmental changes

PROMOTION OF A DATA-DRIVEN RESEARCH CULTURE

- **Cultural shift in Social Sciences and Humanities and Physical Sciences:** the adoption of digital tools in SSH, such as in digital humanities, demonstrates the cultural shift towards data-driven research. Similarly, in Physical Sciences, the use of advanced computing for Particle Physics experiments highlights the significance of digitalisation in managing and analysing large-scale data

INTERDISCIPLINARY COLLABORATION FACILITATED BY DIGITALISATION

- **Energy research:** digitalisation is integral to the development and optimisation of smart grids, directly impacting the integration of renewable energy sources and enhancing energy efficiency

- **Health and Food safety:** the health sector's move towards telemedicine and digital health records showcases the impact of digitalisation on improving patient care. In food safety, digital tools for supply chain monitoring and contaminant detection underline the importance of digitalisation in ensuring public health

TABLE 1.

Enhanced data capabilities across domains: selected examples

DIGITALISATION: THE NEW PULSE OF RIS

Digitalisation is transforming RIs by enhancing computing networks and software capabilities. This shift towards integrated digital ecosystems is revolutionising how research is conducted. For instance, the [EuroHPC](#) initiative is critical in fields like climate modeling and genomic research, as it provides the computational power needed to process extensive datasets.

[EOSC](#), on the other hand, is pivotal in creating a unified federated platform for sharing and reusing research data, tools and services across disciplines, including [H&F](#), [SSH](#) and [ENV](#), but also opens up new avenues for innovation and discovery, solidifying its role as a catalyst in the ever-evolving realm of Research Infrastructures. **[see Table 1]**

INTEGRATIVE POWER OF E-INFRASTRUCTURES: A NEW SCIENTIFIC SYNERGY

In the evolving landscape of European RIs, a transformative narrative is unfolding, driven by the trend to seamless integration between e-infrastructures and each ESFRI RI, fostering exchange and common approaches. This integration marks a new era of scientific exploration, where digital backbones intertwine with physical research facilities, creating a symbiotic relationship that enhances the capabilities and reach of research endeavours. At the heart of this narrative is the role of e-infrastructures in bolstering the functions of ESFRI RIs. These digital platforms, encompassing advanced data repositories, high-speed networks, and cloud computing, are not mere additions but pivotal elements that empower RIs across various domains.

In [ENV](#), for instance, the integration of e-infrastructures with observational networks has led to a revolution in data collection and

analysis, enabling researchers to monitor and predict environmental changes with greater accuracy and detail.

This integration is instrumental in fostering interdisciplinary research. By bridging disparate scientific fields, **e-infrastructures facilitate a collaborative arena where data and tools are shared seamlessly**. In the **H&F** sector, e-infrastructures enable the convergence of genomic data with environmental analytics, leading to groundbreaking studies on the interplay between environmental factors and human health. Such interdisciplinary endeavors underscore the transformative power of integrating e-infrastructures in research.

Furthermore, the integration of e-infrastructures in research is **reshaping research methodologies, steering them towards a more data-driven approach**. In **SSH**, digital tools and e-infrastructures are unlocking new forms of data analysis, offering fresh perspectives on social phenomena. This digital transformation also aligns closely with the **Open Science movement**, democratising research by making data more accessible and fostering global scientific collaboration.

The narrative of e-infrastructure integration extends to the realms of **PSE** as well. Here, the complex demands of research in areas like Materials Science, Astrophysics and Energy are met by the robust computational power provided by **high-performance computing facilities** within e-infrastructures. This integration not only supports the intricate computational needs but also catalyses innovations in these fields.

The narrative of integration continues to evolve, as e-infrastructures are proving indispensable in the contemporary research infrastructure ecosystem. They are the digital sinews that connect and empower various ESFRI infrastructures, driving forward a future where research is more collaborative, innovative, and impactful. This **integration is not just a trend but a paradigm shift** in how research is conducted, promising to unlock new horizons in the quest for knowledge and discovery.

USER SUPPORT: NAVIGATING THE EVOLVING FINANCIAL NEEDS

ALIGNING EU, NATIONAL, AND REGIONAL FUNDING: THE CHALLENGE OF COORDINATION

One of the primary challenges facing European RIs is the service provision to users often supported by project funding sources at the European Union (EU), national, and regional levels. This requires **integration of policies and funding cycles**, which can be complex due to differing priorities and administrative processes. Thematic reports focusing on each domain in Section 1 highlight the difficulty in synchronizing EU-funded large-scale infrastructural projects with national and regional funding that often centres on more localised research initiatives¹. A further challenge is also to coordinate funding sources of distributed RIs that span across a large number of Member States (MS).

BALANCING SERVICES FOR BASIC AND APPLIED RESEARCH: DISTRIBUTION OF RESOURCES

Another significant challenge is **balancing the coverage of basic and applied research**. Although this distinction can be seen as being artificial, ensuring that both poles of the spectrum are covered in the RI service portfolio is crucial for the overall health of the research ecosystem. As an example, thematic reports in the **Health** field indicate the necessity for services encompassing fundamental biological research in medical sciences, as well as medical-orient-

ed initiatives such as translational research aimed at leveraging these findings to develop practical health solutions. Similarly, in the **Energy** domain, there is a pressing call to support both basic research geared towards uncovering new materials or processes, and applied science efforts which would translate the discoveries to economic innovation and finally to pre-prototype devices. Technology transfer plays a pivotal role in facilitating the transition of research outcomes into practical applications and innovations.

FOSTERING COLLABORATIVE SERVICE MODELS: INTERDISCIPLINARY AND CROSS-DOMAIN CHALLENGES

As research increasingly becomes interdisciplinary and cross-domain, services often need to adapt to **support collaborative projects that span different scientific areas**. This requires a shift from traditional service provision, which is often discipline-specific. Energy research, as mentioned in **Energy** dedicated chapter in Section 1, often involves collaboration across **Physics, Engineering, Environmental Science, Social Science** and Policy, necessitating a more flexible and inclusive service provision approach.

SUSTAINABILITY OF LONG-TERM FUNDING: ENSURING CONTINUITY

A perennial challenge for RIs is securing long-term funding that ensures the sustainability and continuity of service provision for enabling excellent research. Short-term grants and fluctuating funding streams can hinder long-term Research Infrastructure implementation and development as well as its maintenance.

¹ See Section 1 – Thematic areas

The funding challenges facing services in European RIs are multifaceted, involving the coordination of various funding sources, balancing different types of research and the needs of users coming from a broad range of disciplines and thematic areas, fostering collaborative and interdisciplinary projects for the development of the European Research Area, ensuring long-term sustainabil-

ity, and aligning with EU policies. Addressing these challenges requires a **concerted effort from funding bodies, policymakers, and research institutions to develop more flexible, strategic, and integrated project funding models**. Overcoming these challenges is crucial for the advancement and impact of RIs in the European research landscape.

COLLABORATION AND INTERCONNECTEDNESS

INTERDISCIPLINARITY AND CROSS-DOMAIN COLLABORATION

The trend towards interdisciplinarity and cross-domain collaboration is becoming increasingly crucial in the landscape of European Research Infrastructures. All ESFRI Strategy Working Groups indicate a growing emphasis on integrating various scientific disciplines in their thematic reports in Section 1. This trend is evident in how RIs are evolving to address complex societal challenges, EU missions, and transitions towards green and digital futures. Such integration is critical to harness the collective strengths of diverse research fields. The identified trend towards interdisciplinarity and

cross-domain collaboration underlines a significant paradigm shift in European Research Infrastructures. This shift is characterised by a move away from isolated, discipline-specific research **towards more integrated, collaborative approaches that leverage digital technologies and shared resources**. This trend manifests itself through cooperation within RI ecosystems, for instance through data exchange and development of common services and technologies. RIs are better equipped to address the multifaceted nature of contemporary scientific challenges and contribute effectively to European Research and Innovation (R&I) strategies. This approach would not only enhance the scientific output of RIs but would also provide tools and skills to help address societal needs and EU strategic priorities.

SOCIETAL MISSION: ALIGNING RESEARCH WITH GLOBAL CHALLENGES

As prominently highlighted in the thematic reports in Section 1, RIs in the EU are increasingly aligning their efforts with societal challenges and long-term missions. **RIs strategic response to global challenges**, such as climate change, public health, and sustainable energy closely **aligns with EU policy objectives** like those outlined in the European Green Deal² and key commitments and actions announced by the EU at COP28³. Not only are RIs focusing on the scientific and disciplinary aspects of these challenges, but they are also incorporating interdisciplinary approaches that bring together diverse expertise. This approach is crucial in addressing complex issues spanning multiple domains, such as combining **Environmental Science** with **Social Sciences** to tackle climate change impacts on societies.

continuity and comprehensive tackling of issues that require persistent efforts. Examples from thematic reports show that RIs are establishing enduring partnerships across various sectors, including industry, government, and international bodies, fostering a holistic approach to research. Additionally, the advancement of digital technologies, especially AI, is facilitating the creation of data-driven solutions to societal issues, bolstering the capacity of RIs to deliver insightful and impactful research outcomes.

STRUCTURAL AND COLLABORATIVE RESEARCH MODELS

To effectively address these challenges, RIs are adopting structured and sustained collaborative research models. These models facilitate long-term commitment and resource allocation, ensuring

PUBLIC ENGAGEMENT AND SOCIETAL IMPACT

Lastly, there is an increasing emphasis on public engagement and demonstrating the societal impact of RI activities. RIs proactively communicate their research outcomes, underlining their relevance to societal needs, and engage with the public to ensure that their research is responsive to societal concerns. Through excellence in science and technology, they attract and train the next generation of scientists and engineers essential for the EU. Such trends are reinforcing the role of RIs in society and emphasising their contribution not only to scientific advancement but also to the betterment of societal conditions in line with EU strategic priorities. This underscores the broader impact and relevance of Research Infrastructures in informing and shaping policy decisions.

2. The European Green Deal
https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

3. EU at COP28 Climate Change Conference
https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/climate-action-and-green-deal/eu-un-climate-change-conference/eu-cop28-climate-change-conference_en

GOVERNANCE EVOLUTION

The evolution of governance in EU Research Infrastructures is increasingly being shaped by the need to adapt to rapidly evolving and changing Research and Innovation ecosystems. This trend requires a nuanced under-

standing of the complementarity between fundamental and applied research, the necessity of cross-sectoral collaboration, and the importance of adopting a holistic and open approach.

RIs remain resilient and adaptive, poised to support the continent's green and digital transitions in an autonomous and secure manner.

As RIs continue to evolve within these dynamic ecosystems, their governance structures must also transform to support the seamless translation of knowledge across various stages of R&I, ultimately contributing to a robust and responsive European research ecosystem.

On the other hand, the governance trends at the European level, particularly within ES-FRI RIs and within ESFRI, reflect a **dynamic and responsive approach to the needs of the European research ecosystem**. These trends underscore the importance of strategic alignment, interoperability, openness, adaptability to digital transformation, engagement with societal challenges, and support for cross-domain research. As these trends continue to evolve, they will shape the future direction and effectiveness of RIs across Europe, ensuring their alignment with both scientific advancements and societal needs.

As the European Union navigates an increasingly complex global landscape, the evolution of governance within European RIs must prioritise the **strategic forecasting of dependencies and vulnerabilities**. This forward-looking governance will necessitate a proactive stance on fostering technological independence, ensuring that Europe's reliance on critical components

is matched by an internal capacity to innovate and manufacture. By **reinforcing governance frameworks to support Research and Development (R&D) in strategic technologies**, Europe can mitigate risks associated with foreign supply chains and enhance its long-term economic and political sovereignty. Such a recalibrated governance approach will ensure that European

FIT IN VARIED ECOSYSTEMS

- RIs achieve greater impact by aligning with different R&I ecosystems that range from academic research to industry-led innovation. This involves understanding the unique dynamics and requirements of each ecosystem and positioning their services and expertise accordingly

ROLE IN VALUE-CHAINS

- RIs contribute to various stages of value-chains, from basic research to applied development and commercialisation. By understanding their role in these chains, RIs can enhance their contributions to the development of new products, services, or policies

PARTNERSHIPS WITH TECHNOLOGY INFRASTRUCTURES

- RIs increasingly collaborate with Technology Infrastructures to leverage advanced technologies. This relationship is non-linear and context dependent. In many cases, these partnerships are crucial for enhancing research capabilities and outputs and valorising RIs role in a complete R&I ecosystem or specific value-chain

SYNERGY AND COMPLEMENTARITY WITH OTHER ENTITIES

- Effective partnership and complementarity with other entities, such as universities, industry, and government agencies, are key to enhancing the impact of RIs. These relationships enable RIs to leverage additional expertise, resources, and networks

ADOPTING TO EVOLVING NEEDS OF STAKEHOLDERS

- RIs remain relevant and impactful by continuously adapting to the evolving needs of their stakeholders. This involves staying attuned to changes in scientific priorities, market demands, and societal challenges
-

TABLE 2.

Strategic positioning in R&I ecosystems

ECOSYSTEM INTEGRATION

European RIs are progressively becoming more integrated into the R&I ecosystem, marking a pivotal shift in their function and operation. By building interfaces with a diverse range of infrastructures and organisations in industry and academia, and by being responsive to both immediate and long-term challenges, RIs are positioning themselves as key players within the broader R&I ecosystem. Not only does this approach enhance the impact and relevance of RIs, but it also ensures their adaptability and resilience in the face of evolving scientific, technological, and societal landscapes. Research Infrastructures in Europe enhance their impact and relevance by strategically positioning themselves within **diverse R&I ecosystems and value-chains**.

This strategic positioning involves finding their fit and acting in complementarity to other entities, including **Technology Infrastructures (TIs) and partnerships**. The distinction between Research Infrastructures and TIs is not clear and, in many cases, it is deemed as artificial. As all infrastructures provide services to industry and support the development of crucial skill sets to capacitate knowledge intensive economies, an ecosystem-based policy should focus on supporting the services provided, not on atomising funding streams by artificially isolating typologies of infrastructures. **[see Table 2]**

BRIDGING THE DIVIDE: ADDRESSING KEY CHALLENGES AND NEEDS IN RIs

Across various domains of Research Infrastructures, a comprehensive analysis reveals pervasive challenges and unmet needs that transcend specific disciplines. It is crucial to facilitate collaboration and interconnectedness between RIs from diverse domains, fostering synergies in addressing societal challenges, Horizon Europe missions, and the green and digital transition.

In addition to nurturing collaboration and interconnectedness, a crucial need is the formalised assessment and management of risks associated with the overreliance on external products and technologies. The current geopolitical context, underscored by supply chain vulnerabilities revealed during the Ukrainian conflict, emphasises the **imperative for a robust risk assessment framework**. This framework should prioritise the development of internal capacities and the strategic foresight to anticipate disruptions. European Research Infrastructures can inform policy decisions that protect and advance Europe's energy independence, ensuring resilience against external economic and political pressures.

European RIs could identify possible technical solutions, including the new digital technologies, for safeguarding strategic autonomy and aligning with the European vision for a sustainable, green, and digitally integrated continent. Indeed, **European deep technology** is key for tackling the most pressing global challenges such as climate change, sustainable energy, health, as well as for accelerating innovation. Moreover, it would contribute to create new jobs and companies.

Competence development gaps, recruitment problems and the evolving nature of digital infrastructures underscore the necessity for **RI-oriented prioritised skill development and training programs**, notably through cooperation between RIs and academia. These programs should equip researchers with the capabilities to navi-

gate and harness the benefits of emerging technologies, including Artificial Intelligence. A wider and more informed discussion about the ethical and societal implications related to the application of AI tools, particularly in the **Social Sciences & Humanities** and the **Health & Food** domains, is necessitated.

Retention of highly qualified staff is something that RIs are feeling as urgent. Training and professional development is a key solution to this challenge. Also, the development of HR policies and standardisation of competences for the mobility and career development of staff is needed. Projects such as RItrain 1 and 2 have reflected upon this challenge involving a variety of RIs from different disciplines.

Synergies and interoperability between RIs emerge as critical challenges, with the existing lack of smooth interaction between initiatives such as **EuroHPC** and **EOSC** impeding the realisation of potential impacts. To address this, there is a pressing need to focus on developing and promoting solutions, standards, funding instruments, and best practices for seamless data sharing, management, and interoperability across RIs and e-infrastructures.

Sustainable service provision and development of common technologies and corresponding funding models pose a perennial challenge, with fragmented and inadequate funding threatening the long-term added value of RIs. Establishing funding mechanisms that account for the full life cycle of RIs, as well as the dif-

ferent needs of distributed and single site RIs, is paramount to ensure continuity and adaptability to evolving research needs.

While crucial, **international collaboration** faces hurdles such as **fragmented funding and limited coordination**. A need exists to strengthen international collaboration efforts, fostering cohesion and aligning goals to address global challenges effectively. Furthermore, crisis preparedness and response mechanisms, despite their potential for cross-domain collaboration, currently

lack the necessary interaction. Establishing mechanisms for cross-domain collaborations, assessing the impact of challenges such as air pollution, and exploring socio-economic effects are essential actions aligned with EU strategies.

Efficient policy directionality and governance structures are necessary to align RIs research outputs with societal goals and expectations. Policies and governance should be constructed to support both directed and 'free' research, and the important in-

teractions between them. The evolution of research landscapes and societal demands requires articulating and integrating governance structures at various levels.

In summary, the interconnected nature of challenges and needs in the RIs landscape calls attention to the need of collectively addressing them. This approach would lead to a more cohesive, impactful, and adaptive research ecosystem.

GOVERNANCE DYNAMICS: CHALLENGES AND SOLUTIONS

Across all domains, common challenges emerge, including the imperative for cross-disciplinary collaboration, the multifaceted nature of societal challenges, and the need for inter-, multi-, and transdisciplinarity. The current chapter delves into the intricacies of interdisciplinary collaboration, digital integration, and multilevel articulation governance.

Governance structures at all levels should interact effectively to support the development of efficient, cost-effective, and dynamically developing RIs. Tools to support this include **proactive RI self-assessment, governance structures which allow and encourage RI transformation and renewal** to match evolving research developments and needs, **training programs**, and the definition and use of robust and effective **Key Performance Indicators** (KPIs) in conjunction with qualitative assessments.

Addressing management challenges in several domains involves effective coordination of large-scale experimental facilities, managing the running and renewal of highly complex and expensive infrastructure projects with complex funding flows, and navigating regulatory landscapes. Using tools such as KPIs and structured self- and external evaluations, governance must tackle the unique challenges posed by the scale and complexity of, for example, **Physical Sciences** experiments, demanding highly competent and specialised management personnel and technical and management training programs.

Most critical gaps and needs revolve around **ensuring long-term sustainability**, with a special emphasis on the challenges

of distributed RIs, efficiency, and innovation of Research Infrastructures. Governance interventions are crucial to addressing these gaps, ensuring stable funding, coordinated efforts, and the development of suitable managerial expertise.

Governance trends in **DIGIT** and **ENE** include **strategic long-term resource allocation, increased international collaboration, and the need for more adaptable and responsive governance and financing structures** for increased flexibility. Addressing challenges related to optimising resource allocation, navigating international regulatory differences, and balancing agility with stability require clear governance structures. This is crucial to shift towards transparent frameworks for resource allocation, streamlined international collaboration protocols, and comprehensive training programs for effective Agile governance. In the case of Digital RIs, governance must additionally address issues such as the smooth integration of digital tools, data management, privacy concerns, and the adoption of Agile governance models for efficient development.

Recognising the trend towards collaboration through digital technologies, Research Infrastructures of the **ENV** domain (with

their grouping **ENVRI**) face challenges in **seamlessly integrating digital tools across diverse environmental disciplines**. Strategies for ENV RIs include the establishment of robust platforms for digital integration, the implementation of cross-disciplinary training programs, and the creation of standardised frameworks to facilitate smooth collaboration and communication across different organisational levels. Multilevel articulation, emphasising collaboration at both global and regional levels, gains prominence. Governance challenges in this domain emphasise the need for collaboration with RIs, European large initiatives such as **Copernicus**, space agencies and international programs such as **GEO**.

In the **H&F** domain, governance trends underscore and increasing focus on **inclusive stakeholders' engagement**, including those from the civil society (e.g., patient associations and consumer associations). Stakeholders' commitment and awareness and their conflicting interests are also crucial themes demanding attention. Other key challenges for governance include **long-term sustainability, transparent data governance, ethical considerations** and the need to implement standardised ethical guidelines, and heightened **cybersecurity measures**.

Within the **SSH** domain, governance trends emphasise a commitment to **long-term sustainability planning, smooth integration of digital technologies, and heightened strategies for public engagement**. Challenges mainly revolve around stable funding, rapid technological changes, and effective communication of research outcomes to the

public. To effectively tackle them, strategic planning, continuous digital literacy training for researchers, and comprehensive public engagement initiatives are essential. Governance challenges lie in balancing the interests of diverse stakeholders, addressing resource

allocation (with special emphasis on the challenges posed by distributed RIs), ensuring transparent decision-making processes, and fostering effective international collaborations.

FINANCING THE FUTURE: CRAFTING A SUSTAINABLE FUNDING STRATEGY FOR RIS

The funding landscape for European RIs stands as a critical determinant of their success and impact. Recognizing the evolving nature of RIs and the diverse challenges they encounter, a more streamlined, collaborative, and comprehensive approach to funding becomes imperative.

The ESFRI Stakeholders Forum identified, at its second meetup in September 2023, key challenges and proposed actionable recommendations to enhance the funding ecosystem for RIs. These recommendations offer valuable insights and potential solutions to address the intricate funding needs of RIs, facilitating their sustained growth and impact.

The R&I landscape includes a spectrum of activities, from RIs supporting fundamental research to more applied research, from technological development platforms (Technology Infrastructures) to innovation and commercialisation support mechanisms. Governance and funding mechanisms must allow and enhance **effective development along the R&I development chain**, and seamless **interaction between actions and actors at different Technological Readiness Levels** (TRL) along this chain.

The challenges within the funding landscape are multifaceted, ranging from distinct funding needs for single site and distributed RIs to complexities in navigating intertwined funding sources across multiple countries. The ESFRI Stakeholders Forum underscored the importance of **sustainable funding** for operations and upgrades, avoiding over-reliance on a single funding source, and managing node costs, subsistence, and user travel costs.

In response to these challenges, key actions were recommended. Among the proposed solutions, the following were included: stakeholders dialogue, cooperative efforts between RIs, targeted funding for missions and curiosity-driven research, sustainable operational funding with potential EC co-funding, strengthening of Transnational Access (TNA) schemes, addressing health data complexities, and fostering synergies between EU and national funding. The creation of a unified proposal management system and the development of impact assessment methodologies were also highlighted.

Regarding the Horizon Europe Work Programme (HE WP) and the Framework Programme 10 (FP10), recommendations included the establishment of **integrated funding schemes**, a boost in **TNA schemes**, and an **augmented budget for RI framework programme**. The overarching theme emphasises the necessity for a more streamlined, collaborative, and comprehensive approach to funding RIs.

Interdisciplinary collaboration emerges as a crucial aspect in cross-cutting funding considerations for ESFRI domains. Encouraging projects that span multiple domains promotes a holistic approach to research challenges, fostering innovative solutions. Adequate funding for robust data management practices and support for Open Science initiatives ensure transparency, accessibility, and reproducibility of research.

Funds allocated to integrate emerging technologies within Research Infrastructures keep the domains at the forefront of scientific advancements. Recognising the global nature of contemporary challenges, funding should support the competitiveness of the European RIs so to become strategic and attractive at international level.

DOMAIN-SPECIFIC FUNDING CONSIDERATIONS

The increasing reliance on digital technologies across all scientific domains is a prominent trend. In **DIGIT** RIs, focus on cybersecurity and data management is essential. Yet, funding gaps for **developing and maintaining state-of-the-art digital infrastructures** and addressing the **digital divide** require attention. A much stronger dialogue between all domains should not only be encouraged but realised fully through the awareness of the necessity of interdisciplinary research. Emphasis on digital and data-driven research methodologies is a growing trend.

Energy independence and security are vital for Europe. The **ENE** domain witnesses a transition towards sustainable and decarbonised energy sources, i.e. technologies that produce low net carbon dioxide emissions and are deemed environmentally, economically and socially viable for the long-term. The integration of smart technologies for efficient energy systems represents a growing trend. However, funding needs arise for the development and maintenance of energy-related Research Infrastructures. Support for research addressing **energy storage, grid integration, efficient use of energy** as well as the **societal and environmental impact** of energy transitions is crucial.

In the **ENV** domain, a growing awareness of environmental challenges has led to increased funding. While interdisciplinary collaboration is emphasised to address complex environmental issues, funding gaps persist for long-term observations and data collection projects. **Financial sustainability for integrating new technologies into environmental infrastructures** remains a critical need. A holistic view involves understanding the interconnectedness of ecosystems, underscoring interdisciplinary collaboration, prioritising long-term sustainability, fostering technological innovation, promoting global collaboration, engaging the public, and adapting to emerging challenges. The governance framework necessitates informed decision-making, aligning national strategies with European environmental goals, and optimising resource allocation for impactful research endeavours.

In the **H&F** domain, funding considerations encompass advances in precision medicine, personalised healthcare, prediction, and treatment, sustainable and resilient agri-food systems. It embraces the integration of big data, AI, and other technologies in health and agri-food research. Funding needs include support for implementation of **cutting-edge medical technologies and equipment**, as well as for **tools in translational research** aimed at bridging the gap between laboratory discoveries and clinical applications. Additionally, financial support is required for research on **climate-resilient**

crops, and sustainable and environmentally friendly agricultural practices. Interdisciplinary projects addressing the whole health and the whole agro-food value chains require financial backing to ensure access to services by the RIs.

In **PSE**, advancements in technology and science drive the need for cutting-edge Research Infrastructures. While collaborative projects with industry accelerate innovation, persistent challenges include funding gaps for **maintaining and upgrading equipment**, financing the **implementation and operation phases of large-scale RIs**, and **bridging the divide between academia and industry**.

The recognition of the importance of **SSH** in addressing societal challenges and informing policymaking is evident. However, stronger ties should be established with researchers dealing with missions and societal challenges across all domains. Remote data access and specific questions of data security and privacy demand further development of infrastructure, as well as the integration of AI. Funding for **large-scale, cross-disciplinary projects addressing the challenges of digital transformation** is limited. However, this challenge requires sustained financial investments. SSH RIs are distributed Research Infrastructures with specific challenges for sustainable funding.

SHAPING TOMORROW: RIs TRANSFORMATIVE POWER IN SCIENCE, SOCIETY, AND BEYOND

The anticipated impacts across diverse Research Infrastructure domains collectively contribute to advancing scientific knowledge, fostering innovation, and addressing societal challenges. This influence extends beyond academia, significantly impacting policy and economic sectors.

RIs serve as **vital sources of data and expertise that inform policymaking**, ensuring that scientific advancements are aligned with societal needs and government agendas. Economically, **RIs are catalysts for innovation**, driving industrial competitiveness and contributing to job creation and economic growth, particularly in high-tech sectors. This is further amplified by the interdisciplinary collaborations spanning across these domains, bringing together diverse expertise and perspectives to drive innovative solutions.

Additionally, the role of RIs in education and training is pivotal for **developing skills and building capacity across domains**, which is essential for sustaining the European research community and industry. These infrastructures are not only hubs of scientific discovery but also centres of learning and professional development, shaping the next generation of scientists and industry leaders.

In the **PSE** domain, cutting-edge RIs like the **European XFEL**, **ESRF-EBS**, **ILL** and **ELI ERIC** are pivotal in **advancing our understanding in fields ranging from Material Science to Pharmaceuticals**. These infrastructures exemplify interdisciplinary innovation and serve as platforms for education and skill development, often collaborating with sectors like Biology and Medicine to develop new diagnostic tools and treatments, demonstrating the potential for cross-domain innovation. Extremely powerful telescopes like **SKAO**, **CTAO**, **ELT** and **ET** are designed to transform the understanding of the universe and to provide instruments for new insights in cosmic evolution, composition, and astrobiology.

In the **ENE** sector, RIs such as **ECSEL ERIC**, **JHR** and **IFMIF-DONES** are crucial in **sustainable decarbonised economic development and energy independence and security**, including education and training cross-linking disciplines like Environmental Science, Engineering, and Economics, to address energy challenges holistically.

The **DIGIT** domain, with infrastructures like **EuroHPC** and **EOSC**, showcases the impact of **synergies between digital technologies and various research fields**. These digital RIs enable seamless interoperability and future developments, integrating data and tools from various disciplines. They are at the forefront of promoting Open Science, facilitating access to scientific data and resources. The Open Science approach accelerates research, fosters collaboration, and democratises access to scientific knowledge.

In the **SSH** domain, the application of AI and digital tools, facilitated by RIs like **CLARIN ERIC** and **DARIAH ERIC**, offers profound **insights and critical scrutiny of AI's ethical implications**. These collaborations, involving Computer Science, Ethics, and Social Sciences,

highlight the role of SSH in shaping societal values and contributing to the responsible development of technology. They also underscore the importance of integrating digital tools and Open Science principles in SSH research, enhancing its impact and relevance. In the same vein, **ESS ERIC**, **SHARE ERIC** and **GGP** have been key contributors to a more holistic understanding of the COVID pandemic from childhood to old age.

The **ENV** RIs support research through **advanced data provision**. These infrastructures collaborate with domains such as Climate Science, Biology, and Geology, contributing significantly to our understanding and addressing global environmental challenges. They are also key in educating and training environmental scientists, ensuring a continuous development of skills and expertise in this critical area. Furthermore, RIs in this domain play a critical role in promoting environmental sustainability, climate action and biodiversity loss. Their contributions resonate with global and EU-specific sustainability goals, providing essential data and insights for environmental policy and sustainable development strategies. It is imperative to cultivate awareness regarding the ongoing challenge of **effectively communicating with policymakers and the general public to instil trust** in ENV RIs advanced datasets, environmental research, and measurements. This aspect necessitates sustained attention and effort.

In the **H&F** domain, RIs are central in **addressing health-related challenges**. These range from enhancing diagnostic efficiency to advancing drug and treatment development, addressing pandemic threats, ensuring food security and safety, and devising strategies to enhance the food supply chain. Their interdisciplinary collaborations, involving domains such as Genetics, Nutrition, and Public Health, are instrumental in biomedical research, addressing challenges such as infectious diseases and antimicrobial resistance. They also emphasise the importance of skills development and capacity building in the H&F sectors, aligning with HE missions like Cancer and Climate Adaptation.

This chapter has underscored the interconnected and multifaceted nature of Research Infrastructures. Their combined impact on scientific advancement, societal welfare, and the tackling of global challenges is evident. This impact is significantly bolstered by the power of interdisciplinary collaboration, skills and capacity building, and the integration of Open Science and digital technologies. The broader impacts of RIs on policy, the economy, sustainability, and environmental protection highlight their vital role in shaping a more informed, sustainable, and prosperous future. **[see Table 3]**

	MAIN CONTRIBUTIONS	IMPACTS	IMPACT IN KEY POLICY AREAS
DATA, COMPUTING AND DIGITAL	Seamless interoperability, promoting Open Science, accelerating Research & Innovation	Democratised scientific knowledge, digital transformation in research	Facilitating the EU's digital single market strategy, promoting Open Science and digital collaboration
ENERGY	Sustainable economic development, energy security, skills & workforce development	Sustainable energy transitions, international collaboration, strategic energy independence, economic growth	Aligning with, and contributing to improving, EU's Green Deal and energy policies, contributing to decarbonisation and Sustainable Development Goals
ENVIRONMENT	Advanced data provision for environmental research, education and training, promoting sustainability and climate action	Data-driven environmental policy, sustainable development strategies	Contributing to EU environmental policies and sustainability goals, data-driven policy making
HEALTH & FOOD	Improving health outcomes, food safety, biomedical research, addressing global health challenges	Advancements in healthcare and nutrition, alignment with Horizon Europe missions	Supporting EU health policies, contributing to public health and food safety initiatives
PHYSICAL SCIENCES & ENGINEERING	Multi-Messenger research on fundamental Physics, Astronomy, Quantum Materials Science, Nanoscience	Cross-domain innovation, next-gen diagnostics and treatments	Supporting EU's research and innovation strategies, influencing policy in Material Science, pharmaceuticals, and other application fields
SOCIAL SCIENCES & HUMANITIES	Evidence and data about society and cultural heritage. Analysis of societal values and behaviour Insights in cultural and societal development, hereunder AI ethical implications, shaping societal values, integrating digital tools in research	Data-driven knowledge about society and culture Responsible technology development, enhanced research impact through evidence for policy	Providing evidence for EU policies in various fields, such as social policy, climate policy, R&I policy. Influencing EU policies for the development of fair social policies hereunder on digital ethics, shaping societal values and responsible technology development

TABLE 3.

Summary of key contributions and impacts per knowledge domain in the current landscape

MULTIPLE DIMENSIONS OF THE LANDSCAPE

As we delve into the evolving landscape of Research Infrastructures, we are met with a realm where innovation and tradition intersect, creating a multifaceted tapestry of scientific endeavour. The present chapter aims to unravel this complexity, shedding light on the overarching themes that are redefining the essence of RIs: Technological Convergence, Sustainability and Green Innovation, Adaptive Response to Global Challenges, Data-Driven Research Paradigm, and Ethical and Societal Responsibility.

These themes are not mere facets of scientific progress but are the keystones shaping the future trajectory of Research and Innovation. These dimensions collectively forge a path toward a future that is not only technologically advanced but also ethically grounded and responsive to the ever-evolving needs of society.

CHARTING THE FUTURE: EMBRACING SUSTAINABILITY, AGILITY, AND ETHICS IN RIS

Technological Convergence: At the heart of several modern RIs lies the convergence of strongly developing technologies. Digitalisation, AI and quantum computing are shaping a new era of scientific discovery and innovation.

Sustainability and Green Innovation: The pursuit of sustainability transcends specific domains and permeates every facet of society, making it a crucial theme in contemporary RIs. This encompasses efforts to develop sustainable energy systems, materials which can be sourced and used sustainably, and environmentally benign practices that align with major goals regarding health, climate, and biodiversity protection. However, this pursuit is often challenging, given that RIs typically operate at the forefront of technological progress where sustainable solutions are still to be developed.

Adaptive Response to Global Challenges: The capacity of RIs to rapidly adapt and respond to global challenges, such as health crises, environmental changes and biodiversity loss, is crucial and has already been proved during the COVID-19 crisis. This involves developing flexible infrastructures that can pivot to meet emerging global needs, such as pandemic response or climate resilience, and the Sustainable Development Goals (SDG) as defined by the United Nations.

Data-Driven Research Paradigm: The shift towards data-intensive research methodologies is redefining scientific inquiry across all domains. This paradigm shift involves harnessing big data, improving data analytics, and ensuring data interoperability for enhanced research outcomes.

Ethical and Societal Responsibility: As RIs advance, there is a growing emphasis on ethical considerations and societal impact, in that future technology and practices should not cause significant environmental or social harm. This dimension encompasses responsible research practices, addressing societal challenges, and ensuring that technological advancements align with ethical standards.

ENACTING TRANSVERSAL ELEMENTS ACROSS RI DOMAINS

Building upon the foundational understanding established in the previous section, we transition to an analysis of the transversal elements and the practical application and operational realisation of overarching themes across RIs domains. This section delves into the tangible aspects of RIs, dissecting how the key concepts of Digitalisation, Greening, Crisis Preparedness and Response, Data-intensive Approaches, and Inter-, Multi-, Transdisciplinarity are actively woven into the fabric of various RI domains. Each transversal element is intrinsically linked to the broader dimensions previously explored, exemplifying how strategic visions are translated into actionable realities.

As we navigate through these elements, we uncover the synergies between theoretical concepts and practical implementations, highlighting the **dynamic and interconnected nature of modern RIs**.

Figure 1 visually represents the linkage between the transversal elements in the RIs landscape and their corresponding overarching multiple dimensions. Each transversal element (on the left) is connected to the relevant key concept (on the right) through lines, illustrating the practical realisation of the broader themes in specific operational contexts.

LINKING TRANSVERSAL ELEMENTS TO MULTIPLE DIMENSIONS IN THE RI LANDSCAPE

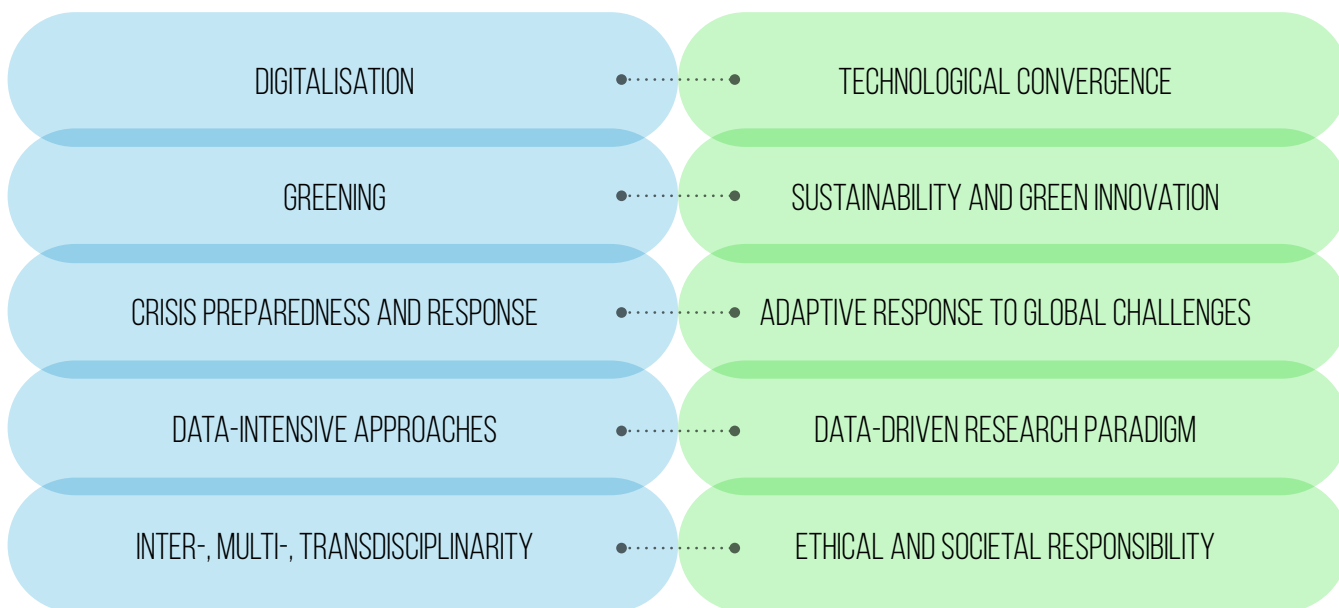


FIGURE 1.

Synergy in science: mapping transversal elements to key dimensions in Research Infrastructures.

DIGITALISATION

Digitalisation acts as a practical realisation of the technological convergence. For instance, the EuroHPC enables high-performance computing and data sharing across various scientific fields, enhancing research capabilities in domains like H&F and ENV.

GREENING

Initiatives for operationalising sustainability, aimed at reducing environmental impacts, are evident in domains like ENE, where technologies with low carbon dioxide emission footprint can be developed. Greening initiatives are transversal, spanning various domains. A general requirement for greening is that domains such as SSH and PSE should also contribute. For instance, PSE can contribute to reducing the material intensity of the economy.

CRISIS PREPAREDNESS AND RESPONSE

Translating adaptive response into action, RIs in the H&F domain have played a crucial role in crisis management, exemplified by rapid Research and Development during the COVID-19 pandemic.

DATA-INTENSIVE APPROACHES

Reflecting the shift to data-driven research, RIs across domains emphasise standardised data sharing, security, and accessibility. An example is the ENV domain's reliance on integrated data for climate action and biodiversity conservation.

INTER-, MULTI-, TRANSDISCIPLINARITY

Interdisciplinary collaboration is essential for operationalising ethical and societal responsibility. To address complex challenges ethically and responsibly, collaboration across domains is crucial. This is exemplified by the collaboration between RIs from different projects funded under Horizon Europe missions.

RESILIENCE IN ACTION: RIS PIVOTAL ROLE IN CRISIS AVOIDANCE AND MANAGEMENT

Research Infrastructures across various domains play a crucial role in crisis management, offering crucial support in understanding, responding to, and recovering from diverse challenges.

In the **DIGIT** domain, the exploitation of synergies between **EuroHPC** and **EOSC** holds the potential for immeasurable impacts. e-infrastructures have already influenced RIs and RI Clusters through computing and data infrastructures, establishing a foundation for crisis-related analysis, simulations, and decision-making.

The value of **SSH** research is acknowledged for contributing to societal resilience and policymaking. Building ties between the SSH cluster and EOSC, particularly with the interconnection between EOSC and EuroHPC, presents an opportunity for enhanced integration. SSH RIs, through platforms and coordinated data collections, can play a pivotal role in articulating complex research questions as well as understanding societal shocks and formulating effective crisis responses.

ENV RIs collaborate across operational and research ecosystems within their domain, offering essential data for environmental crises. Their transversal elements, including observational platforms and networks, enhance early warning systems and support post-disaster recovery.

H&F RIs significantly contribute to Horizon Europe missions, addressing health crises, safe treatments and predictions, and ensuring food safety. Leveraging expertise and collaborative networks, RIs in this domain play a crucial role in crisis preparedness, re-

sponse, and recovery, providing access to state-of-the-art facilities and data for accelerated research.

Avoiding a crisis is better than managing it. Several major potential future crises relate to energy supply or environmental disruption caused by energy production and use. **RIs can enhance Europe's energy security and independence by exploring new scenarios for sustainable energy production, distribution, and use.** Optimising the multifaceted energy system demands multidimensional approaches spanning many research fields and the full Research and Innovation cycle.

ENE RIs provide a unique base of competences which will be useful in relevant acute situations, providing crucial technical and practical support for society and decision-makers. Recent geopolitical tensions, as evidenced by the Ukrainian conflict, have emphasised Europe's need to reassess its energy supply chain resilience. The current reliance on non-European sources for critical components of the green transition, such as solar cells and batteries, represents a strategic vulnerability. Energy RIs must pivot not only to support the existing transitions but also to ensure Europe's long-term energy independence. By accelerating the development of domestic technologies and securing a self-reliant supply chain, Energy RIs will underpin Europe's strategic autonomy in energy technology, while

simultaneously bolstering its capacity for crisis resilience. This strategic realignment is essential as Europe fortifies its energy systems against external shocks and move towards a truly integrated and sustainable energy policy.

The domain of **PSE** illustrates the impactful role of RIs through history and in recent advancements. Their contributions are broad, covering areas from medical technologies and imaging to innovative materials for the circular economy, and pioneering energy solutions like Photovoltaics, Generation IV fission and fusion. These RIs are crucial in diagnosing global challenges, providing essential training, and transferring expertise. They facilitate the development of technological solutions critical during crises, underscoring their vital contribution to societal welfare and economic development. Through their work, PSE RIs are at the forefront of detecting problems and driving technological innovations, demonstrating a pivotal role in crisis management and the broader scientific ecosystem.

Interdisciplinary collaboration is decisive in crisis management, addressing societal challenges, and facilitating transitions. **ES-FRI's role in fostering cross-domain collaboration is underscored to enhance links for effective crisis response.**

Additionally, recognising the **significance of AI in crisis management is essential.** AI tools applied in the SSH domain contribute to understanding crises. Discussions on AI should incorporate social and cultural dimensions to enable decision-making during crises.

SCIENTIFIC FRONTIERS: ALIGNING RI LANDSCAPE WITH HORIZON EUROPE'S VISION

The landscape of European Research Infrastructures has been intricately intertwined with the Horizon Europe (HEU) missions, reflecting a dynamic interplay between scientific endeavours and societal challenges⁴. Across various domains, RIs contribute significantly to the realisation of HEU missions, playing a pivotal role in advancing research, innovation, and addressing key societal goals.

4. EU Missions in Horizon Europe
https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe_en

The **DIGIT** domain's landscape is marked by the potential for synergies between **EuroHPC** and **EOSC**, forming a critical foundation for future developments. RIs facilitate the **seamless interoperability** between these pillars, enhancing computing and data infrastructures. If realised, this synergy promises significant impacts, especially in crisis management scenarios. RIs, through their computing capabilities, contribute to mission-oriented objectives by providing advanced tools and solutions.

The **SSH** landscape emphasises the value of research in contributing to **societal resilience, sustainable development, and policymaking**. RIs in this domain are particularly called upon to build ties and bridges with **EOSC**, ensuring that they contribute to the sustainable European advanced computing infrastructure. Integration initiatives, such as interoperability between social surveys, or RIs in the Humanities like **CLARIN ERIC** and **DARIAH ERIC**, are proposed to maximise synergies and create a cohesive core of data for informed policymaking.

Within the **ENV** domain, the landscape encompasses collaboration between observational and research ecosystems, underscoring the multifaceted nature of Environmental Science. Environmental RIs address global challenges outlined in the United Nations' 2030 Agenda⁵, aligning with EU priorities such as the Green Deal and

5. The United Nations 2030 Agenda for Sustainable Development
<https://sdgs.un.org/2030agenda>

digital transition⁶. **ENV RIs contribute to sustainable development, climate action, and disaster risk reduction, proving crucial in tackling SDGs**, such as 'Climate Action' (SDG 13), 'Life below Water' (SDG 14) and 'Life on Land' (SDG 15), and EU missions, such as 'Adaptation to Climate Change' and 'Restore our Oceans and Waters by 2030'.

The landscape in **H&F** sees RIs as **essential contributors to HEU missions**. RIs support Horizon Europe missions with particular focus to 'Cancer', 'Adaptation to Climate Change', 'Restore our Oceans and Waters', 'A Soil Deal for Europe', and '100 Climate-Neutral and Smart Cities by 2030'. By providing access to cutting-edge facilities, data, and expertise, RIs accelerate progress towards achieving mission goals. The transformation of RIs in H&F, embracing digitalisation, sustainability, and collaboration, aligns with the broader objectives of HEU.

In the **ENE** domain, RIs are positioned at the core of the green and digital transitions. Rooted in the advances of cutting-edge science and technology, a new wave of innovation is underway: **deep tech innovation**. New technologies for robust, secure, economic, and socially and environmentally benign energy systems will be a cornerstone of Europe's future well-being. Energy RIs are extremely well-aligned with the currently defined European objectives, and this sector can be expected to remain cen-

6. A Europe fit for the digital age
https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age_en

trally relevant for the foreseeable future. Moreover, recent geopolitical events, notably the Ukrainian conflict, have highlighted the critical issue of Europe's overreliance on external sources for key energy technologies such as solar cells and batteries. This dependence poses a stark risk to the EU's strategic autonomy and economic security. In response, there is an urgent need to bolster internal capacities through RIs, fostering the development and scaling of **homegrown innovations** in these sectors. Strengthening Europe's position in the global energy technology market not only supports the green and digital transitions but also ensures a more resilient and self-reliant energy future.

PSE RIs have fundamentally transformed our understanding of the universe and our place within it, offering unparalleled insights at the very limits of time and space resolution. By enabling the detection and harnessing of new natural forces, they act as **catalysts for disruptive technologies and innovations**, thus aligning seamlessly with the transformative goals of Horizon Europe missions. Beyond basic research, these RIs extend their impact to a multitude of domains including environmental, social, cultural and energy research. Their contributions are vast, from exploring the mysteries of Astronomy and Astroparticle Physics, shedding light on the origins and structure of the universe, to advancements in Particle and Nuclear Physics that push the boundaries of what we know about matter and the forces that govern it. The cross-cutting nature of Analytical Physics RIs is evident in their support for research in Materials Science, enabling breakthroughs in medical technologies and treatments for diseases, imaging for H&F, development of materials for a circular economy, and strategies for climate change mitigation. Examples of such pioneering work include the **European XFEL** for probing the atomic details of viruses, or the **ESRF-EBS** for advancements in Materials Science.

EVOLVING PARADIGMS: THE NEXT HORIZON IN RI INTEGRATION AND INNOVATION

The cross-disciplinary and cross-domain challenges within the Research Infrastructures landscape are integral to addressing the complexities of crisis management, Horizon Europe missions, and the green and digital transition. Inter-, multi-, and transdisciplinarity are recognised as crucial, yet the existing domain-oriented structure poses challenges for fostering collaboration across diverse RIs. Synergies between domains should be enhanced, especially by involving RIs from the **SSH** domain in environmental considerations.

Networking and clustering of RI access and services should be prioritised to facilitate seamless cooperation, supporting research communities across all domains. This is essential to harness the collective strength of RIs in addressing societal challenges, HEU missions, and the green and digital transition.

Furthermore, a layer of complexity and opportunity is added by the integration of RIs with advanced technologies and deep tech expertise. This integration aims to accelerate innovation and to engage citizens in new technologies, such as AI and Machine Learning, as well as big data, communications and networks, cybersecurity, data protection, and virtual reality. AI tools are increasingly applied in all domains, demanding a wider, informed discussion about the **potential ethical implications and societal values embedded in these technologies**.

The challenges posed by the evolving landscape, including interdisciplinary demands and the integration of AI, underscore the necessity for further fostering cross-domain synergy and collaborative approaches within the ESFRI RIs ecosystem.

The transformation of RIs towards interdisciplinary collaboration and the integration of AI is crucial for positioning RIs as effective contributors to crisis management, HEU missions, and the broader green and digital transition, aligning with the evolving needs of society.





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