PART2

LANDSCAPE ANALYSIS

PART2
CONTENTS

The Landscape Analysis provides the current context of the most relevant Research Infrastructures that are available to European scientists and to technology developers typically through peer review of competitive proposals. It provides an advanced analysis of the scientific needs and existing Research Infrastructure gaps as well as directions for strategic investments in the future that would help maintain Europe's leadership in the global context. The Landscape Analysis adopts a more service-driven and impact-oriented approach maintaining the principle of excellence science.

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

The Landscape Analysis is composed of three sections.

SECTION 1

PAGE 37

consists of six chapters – one per scientific domain – and describes the state of play of all Research Infrastructures in the corresponding thematic area, their contributions to support frontier research and to provide key data necessary to address the *Grand Challenges*.

Each domain is structured, when needed, in areas or subdomains of research. The gaps, challenges and future needs are analysed for each group of thematic RIs and summarised. For each scientific domain, more general scientific trends have been identified to outline the directions in which the European Research Infrastructure landscape should evolve.

SECTION2

PAGE 117

is an analysis of the interconnections of the different Research Infrastructures, including more general scientific trends across the different scientific domains.

Specific examples of interconnections are shown and discussed indicating in what areas and in which forms the different RIs could work together, and which needs can be addressed by stimulating scientific collaboration across different disciplines. The information on RI-specific interconnections with other domains for the ESFRI Research Infrastructures in Operation Phase or in advanced Preparation Phase is included.

SECTION3

PAGE 147

focuses on the Research Infrastructure services and their broader impacts, describing not what the landscape is, but what it can do. This section has been developed in the form of selected examples in three main areas:

- the analysis of the relevance of ESFRI Research Infrastructures for Sustainable Development Goals (SDGs);
- the analysis of capacity of RIs to respond to emergencies (as for example in the case of the COVID-19 crisis);
- the contribution of ESFRI RIs to the digital transformation (including EOSC).

This section has been prepared to showcase the relevance of RIs for societal challenges, including the capacity to respond to any type of emergencies, and for innovation. Examples have been collected from the ESFRI Landmarks and new potential ESFRI Landmarks.

The Landscape Analysis has been realized by the Strategy Working Groups in the **DATA, COMPUTING & DIGITAL RESEARCH INFRASTRUCTURES (DIGIT)**, **ENERGY (ENE)**, **ENVIRONMENT (ENV)**, **HEALTH & FOOD (H&F)**, **PHYSICAL SCIENCES & ENGINEERING (PSE)**, and **SOCIAL & CULTURAL INNOVATION (SCI)** for the respective domains.

PART2

LANDSCAPE ANALYSIS

SECTION 1

THEMATIC AREAS

The Section 1 of the Landscape Analysis describes the state-of-play of all Research Infrastructures in the corresponding thematic area, their contributions to support frontier research and to provide key data necessary to address the *Grand Challenges*. Each domain is structured, when needed, in areas or subdomains of research. The gaps, challenges and future needs are analysed for each group of thematic RIs and summarised. For each scientific domain, more general scientific trends have been identified to outline the directions in which the European Research Infrastructure landscape should evolve.

The Landscape Analysis in the thematic areas has been realized by the Strategy Working Groups in the respective domain

40 DATA, COMPUTING & DIGITAL RESEARCH INFRASTRUCTURES
48 ENERGY
62 ENVIRONMENT
76 HEALTH & FOOD
88 PHYSICAL SCIENCES & ENGINEERING
104 SOCIAL & CULTURAL INNOVATION

CONTENTS

42 CURRENT STATUS
43 NETWORKING AND OTHER SERVICES
44 DATA INFRASTRUCTURES
45 COMPUTING INFRASTRUCTURES
46 THEMATIC e-INFRASTRUCTURES
47 GAPS, CHALLENGES AND FUTURE NEEDS

PART2

LANDSCAPE ANALYSIS - SECTION1

DATA, COMPUTING & DIGITAL RESEARCH INFRASTRUCTURES

DATA, COMPUTING & DIGITAL RESEARCH INFRASTRUCTURES

A Digital Infrastructure (DI) is broadly defined as a set of information and communication technology components that are the foundation of ICT-services. These include typically physical components - computer and networking hardware and facilities - but also various software and network components.

The term e-Infrastructure is commonly used to indicate advanced fully integrated communication and information processing services, which provide transparent, easy, cheap and secure access to all types of distributed resources - computers, databases, heavy research instruments.

Digital Infrastructures are expected to boost research, growth, innovation and job creation, and it is clear that education of digital scientists and practitioners are a priority for Europe as this can effectively give people the knowledge, skills and competences to use and benefit from scientific data. Recent discussions around 5G and COVID-19 contact tracing amplify the need for European sovereignty when it comes to Digital Infrastructures and the handling of data. It is important to recognise that Digital Infrastructure control and data regulation are complementary and can be combined in various ways[1].

The European e-Infrastructure landscape includes Networking, Computing, and Data Infrastructures, on the national, regional and institutional level. The e-Infrastructure services at the European level are often being provided by federating national e-Infrastructures in a collaborative setting, and the European initiatives are therefore dependent on the existence of strong and coherent national e-Infrastructure nodes[2]. To describe this ecosystem, e-IRG has introduced the concept of the e-Infrastructure Commons in its White Paper 2013[3]. Building on this and other notions the concept of the European Open Science Cloud (EOSC) has emerged.

The **EUROPEAN OPEN SCIENCE CLOUD** is an environment for hosting and processing research data to support European research. The EOSC gained rapidly impetus and attention with the definition of an implementation roadmap in March 2018[4].

The European Open Science Cloud intends to offer to the researchers a virtual environment with open and seamless services for storage, management, analysis and re-use of research data, across borders and scientific disciplines by federating existing Data Infrastructures.

EOSC is being co-created in a series of projects funded by the European Commission and initiatives from Member States (MS) and Associated Countries (AC). The contribution of MS and AC will constitute the bulk of the resources that will be made available by the contributing organisations and thus their role is of fundamental importance also in the governance of the EOSC. EU countries and countries associated with Horizon 2020, represented in the EOSC Governance Board, agreed unanimously to run the EOSC as a co-programmed European Partnership under Horizon Europe from 2021.

The EOSC Association[5] was established as International non-profit Association under Belgian Law (AISBL) law on 29th July 2020 with four founding members: GÉANT, CESAER, CSIC and GARR. Members and Observers of the EOSC Association include research funders, research performing organisations, Research Infrastructures, data service providers and others. As of today the activities of the Working Groups of the EOSC Executive Board have produced several important results[6] one of which is the document *Solutions for a Sustainable EOSC - A FAIR Lady report* from the EOSC Sustainability Working Group, which explored possible means for sustaining the EOSC beyond its initial phase. The launch of the European Partnership for the EOSC, in close cooperation with the Members States and the respective research communities was on the 23rd of June 2021. The new EOSC European Partnership will ensure, until at least the end of 2030, a coordinated approach from the European Commission and the stakeholders in investments and initiatives in the EOSC ecosystem with the help of the Member States and Associated Countries. An EU investment of almost € 500 million and an in-kind contribution of the partners of also € 500 million are foreseen in the period 2021-2027. The aim is to improve the storing, sharing and reusing of research data across borders and scientific disciplines[7].

1. New report on European Digital Infrastructure and Data Sovereignty. A policy perspective (2020) https://www.eitdigital.eu/newsroom/news/archive/article/new-report-on-european-digital-infrastructure-and-data-sovereignty/

2. National Nodes - Getting organised; how far are we? e-Infrastructure Reflection Group (2020) http://e-irg.eu/catalogue/eirg-1006

3. e-IRG White Paper 2013. e-Infrastructure Reflection Group (2013) http://e-irg.eu/documents/10920/11274/e-irg-white-paper-2013-final.pdf

4. Implementation Roadmap for the European Open Science Cloud. Commission Staff Working Document (2018) https://ec.europa.eu/transparency/regdoc/rep/10102/2018/EN/SWD-2018-83-F1-EN-MAIN-PART-1.PDF

5. EOSC Association https://www.eosc.eu/

6. Working Groups of the EOSC Executive Board https://www.eoscsecretariat.eu/eosc-working-groups

7. Launch ceremony of the EOSC European Partnership https://ec.europa.eu/info/news/launch-ceremony-eosc-european-partnership-during-ri-days-2021-2021-jun-23_en

Since the beginning of the year 2019, five ESFRI Cluster projects – PaNOSC, ENVRI-FAIR, EOSC-Life, ESCAPE, SSHOC – have been launched to link to the European Open Science Cloud. The five ESFRI Cluster projects aim together to implement interfaces, to integrate computer and data management solutions, to create cross-border and open cooperation spaces and to promote clouds via the EOSC portal for a larger user community. As stakeholders of EOSC these projects were invited to contribute to the development and implementation process. The overall expectation of these projects is that EOSC will enable the accessibility and re-use of research data, increase scientific value of research data, and deliver an interoperable environment of Data Infrastructures. The projects expect EOSC will bring the added values of the infrastructure for sustainable use of research data and a virtual research environment enabling real-time collaboration between researchers using FAIR data[8].

II CURRENT STATUS

e-Infrastructures[9] 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). Federated, national Infrastructures and European initiatives will benefit scientific communities by providing trusted and open environments to store, share and re-use scientific data and results, as well as benefit from fast connectivity, high-capacity cloud solutions, and supercomputing capability system.

Throughout the MS and AC, a large variety of data processing services are available: from local, regional, and national services to international services. Large, international scientific collaborations have often created their own e-Infrastructure ecosystem, for example, the Worldwide LHC Computing Grid (WLCG), the highly distributed data processing approach for CERN's LHC experiments. Historically, two general classes of computation have provided data processing: High-Throughput Computing (HTC) and High-Performance Computing (HPC). HTC systems involve running many independent tasks that require a large amount of computing power and are optimised for large data processing tasks. HPC is commonly used to describe super-computing facilities, which process data in parallel and are optimised for a maximum number of computing operations per second. Although communities and their use cases could be generally assigned to one of the two computing models until around 2010, in recent years, more and more cases of heterogeneous use cases have emerged, which require a mix of both, high-data throughput and large number of computing operations per second, and thus, demand heterogeneous systems. The separation of the different types of computing e-Infrastructures is at least in part due to European funding strategies and organisations.

Based on a partnership model, EGI and EUDAT co-ordinate at an international level significant HTC and data services, whereas HPC centres join the **ESFRI Landmark PRACE** partnership initiative and participate in EuroHPC. The mission of PRACE is to enable high-impact scientific discovery and engineering research and development across all disciplines to enhance European competitiveness for the benefit of society. PRACE seeks to realise this mission by offering world-class computing and data management resources and services through a peer-review process.

The **ESFRI Project SLICES** is a distributed e-Infrastructure that focuses mainly on cloud and edge computing, Internet of Things (IoT) and networking/future internet. Traditionally, the e-Infrastructures focussed on centralised High-Performance Computing, distributed High-Throughput Computing, storage or network but it is true that dedicated e-Infrastructure on cloud and edge computing, IoT and networking has been missing in the European Roadmap of Research Infrastructures. As the clear difference between computing, network and storage is vanishing, the infrastructure SLICES in the Roadmap 2021 covers the gap. Providing the research and engineering community with a fully controllable, programmable virtualized Digital Infrastructure test platform distinguishes this infrastructure from more traditional/operational infrastructures as well. SLICES will allow academics and industry to experiment and test future, possibly long-term and disruptive DIs, essential for European research: a holistic and comprehensive approach whereby all computing, networking, storage, and IoT resources can be combined to continuously design, experiment, operate, and automate DIs full life cycle management, providing a playground for research on Future Internet and distributed systems.

The **ESFRI Project SoBigData++** (henceforth SBD++) aims to establish a European infrastructure of big data and social data mining, using new methods and implementing it in differ-

8. ESFRI cluster projects position papers (January 2020) *https://www.fairsfair.eu/sites/default/files/ESFRI_clusters_position_on_EOSC_jan_2020_v1.pdf*

9. Landscape of EOSC-related infrastructures and initiatives. Report from the EOSC Executive Board Working Group (WG) landscape (2020) *https://op.europa.eu/it/publication-detail/-/publication/cbb40bf3-f6fb-11ea-991b-01aa75ed71a1*

ent fields of data analysis. This is in line with current scientific trends in machine learning and data science to promote ethically sound and open research in large datasets that democratizes the value of data science. SBD++ is expecting to become the leading RI for realizing large-scale social mining experiments.

The **ESFRI Project EBRAINS** is defined as the *one-stop-shop* that is offering scientists and developers the most advanced tools and services for brain research. Human Brain Project (HBP), which is one of the FET flagship projects, is the developer and the provider of EBRAINS. As HBP has the internal means to create a self-contained structure, it is a challenge to create an outward looking environment and the questions that are raised show much this is already the case and how much effort would it need to serve groups that are not part of the original HBP project. The overall Digit Landscape is represented in **Figure 1**.

NETWORKING AND OTHER SERVICES

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

In terms of organisation and funding, the European NRENs are diverse. Some are funded directly from government budget; 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 focussing on just the network. Nevertheless, they have important similarities. All NRENs offer high-performance networks suited to the special needs of research and education, with the headroom required for the bursts in traffic which are unique to research and large instruments, and the capability to serve research collaborations like ESFRI's with specialised network support.

Additionally, all European NRENs offer critical access and identity services such as eduroam and eduGAIN. 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, the 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 provide users with highly reliable, unconstrained access to computing, analysis, storage, applications and other resources, to ensure that Europe remains at the forefront of research. GÉANT interconnects 38 NREN partners, and it is the largest and most advanced Research & Education (R&E) network in the world. GÉANT connects over 50 million users at more than 10,000 institutions across Europe and supports all scientific disciplines. The backbone network operates at speeds of up to 500 Gbps and reaches over 100 national networks worldwide. Since its establishment over 20 years ago, the GÉANT network has progressively developed to ensure that European researchers lead international and global collaboration. Over 1,000 terabytes of data are transferred via the GÉANT IP backbone every day.

More than just an Infrastructure for e-science, it stands as a positive example of European integration and collaboration. GÉANT 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. With more than 40 partners and associates across Europe and a multi-million euro budget, GÉANT has met the challenge of complex international project management. GÉANT also provides consultancy on network-related projects. GÉANT has national members (one per state) and representative members (represent at least two legal entities of different countries), associate (no voting rights) and the possibility of establishing working committees. According to the most recent report: more than 80% of the universities are connected to GÉANT, with 86% of all university-level students serviced in those 40 countries; that is, a total of 25 million university students. The GÉANT network reaches in excess of 50 million users involved in Research & Education in the region. GÉANT network also offers connectivity to other world regions (AfricaConnect2, CAREN, EUMEDConnect3, EaPConnect, TANDEM and others).

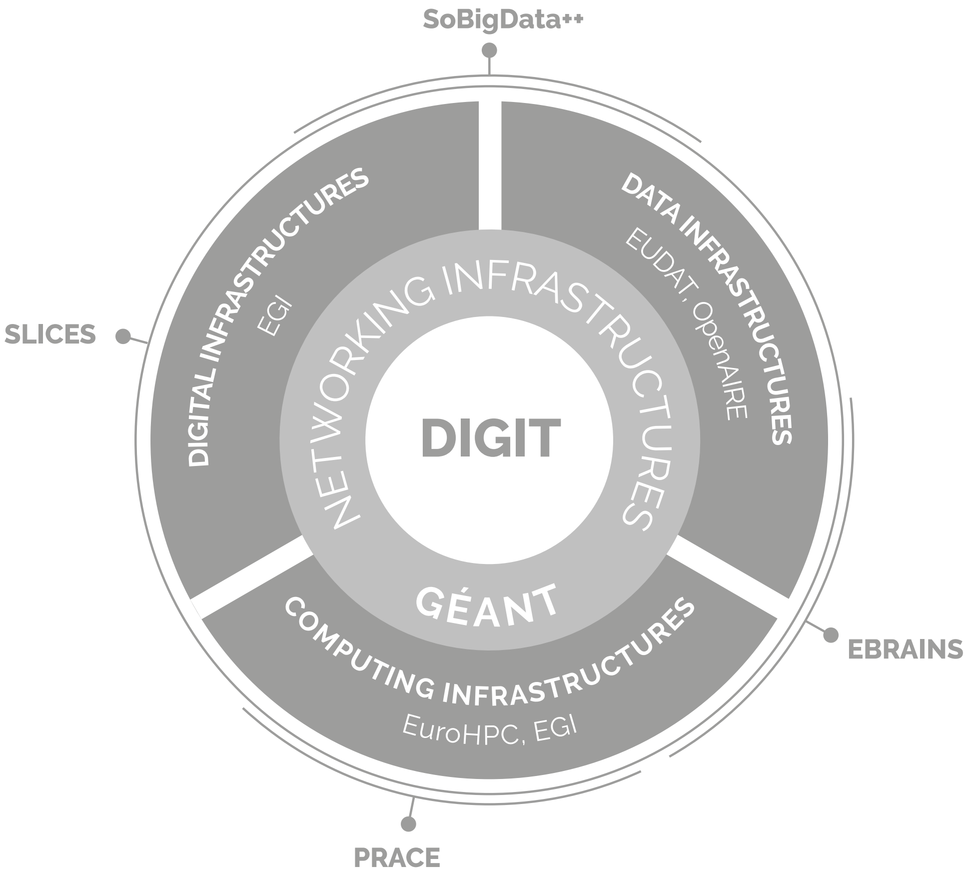

FIGURE 1.
The Landscape of the Data, Computing & Digital Research Infrastructures domain

DATA INFRASTRUCTURES

According to the Open Data Institute definition, "Data infrastructures consist of data assets supported by people, processes and technology". In the context of this report, we consider Data Infrastructures the technical and human infrastructures, which support management and sharing of research data. The Re3Data project provides a global research data repository registry.

EUDAT is a Collaborative Data Infrastructure (CDI), which manages data spanning from European research data centres and community data repositories. EUDAT aims to support sharing and preserving data across borders and disciplines. European researchers and practitioners from any research discipline can preserve, 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 geographically distributed, resilient network distributed across 15 European countries. Data is stored alongside some of Europe's most powerful supercomputers. One of EUDAT's main ambitions is to bridge the gap between RIs and e-Infrastructures through an active engagement strategy, using the communities that are in the consortium as EUDAT beacons and integrates others through innovative partnerships. EUDAT offers common data services, supporting multiple research communities as well as individuals, through a network of 36 European organisations. Its main services are the following: B2DROP, B2SHARE, B2SAFE, B2STAGE, B2FIND, B2HANDLE and B2ACCESS. EUDAT has a dual governance structure. As a EU-funded project, it operates through the respective bodies found in most EU projects, i.e. as defined by its Consortium Agreement. As an e-Infrastructure that provides a set of common data services, it operates on the basis of the EUDAT CDI.

Generic and thematic service providers may join the EUDAT CDI network by signing a specific collaboration agreement.

Scholarly communication initiatives and services are a relevant component of the current landscape, especially for the long tail of science. These initiatives originated from the movement to provide open access to publications, but are now applying open access principles to data (e.g. FAIR data) and other types of research products. **OpenAIRE** is a key initiative in this area having started as a supporting facility for Open Access (OA) policy of FP7 and H2020, and developing a set of mechanisms to implement and monitor open science in Europe. Services, which OpenAIRE can provide within the EOSC, are:

- a recognised national network of 35 nodes (National Open Access Desks), which are expert organisations offering local support, training and policy alignment on Open Access and Research Data Management (RDM);
- a suite of standards, the OpenAIRE Guidelines for Content providers, and services to allow content providers to make publications, data, software to share them in EOSC following open and FAIR principles (more than 1000 already registered);
- a set of services to help researchers do open science;
- Zenodo – a catch-all repository;
- Argos – an actionable DMP service linked out of the box to EU and national infrastructures;
- Amnesia – an anonymisation tool;
- the OpenAIRE Research Graph, a global contextual catalogue of research results linked together which is the basis for intelligent, AI-based discovery;
- the Open Science Observatory to monitor different aspects of open science in Europe.

COMPUTING INFRASTRUCTURES

Computing Infrastructures typically include High-Performance Computing optimised for high memory and CPU intensive tasks and High-Throughput Computing optimised for tasks which can be divided into subtasks which distributed across multiple servers; however, Infrastructures for more specialised computing architectures also exist (e.g. GPU clusters).

At the European level, there are two significant infrastructures supporting HPC: the **EuroHPC JU** (EuroHPC Joint Undertaking, JU) and the **ESFRI Landmark PRACE**.

The EuroHPC Joint Undertaking has acquired pre-exascale and petascale supercomputers (the EuroHPC supercomputers) which will be located at and operated by supercomputing centres (Hosting Entities) in the Union. Once these systems come online, the Joint Undertaking will manage the Union's access time – from 35% up to 50% of their total capacity – of these supercomputers. From April 2021, access time will be 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.

The EuroHPC Joint Undertaking was established to enable the co-ordination of efforts and the sharing of resources at European level with the objective of deploying a world-class High-Performance Computing Infrastructure and a competitive innovation ecosystem in supercomputing technologies, applications and skills in Europe. EuroHPC JU will permit the EU and participating countries to co-ordinate their efforts and share resources with the objective of deploying in Europe a world-class supercomputing Infrastructure and a competitive innovation ecosystem in supercomputing technologies, applications and skills.

The Members of the Joint Undertaking are the following:

- the European Union, represented by the Commission;
- Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Montenegro, the Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and Turkey;
- the European Technology Platform for High-Performance Computing (ETP4HPC) Association and the Big Data Value Association.

EuroHPC JU is developing a world-class supercomputing Infrastructure and has started with the procurement and deployment in the EU three pre-exascale supercomputers (capable of at least 1017 calculations per second) and five petascale supercomputers (capable of at least 1015 calculations per second) that will be located across the European Union and will be available to Europe's private and public users, scientific and industrial users everywhere in Europe.

The three pre-exascale supercomputers will be located at the following supercomputing centres:

- Lumi (Large Unified Modern Infrastructure) in CSC – IT Center for Science, Finland
- LEONARDO (precursor to exascale supercomputers) in CINECA, Italy
- Mare Nostrum 5 in Barcelona Supercomputing Centre, Spain

The five petascale supercomputers are located in the following centres:

- IZUM, Slovenia
- IT4Innovations National Supercomputing Center, Czech Republic
- Minho Advanced Computing Centre, Portugal
- Luxprovide, Luxembourg
- Sofiatech Park, Bulgaria

The **ESFRI Landmark PRACE** offers a pan-European supercomputing Infrastructure, providing access to computing and data management resources and services for large-scale scientific and engineering applications at the highest performance level. PRACE aims to support all scientific disciplines that need HPC to achieve high impact discovery by offering world-class computing and data management resources and services through a centralised peer-review process. PRACE members provide the computer systems and operations accessible through PRACE. Four hosting members – BSC representing Spain, CINECA representing Italy, GCS representing Germany and GENCI representing France – secured funding for the initial period from 2010 to 2016. PRACE has 26 members, representing European Union Member States and Associated Countries.

The PRACE RI has two forms of members:

- Members – a government organisation or legal entity representing a government. The PRACE RI accepts only one member per Member State of the European Union or an associated country as described in article 217 of the European Union Treaty. Further, to be eligible as a PRACE RI member the legal entity must be responsible for the provisioning of HPC resources and associated services.

- Hosting Members are members who have committed to fund and deliver PRACE RI computing and data management resources. There are 5 Hosting Members: France, Germany, Italy, Spain, and Switzerland.

In 2017, PRACE has engaged in the second period of the Partnership, securing the operations of the infrastructure until 2020, and adding a fifth Hosting Member, ETH Zurich representing Switzerland. During this second phase, PRACE will offer an initial performance above 62 Petaflops in 7 complementary leading-edge systems, offering a total of 4,000 million core-hours per year (75 million node hours).

PRACE also offers training services to users, through the PRACE Advanced Training Centre (PATC), PRACE Training Centres (PTC), PRACE seasonal school, and through online training material, including Massive Open Online Courses (MOOCs). Some joint training activities are provided by PRACE and EUDAT. PRACE is also using some services of GÉANT's network e-Infrastructure to provide European users access to Tier-0 systems. The PRACE project partners received funding from the EC under the PRACE Preparatory and Implementation Phase Projects for a total of € 97 million, complemented by the consortium budget of over € 60 million. PRACE is now in its 6th Implementation Phase Project. PRACE offers its computing services to projects or entities and the services of other e-Infrastructures (such as EOSC and GÉANT).

In terms of HTC, at the European level, **EGI** is a federated e-Infrastructure initially set up in order to provide advanced computing services for R&I using grid-computing techniques but which now also encompassed cloud computing Infrastructures. EGI is publicly funded and comprises over 300 data centres and cloud providers spread across Europe and worldwide. EGI offers a wide range of services for compute, storage, data and support. EGI has been funded by a series of EC research projects such as DataGrid and Enabling Grids for e-science.

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 intensive science and innovation.

Regarding the services, EGI delivers advanced computing services to support scientists, multinational projects and RIs. The 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 and data, training. EGI provides access to over 700,000 logical CPUs and 500 PB of disk and tape storage.The services can be requested by anyone involved in academic research and businesses and they can be categorised in the following groups: computing, storage and data, training. EGI provides access to over 700 000 logical CPUs and 500 PB of disk and tape storage.

THEMATIC e-INFRASTRUCTURES

RIs are key elements of modern research. By providing services to a very broad variety of users, they create a shared and collaborative research environment, the so-called RI ecosystem, which has shaped big science for decades. In Europe, this includes the creation of the European Organization for Nuclear Research (CERN) in the mid-1950s, for particle physics research, and the European Southern Observatory (ESO) for astronomy in the early 1960s. From their early beginnings, both of these large RIs faced the challenge of managing large amounts of data they produced by developing data technologies and related policies.

RIs also had to develop schemes and processes to overcome challenges raised by the growth of the number of transnational RIs, the increased complexity of scientific problems and societal challenges (often requiring the collaboration of diverse user communities) and the exponential growth of data. Data protocols, quality control and management plans throughout the entire data lifecycle were developed along with the relevant technologies. Thematic RIs are therefore an indispensable and even a driving element of the EOSC data management chain.

The importance of thematic services provided to users of an RI and their interoperation with generic e-Infrastructures has been recognized by ESFRI by adding explicit attention to the development e-Needs in the lifecycle analysis of RIs. The ESFRI Roadmap thereby identifies the needs of the European scientific community in terms of Research Infrastructures including e-Infrastructures.

An example of this interdependency is the collaboration between CERN, SKAO, GÉANT and PRACE, which will see the organisations work together to help realise the full potential of the coming new generation of HPC technology. During an initial period of 18 months, the collaboration will develop a benchmarking test suite and a series of common pilot 'demonstrator' systems. The next-generation of HPC technology offers great promise for supporting scientific research. Exascale supercomputers – machines capable of performing a quintillion, or a billion billion, calculations per second – are expected to become a reality in the next few years. This change in the power of HPC technology, coupled with growing use of machine learning, will be vital in ensuring the success of big science projects scheduled to come online this decade, such as SKAO and CERN's High-Luminosity Large Hadron Collider.

GAPS, CHALLENGES AND FUTURE NEEDS

Despite the tremendous progression on Digital Research Infrastructures in general and e-Infrastructures for research in particular there is still a need for a (distributed) Research Infrastructure, which enables top quality computer science on the development of digital infrastructures itself. Another interesting development related to the collaboration between industry and publicly funded e-Infrastructures concerns GAIA-X[10]. This is a project initiated by Germany and France aiming to develop common requirements for a European Data Infrastructure. In September 2020, 22 companies and organisations – 11 from Germany and 11 from France as founding members – established an international non-profit association under Belgian law, the GAIA-X, European Association for Data and Cloud. The focus of GAIA-X is more industry oriented while EOSC is largely composed by public research organisations. The current collaboration opportunities and expectations between EOSC and GAIA-X are still unclear, although there are potential commonalities: both intend to create "a federated data infrastructure based on European values". Common ground could emerge between GAIA-X and the next iteration of EOSC (serving industry) as described in the *Fair Lady report*.

The biggest challenges for the coming years will lie in further developing the EOSC concept into a working ecosystem, that serves the needs of the European research communities. These challenges broadly concern two levels: i) the interplay between generic and thematic e-Infrastructure service provisioning, and ii) the federation of institutional and national services up to the European level. Most of these challenges are organisational rather than technical.

The initial steps should lead to what is called a *Minimum Viable EOSC*, consisting of an EOSC Core, which should provide the functionality that is required to enable open science practices to occur across domains and countries according to the EOSC interoperability framework, the federated data and the EOSC Exchange, a digital marketplace that builds on the EOSC-Core to offer a progressively growing set of services exploiting FAIR data and encouraging its reuse by publicly funded researchers.

Many aspects need to be addressed among which the most important ones are: (i) implementation of this EOSC Core; (ii) definition of an architecture (Hardware and Software) that will allow to deploy new services; (iii) provide support and competences for turning to FAIR those data that are currently not compliant but are of interest for the scientific communities; (iv) create incentives for the researchers in making research data open and contribute to the creation of skills and careers in Data stewardship; (v) refine the sustainability and funding of EOSC with the correct mix of community support and business model.

10. GAIA-X: A Federated Data Infrastructure for Europe
https://www.data-infrastructure.eu/GAIAX/Navigation/EN/Home/home.html

CONTENTS

50 ENERGY SYSTEMS INTEGRATION
50 CURRENT STATUS
52 GAPS, CHALLENGES AND FUTURE NEEDS

53 RENEWABLE ENERGY
53 CURRENT STATUS
54 GAPS, CHALLENGES AND FUTURE NEEDS

55 EFFICIENT ENERGY CONVERSION AND USE
55 CURRENT STATUS
56 GAPS, CHALLENGES AND FUTURE NEEDS

57 NUCLEAR ENERGY
57 CURRENT STATUS
59 GAPS, CHALLENGES AND FUTURE NEEDS

59 CROSS-SECTIONAL ENERGY RIs
59 CURRENT STATUS

PART2

LANDSCAPE ANALYSIS - SECTION1

ENERGY

ENERGY

A secure and cost-efficient energy supply is a major factor for social and economic development. Worldwide the energy sector has very high growth rates due to rapidly rising GDP in quite a number of countries. However, power and heat supply for the different sectors contribute significantly to global CO2 emissions and have other major impacts on the environment.

On one hand, for the medium term, the transformation of the energy system towards a climate neutral and environmentally and socially compatible energy system has been and will further be one of the major global challenges worldwide. On the other hand, this necessary transformation also provides market opportunities for new technologies both for application within and outside of the EU.

The EU has made the underlying political and technological objectives to one of its major fields of activity, which is reflected by a great number of large strategic activities, e.g., the Green Deal that has been launched recently. The common efforts need persistent investments, starting from R&D infrastructures which provide the basis for innovation.

It is expected that the energy transformation has to be achieved by more flexible, more integrated ways of provision, consumption, transport and storage of energy while at the same time promoting the development of existing and novel energy technologies. Energy innovation is driven by a common effort from industry and research as well as from the society. In contrast to other, more long-term-oriented fields of science, due to a high market-pull energy research is in many ways a highly dynamic field, with rapidly changing requirements and fast learning curves in terms of TRL-levels – e.g. the development of hydrogen technologies in the recent years. Moreover, the complexity of any energy system in a society leads to the consideration not only of TRL but also of System Readiness Level, which often does not receive enough attention. To jointly achieve the objectives of climate protection and economic growth, a technology-open approach is necessary, following different R&D pathways that lead to an integrated system with tailor-made solutions optimally adapted to locations, consumer needs, environmental and socio-economic requirements, as well as consideration on material resources and their cyclic use. Energy RIs, therefore, have to provide the necessary flexibility and, at the same time, offer reliable and sustainable services to their community.

Energy Research Infrastructures (RIs) have a major role in joining Europe's efforts to drive forward, test and demonstrate technologies and their interplay in the future energy system. To a great extent they are interdisciplinary undertakings, as expertise from Physics, Engineering, Computer Science, Earth Sciences and other academic fields, such as Environmental, Social and Economy-related Sciences, have to work together to develop and implement energy technologies and system solutions. This is reflected by strong interactions of the energy field with other ESFRI domains. Especially in the highly diversified field of energy, ESFRI RIs have the potential to accelerate developments by leveraging synergies for the respective technological community. In addition, to ensure maximum impact, integration into the international community[1] by adequate cooperation instruments is important.

This Landscape Analysis for the Energy domain is divided in five main subfields: **ENERGY SYSTEMS INTEGRATION** – including networks, transport, storage and smart cities/districts; **RENEWABLE ENERGY** – solar, renewable fuels, wind, geothermal, ocean; **EFFICIENT ENERGY CONVERSION AND USE** – energy in buildings and in industry, Power-to-X, CCSU; **NUCLEAR ENERGY** – fusion and fission; and **CROSS-SECTIONAL ENERGY RIs** – materials and data, simulation and modelling. For each subfield, the Current Status will be presented, followed by an analysis of the Gaps, Challenges and Future Needs.

A representation of the organization of the Energy Landscape and the portfolio of Energy RIs is shown in **Figure 1**.

A few comments could be made. Firstly, while it is widely recognized that the Energy field is of paramount importance for achieving a sustainable development in Europe and in the world, both the total number of RIs is low and their distribution indicates a lack among some of the fields identified in the Landscape Analysis: being a strategic document, this should be highlighted to the ESFRI stakeholders. Secondly, the nature of the RIs is very diversified: some are distributed ones and can enter into operation on a short time scale, others are single-sited with very high investment costs and long construction time before operation. For example MYRRHA, which was recently assessed as having a very high scientific value, has an operational horizon around 2035 with a cost estimate of € 1.6 billions.

1. The European Research Infrastructures in the International Landscape (RISCAPE) https://riscape.eu/

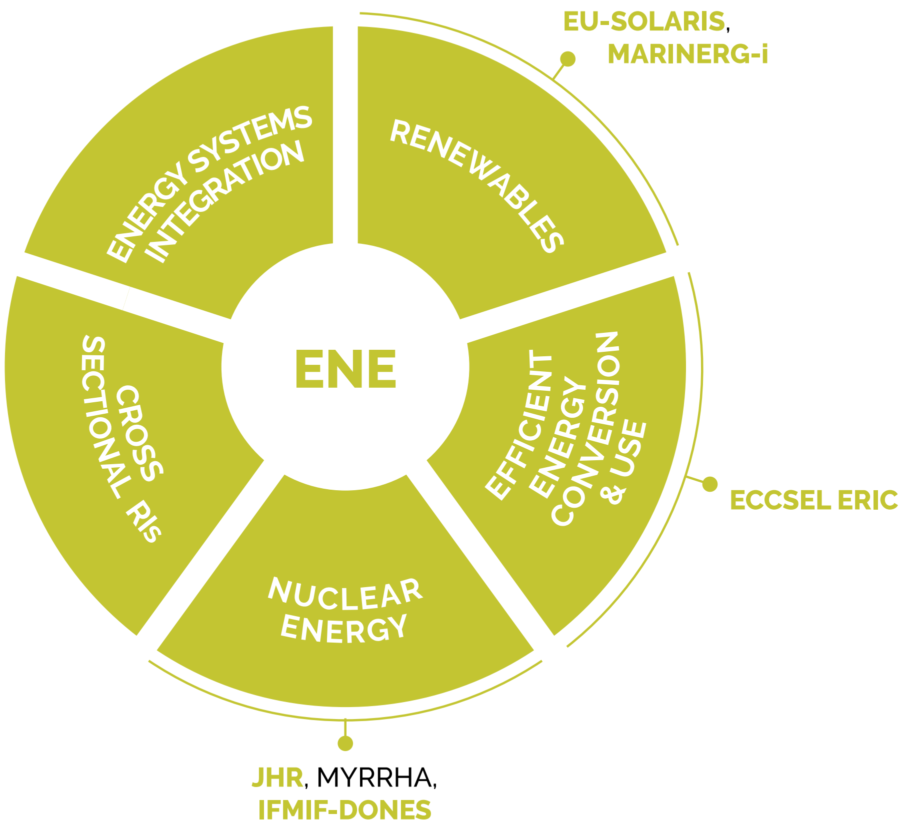

FIGURE 1.
The Landscape of the Energy domain.

ENERGY SYSTEMS INTEGRATION

In May 2019, the EU launched the EU Clean Energy Package[2] which in itself is an integration of eight legislative acts that contribute to shaping the Energy Union and fulfilling the EU's Paris Agreement commitments. This will also provide and incentivise further significant investments in sustainable energy infrastructure for smart energy distribution, storage and transmission systems. European Regional Development Fund (ERDF) support is also available to improve energy efficiency and security of supply through the development of smart energy systems[3]. The Clean Energy Transition Partnership and SET-Plan under Horizon Europe Research & Innovation programme 2021-2027 and the Energy Roadmap 2050[4] also highlight the expectation that fossil fuels will continue to have a role in European primary energy in the foreseeable future. It is thus of utmost importance to boost energy efficiency in concert with sustainable use of effective energy sources and carriers[5]. However, there is a need to research the design, operation and integration of all parts of the energy systems of the future in a safe and secure manner as Europe transitions from a traditionally centralised system of generation to a much more distributed energy generation portfolio. This main focus of this section is on the technical aspects of the future energy systems and their integration. It is also important to point out that the socio-economic and human behavioural aspects are of equal importance as the Energy Citizens rights and entitlements are at the heart of the new EU Clean Energy Package.

2. Clean energy for all Europeans package
https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en

3. Energy Plan – Smart Energy Systems
http://www.energyplan.eu/smartenergysystems/

4. Energy Roadmap 2050, Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the regions, COM(2011) 855 final, 15.12.2011
https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0885:FIN:EN:PDF

5. Energy Efficiency and its contribution to energy security and the 2030 Framework for climate and energy policy, Communication form the Commission to the European Parliament and the Council, COM(2014) 520 final, 23.07.2014
https://ec.europa.eu/energy/sites/ener/files/documents/2014_eec_communication_adopted_0.pdf

II CURRENT STATUS

ENERGY NETWORKS

The future European energy system, with an envisaged much higher penetration of renewables given the Member States increased ambitions and requirements under their National Energy and Climate Plans (NECP's), needs an extremely strong interplay between different energy carriers such as electricity, heating and cooling – e.g. gas and other chemical fuels. Such a system demands control of intermittent production from renewable energy and variable consumption of all carriers as well as energy storage which is an important technology to stabilize the power fluctuations and to define economically and environmentally sustainable options. *Smart Grid* refers to a progressive evolution of the electricity network towards "a network that can intelligently integrate the actions of all users connected to it – generators, energy storage facilities and consumers in order to efficiently deliver sustainable, economic and secure electricity supply and safety". It is a combination of the grid control technology, information technology and intelligence management of generation, transmission, distribution and storage. Energy Management Systems (EMSs) are vital tools to optimally manage the interplay across the variety of systems components, system grids and networks. In fact, the need for new EMSs to minimize emissions, costs, improve security at different spatial and temporal scales is the basis of the RIs in this field that implement the interaction among equipment, communication protocols, simulation and control. Over 450 demonstration projects with different RIs have been launched in Europe exploring system operation, consumer behaviour and new innovative technologies. As these systems evolve it will become an ever-increasing requirement to also research the supply chain demands of materials required for the network infrastructures.

ENERGY STORAGE

Energy Storage on different scales has a crucial role to support energy system stability and security. The energy storage market is starting to develop: costs have been one of the major constraints, as well as regulatory issues, EMSs, and technology capabilities. Advanced EMSs that can coordinate distributed storage over the energy the grids are a challenge for the development of large scale transmission and distribution grids and for the satisfaction of different kinds of demands (electrical, loads, thermal loads, etc.). RIs to support the design and evaluate grid reference architectures are required. Demonstration and test of energy storage at medium and large scale, including the possibility to test completely novel components and new materials, will give practical information on the use and benefits of the new and emerging energy storage technologies and potential contribution to key policy goals set for Europe.

The main players in the electricity/smart grid arena are the European Network of Transmission System Operators for Electricity (ENTSO) and the European Distribution System Operators (EDSO): they aim at implementing a flexible electrical network including a number of demonstrations, similarly to the European Technology Platform for Smart Grid. Major European universities have built up infrastructures beyond the laboratory scale to operate in real case studies.

The main strategic research agenda challenge is to be able to build and control, through flexible and fast EMSs, an energy infrastructure which can be adapted to a large variety of production and storage systems – weather based energy production, controllable plants, solid state and gas based storage systems – from the development of single component to a complete complex energy system – e.g. a city level energy system involving heat, electricity and transport. Most smart energy network projects have focused on enabling the electricity system to match electrical demand with the variable electricity production of renewable sources however, these should also look at a mix of energy carriers. Therefore, future energy systems need to develop the potential to deal with the challenges of even more complex combinations of demand, supply and distribution. Such test systems should combine meteorological forecasts, energy production facilities (central and distributed), storage devices and systems, end-user components, penetration of renewable, different energy carriers like electricity, heating/cooling and gas including new market models. Building integrated smart energy network/storage testing and demonstration infrastructure will give manufacturing companies the possibility to test new equipment and EMSs, power producers and network operators' new knowledge about how to operate a future energy network that will strengthen the competitiveness of industry. The ongoing R&D activities on new storage materials and system capacity and energy trading tools could enable the Smart Grid/Energy system and compare well to expensive grid extensions or curtailment approaches. The results of such RI will facilitate decisions on investments connected to the transformation of the energy system for companies as well as for public operators.

EFFICIENT LOW EMISSION TRANSPORT

Transport accounts for over one quarter of the EU Greenhouse Gas emissions and the target is to reduce this by 60% by 2050. The electrification of private transport (as that sector is responsible for over 70% of transport emissions) is starting to gain market traction, however the roll-out is still hampered by costs and some political and techno-economic uncertainties around the roll-out of charging infrastructure. More energy efficient, low emission fuelled vehicles are a significant part of the European Energy System and have an important role to play in achieving EU policy objectives of reducing energy consumption, CO2 emissions, and pollutant emissions. The Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles[6] aims at a broad market introduction of low emission vehicles. A decarbonised energy system can assist towards meeting the future energy demands of the transport sector, with the availability and reducing cost of low emission vehicles. The environmental and technical requirements in the development of battery technology has led to the research of new forms of electrical storage and while there are clear signs of progress there are still issues to overcome. Smart mobility, multi-modal transport, low emission transport and urban mobility are particular priorities given the emergence of extremely aggressive reductions in national transport emission targets under the NECPS. The EU Clean Energy Package also supports investments in infrastructure for smart energy distribution, storage and transmission systems (particularly in less developed regions) and will assist the development of new transport solutions. It is also possible to receive EU support for low-emission transport research investments under the SET Plan aiming at promoting more sustainable multimodal urban mobility services.

In order to make sure that these investments achieve maximum impact, particular emphasis is placed during the 2021-2025 period on the need to ensure a sound strategic environment.

SMART CITIES, COMMUNITIES AND LIVING LABORATORIES

Smart Cities and Communities emphasis has slowly advanced from energy efficiency in buildings to districts and cities. When coupled to appropriately design physical systems, including for example transport systems and thermal energy storage systems, Information and Communication Technology (ICT) can contribute to effective

6. Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles
https://ec.europa.eu/transport/themes/urban/vehicles/directive_en

energy use and interactive balancing of real-time energy supply and demand in cities and communities. Well-designed urban interactive ecosystems can become smart sustainable cities and communities that use ICT-enabled systems and tools to tackle complex environmental and sustainability challenges. The EU is continuing to support rolling out smart city lighthouse projects to demonstrate drastic improvements and interactions in urban energy (including large-scale building renovation), transport, ICT. This is to be firmly embedded in long-term city planning and user participation, and to facilitate transfer of best practices to other cities and communities. The European Innovation Partnership on Smart Cities and Communities (EIP-SCC)[7] aims to promote integrated solutions leading to sustainability and a higher quality of life. The EERA Joint Programme on Smart Cities contributes to this purpose with new scientific methods, concepts and tools. Projects and umbrella networks are established to improve learning between and from these pilot projects. A mapping and analysis of Smart Cities in the EU was published by the EU Directorate-General for Internal Policies in 2014[8] also defining and benchmarking smart cities. Smart Cities can leverage the work of existing EU policy and programmes (e.g. CONCERTO, CIVITAS, Covenant of Mayors, future internet and Smarter Travel, among others) and major European initiatives such as EU Smart Cities Information System[9], Eurocities[10] or European Network of Living Labs (ENoLL)[11]. Shared access to data, with a specific challenge-focused approach, is an attractive proposition for researchers and assist urban decision makers.

7. European Innovation Partnership on Smart Cities and Communities (EIP-SCC)
http://ec.europa.eu/eip/smartcities/index_en.htm

8. Mapping Smart Cities in the EU
http://www.europarl.europa.eu/RegData/etudes/etudes/join/2014/507480/IPOL-ITRE_ET(2014)507480_EN.pdf

9. EU Smart Cities Information System
https://smartcities-infosystem.eu/

10. Eurocities
http://www.eurocities.eu/

11. European Network of Living Labs (ENoLL)
http://www.openlivinglabs.eu/

GAPS, CHALLENGES AND FUTURE NEEDS

ENERGY SYSTEM INTEGRATION

Some research gaps have been identified: improving decision support tools and their data requirements; definition of key performance indicators; smart strategies for "resource on demand" implementation including energy storage; real time knowledge of city parameters; common data repositories; optimization and control structures to integrate energy systems in smart cities; improved design, installation and control of urban energy systems. European RD&I can take a global lead on integration of smart (energy and communication) technologies in existing urban environments, adaptable to specific needs of users and communities. A wide variety of European cities have committed themselves to become urban laboratories to test, iterate and optimise these solutions and processes.

ENERGY NETWORKS AND STORAGE

The main gap is in the design reference architectures and modelling tools for wide scale flexible energy grid control systems that involve different kinds of energy and relate to the local scale (distributed -generation and low voltage grids). These grids will have to be able to deal with the combination of all use cases, including incentives to grid operators and electricity retailers in a liberalized market model whereby competing economical players work in parallel and operate commercial ICT systems to control a common grid infrastructure. Another gap is in the research into transactional arrangements and the testing of enabling economic systems such as blockchain for secure energy trading across multiple platforms that are resistant to cyber security threats. Alongside the electricity network gaps mentioned above there are also gaps in the provision of cost effective large scale energy storage via heat, chemical and physical storage solutions.

EFFICENT LOW EMISSION TRANSPORT

The focus on the need for low emission vehicles and the standardisation of testing of large scale impact is still a gap that needs to be filled. While the commercial vehicle developers are developing the vehicles, there is a lack of understanding on the impact and integration of large-scale electrification of transport on the grid as both an energy demand management enabler (e.g. vehicle to grid, storage system integration and other forms of balancing loads and managing demand across heat, electricity and transport systems) and other distributed storage systems as elements of not just the smart micro grid bus also of the broader energy systems. As the pace of development of electric and autonomous vehicles is picking, it will be important to have RIs to enable researchers to study the legal frameworks as well as the physical infrastructure within which these will operate.

SMART CITIES AND COMMUNITIES

There are still no dedicated Smart Energy City or Community test-bed related RIs in the ESFRI Roadmap. A solution linked to smart cities/communities initiatives could prove to be particularly pertinent and provide a strong business case for aiding future city and community designs. The same applies for Fuel Cell and Hydrogen (FCH), as the maturity of the technologies requires RIs to comply with the applied research requirements in line with industry's needs, including system testing and validation. We stress the important role of ICT, as this will be crucial in several important ways. Data protocols for sharing high volumes of information, attention to data privacy matters and a vision on how ICT will enable the future designs in urban form are all needed.

RENEWABLE ENERGY

Levelised cost of energy (LCOE) have dropped considerably over the last couple of years for renewable energy. This specifically holds for wind and solar photovoltaic (PV), due to the development of new and more efficient concepts (research) as well as economy of scale effects due to the rapid increase of deployment. For all renewable options, including solar PV and wind which have already a substantial market penetration, further massive cost reductions can be achieved through development of new concepts – i.e. tandem solar cells, PV printing technologies, 15 MW turbines. Deployment related barriers such as integration into the energy system, ranging from electric integration to esthetical integration, are of increasing relevance. New concepts require long-term research and state-of-the-art RI and substantial synergies can be obtained in sharing them.

CURRENT STATUS

PHOTOVOLTAIC SOLAR ENERGY

Joint Research Programmes such as the EERA Joint Programme on Photovoltaic (EERA JP-PV) as well as the European Perovskite Initiative for solar cells aim to optimize the use of RIs and contribute to improving EU research and competitiveness of European industry. Europe's competitive edge rests on the excellent knowledge base of its researchers and engineers along with the existing operating infrastructures. Given the increasingly competitive environment, without steady and reliable R&D funding, this advantage is at risk.

The rapid cost reduction of solar PV has continued and the deployment pace has further increased. Deployment related aspects, such as integration in the electricity system, circularity, visual integration as well as multiple use of space are becoming important barriers. The drop in LCOE offers the opportunity to develop and implement new concepts addressing these barriers that are or can become cost competitive. Mass customization, where PV products are tailored specifically to the end-use conditions, is expected to become the dominant way of application in the mid-term. This offers a huge potential to build up the full industrial value chain in Europe again, replacing the uniform mass produced modules that are yet imported. Although the LCOE for solar PV has dropped rapidly, still a substantial potential for cost reduction exist e.g. by increasing the efficiency through tandem solar cells. This requires substantial R&D efforts focusing on new concepts beyond incremental improvements.

RENEWABLE FUELS

The key advantage of renewable fuels obtained from renewable resources resides in that their exploitation does not consume the available stock. Yet, they are often seen only as a way to supply decarbonised fuels. Biofuels produced directly from a biomass feedstock such as ethanol (from sugar-rich or lignocellulose-rich biomass), bio-diesel (from vegetable oil) or methane (from bio digestion of biological wastes) are nowadays a mature technology heavily used in the everyday life of European citizens (e.g. for fuelling cars). The transformation of solid raw biomass into more standard fuels such as char coal or pellets is also considered as biofuels but mainly dedicated to the production of electricity in thermal power plants or for supplying heating to dwellings. This usage has seen an increasing interest the last decades, yet operational difficulties to ensure constant supply of biofuels or to control pollutant emissions and combustion conditions has limited the development of this energy vector. Further sustainable development of renewable fuels could be achieved through gasification of biomass into a synthesis gas that can be burnt in thermal engines modified accordingly. Renewable fuels can also be obtained by hydrolysis of water through electricity generated by renewable resources. To overcome the issues related to storage and transport, hydrogen can be introduced in different liquid or gaseous fuels (e.g. to generate ammonia, bio-methane or methanol) thus benefiting from an existing distribution network. There is a strong connection between renewable fuels and Power-to-X where the energy supply from biomass and renewable production are all merged into one single standardised fuel. Renewable fuels provide a unique way to supply standard fuels supplied from renewable resources and able to replace fossil fuels.

CONCENTRATED SOLAR POWER

Concentrated Solar Power (CSP) works by focusing incoming solar energy, producing heat, which can then be directly used to generate electricity or for some other purpose, or stored for later use. Significant concentrated solar power facilities were constructed in several European countries, propelling Europe to an early technological lead. These facilities are not only in the south but also, for example, in Germany and Denmark. CSP research and research collaboration is well established in Europe, not least through the **ESFRI Landmark EU-SOLARIS**. After a period of rapid European expansion of CSP production from about 2007 until 2013, generally reduced energy costs and increasing competition from photovoltaics led to lower rates of growth than had been envisaged, especially in Europe.

The possibilities for direct industrial use of heat and especially the implicit storage potential of CSP provide major advantages compared to photovoltaics, e.g. by allowing electricity production, in practice for a number of hours, when there is no incoming solar energy. As the proportion of non-dispatchable generation such as wind and photovoltaics in the grid system grows, the price premium for semi-dispatchable production will increase, possibly making CSP again more competitive. Future CSP research should therefore consider both unit costs for CSP production and CSP's possible future roles in the electricity and industrial systems in Europe and globally.

WIND ENERGY

Many initiatives coordinate the research activities in Europe: the European Wind Industrial Initiative (EWII) and EERA Joint Programme on Wind energy, European Technology and Innovation Platform on Wind Energy (ETIPWind) driven by the European wind energy industry and coordinated by the European Wind Energy Association, and the European Academy of Wind Energy. Upscaling of wind turbines is seen as one of the major pathways to reduce the LCOE of wind energy. It was expected that beyond a certain power, radical new concepts and new materials were needed. However, over the years the size and power of wind turbines have increased through incremental innovation. These innovations combined with large scale manufacturing have led to a rapid drop in LCOE and increase in deployment.

As holds for solar PV, deployment related aspects, such as environmental impact on marine life as well as birds and bats, circularity, visual aspects and specifically integration in the electricity grid, are now becoming important barriers. The potential for a further cost-effective decrease of the LCOE is huge, though substantial R&D efforts are required to harvest this potential. The share of offshore wind has increased rapidly over the last five years, however using specifically the potential offered by shallow waters. In order to harvest the huge potential for floating wind, substantial R&D efforts are still needed. On top of the existing RIs on wind turbine test fields, component test facilities, materials testing and wind tunnels, new facilities are required – e.g. on system integration and floating wind.

GEOTHERMAL ENERGY

While high temperature geothermal energy for electricity production in magmatic geological areas is well established, possibilities that may radically enhance production, such as use of deep superheated fluids, are being actively investigated. A number of major initiatives investigating Enhanced Geothermal Systems (EGS) are ongoing in Europe, including Finland, Germany, France, Switzerland and other countries. In EGS, the permeability of the deep subsurface is increased using hydro-fracturing and other methods, potentially allowing major geothermal production almost anywhere. Geothermal energy for heat and cold extraction and storage is an increasingly important component in the energy balance of buildings and major facilities are now in use or under construction in several countries.

A number of major challenges need to be addressed if the vast potential of geothermal energy production and storage is to be fully developed, including testing of engineering materials, drilling and stimulation (hydrofracturing) technologies including modelling and assessments of geomechanics and induced seismicity, and reservoir assessment and management, including, for example, co-use for geothermal and other purposes of space beneath large cities. Many relevant major research institutions are involved in the ongoing EERA Joint Program on Geothermal Energy.

OCEAN ENERGY

The recently launched EU Strategy[12] to harness the potential of offshore renewable energy for a climate neutral future provides a clear signal of commitment to the sector and a realisation that there is a need to use new renewable technologies including Ocean (Wave, Tidal and Floating wind) as well as grow offshore wind. The most relevant EU initiatives are: Clean Energy Transition SET Plan (including Ocean Energy) and European Technology and Innovation Platform and EERA Joint Programme on Ocean Energy (10 institutions from 8 EU countries); EU-OEA (80 members); OCEANERA-NET with EU research organizations from 9 countries; MARINET2 network with 57 testing facilities at 38 research organisations from 13 countries and the intergovernmental collaboration Ocean Energy Systems Technology Collaboration Programme OES with 21 countries.

The EU Strategy goal is to install 60 GW of offshore wind and at least 1 GW of ocean energy by 2030 and to reach 300 GW of offshore wind and 40 GW of ocean energy by 2050. However, many systems have not been tested yet under real operation conditions and need to undergo final long-term reliability testing before being commercially deployed at scale in harsh environments. There is widespread international interest in ocean energy and it is particularly high in Australia, Asia, US and South America. Currently there are a small number of ocean energy systems installed on the global level. Europe has global leadership in ocean energy technologies and industrial know-how[13].

12. An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future – Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions (2020) *https://ec.europa.eu/energy/sites/ener/files/offshore_renewable_energy_strategy.pdf*

13. Technology Market Report Ocean Energy, JRC117349 JRC (2019)
Facts and figures on Offshore Renewable Energy Sources in Europe, JRC121366 JRC (2020)

GAPS, CHALLENGES AND FUTURE NEEDS

In **PHOTOVOLTAIC SOLAR ENERGY**, it is important to establish a long-term European cooperation in the PV R&D sector, by sharing knowledge, organizing workshops, exchanging and training researchers to accelerate the implementation of innovative technologies in the European PV industry. Furthermore, it will be needed to install relevant pilot production lines to demonstrate these novel technologies and to bring back commercial manufacturing in Europe.

RI is needed for advancements in production of **BIOFUELS**, biomass upgrading as part of optimized logistics concepts, hydrogen production based on gasification with reforming, efficient cultivation systems for third generation biofuels sources and system integration schemes between different sources and with the grid.

The challenge of maintaining a stable grid system including a large volume of non-dispatchable renewables (largely wind and solar) is very large, in a future scenario without fossil fuels, and **CONCENTRATED SOLAR POWER** can in principle contribute to here, even on longer time scales – given sufficient economies of scale in the thermal storage. Lack of standardization is seen as an obstacle to rapid cost reduction and definitive deployment of the Concentrated Solar Power sector.

Concerning **WIND ENERGY**, better coordination of EU RIs should create the conditions for the long-term development. On top of the existing RIs, there is a need for new multi-actor facilities – especially in the field of integration of wind energy into the energy system as well as for floating offshore wind, which is expected to play a dominant role in harvesting the world-wide potential of wind energy.

The development of new **GEOTHERMAL ENERGY** technologies can be expensive and projects may be high-risk in the sense that commercial success is not guaranteed. Therefore, society cannot rely only on commercial initiatives, and public R&D support is often necessary. A coordinated trans-European initiative to co-exploit existing and new geothermal test sites would appear to be strongly motivated. Such an initiative would naturally link to and significantly enhance existing ESFRI initiatives such as the **ESFRI Landmark EPOS ERIC** (ENV).

In **OCEAN ENERGY**, the establishment of an integrated network of testing facilities is very important, including full scale sites for testing of single units under real operation conditions, as well as up-scaling to the array level (MARINET2, Foresea). There is a need for technical de-risking through the development and implementation of best practices, quality metrics and standards (MaRINET2, Marinerg-i). Increased joint development activity across the test infrastructure community is required to address the technical barriers and deliver viable devices to the market (see for example the **ESFRI Project MARINERG-i**).

EFFICIENT ENERGY CONVERSION AND USE

Seeking enhanced efficiency in energy production (actually, *harvesting* energy from the natural environment), conversion and use is an important and viable aim, even though it is likely that this will not lead to total reductions in energy use as long as the benefits of using more energy will be considered to outweigh costs, including environmental costs. Especially because of the increase in intermittent energy production from renewable sources, energy efficiency is in practice increasingly and intimately related to energy systems integration, and a systems perspective on efficiency is central. This can relate to the capacity factor of wind turbines and the source of electricity during low-wind periods, the use of relatively small-scale thermal storage functions in buildings to buffer variations in electricity production, or to a systems assessment where the true (energy) costs of improved new buildings or renovations is weighed against the potential energy savings. In the broader picture, it is often the true total system of costs and savings to society which should be in focus, not the energy producer's or consumer's perspective, which may be strongly affected by taxes and subsidies. It is likely that significant new Research Infrastructures will be necessary to optimally approach these challenges. As the future system is constructed, it is vital that it can reliably and securely supply the necessary base-load power at all times and at reasonable cost.

II CURRENT STATUS

ENERGY EFFICIENCY IN BUILDINGS

Energy use during the lifecycle of buildings has impact on both total energy efficiency and emissions, and should be considered. For example, concrete production leads to significant CO_2 release. Building design can increase energy efficiency and decrease CO_2 emissions by, for example, allowing future flexibility of use, avoiding energy-expensive constructions that reduce energy consumption during the use but are globally energy-ineffective, smart energy-use control systems, and suitable choices of materials. Also, area planning may indirectly contribute to reduced environmental impact through – e.g. effects on micro-climate and on patterns of human behaviour. The designs also need to consider possible future changes in climate and human activities for the envisaged lifetime of each construction. Neighbourhood heating and cooling systems, including major thermal reservoirs, may have an increasingly important role in contributing to energy efficiency and assisting in balancing future energy systems with significant amount of electricity from non-dispatchable sources.

Energy use for buildings is significant and deserves serious consideration: climatic and other conditions are very different in different parts of Europe, some relevant technologies are evolving, and patterns of human behaviour may change considerably in the coming decades. It follows that various research and demonstration infrastructures of different types and in different places will be important. The complexity and high costs of some relevant infrastructures implies that effective pan-European coordination is imperative.

ENERGY EFFICIENCY AND USE IN INDUSTRY

Several concepts mentioned above regarding buildings and the need for a systems perspective are also relevant for industry, which is a major consumer of energy. In addition, there are major possibilities for improved energy efficiency and/or reduced greenhouse emissions from many industrial processes, as well as for better use of some industrial waste products. Further automation, in traditional and new forms, computer-based modelling, and connectivity will continue to affect industrial production significantly, especially with increased ambitions regarding energy and materials efficiency, waste reduction, product quality and lifetime, and recycling.

Energy reserves (fossil fuels and others) are used in industry not only for energy but also, sometimes simultaneously, as feedstock or chemical reagents, for example for production of plastics, iron and cement. In such production, fossil-based hydrogen as reducing agent could be replaced by, for instance, hydrogen produced using electricity from renewable resources. Various major research and pilot projects are now ongoing in Europe, e.g. in the steel industry[14].

The European financing system should allow major public investment in research as well as pilot and demonstration plants which, while very important, may also be very expensive and in the "grey zone" between research and implementation. The high costs often involved mean that new insights and solutions developed in different European countries should be effectively spread.

POWER-TO-X (P2X) AND HYDROGEN TECHNOLOGIES

Because electricity supply and demand must match instantaneously, an electricity system heavily reliant on non-dispatchable electricity production from renewables will only be viable if there are effective components in the system ensuring that supply and demand balance. The most significant such component is likely to be electricity storage. Batteries are an unlikely solution since the volumes of storage achievable based on current lead- and lithium-based technologies is not sufficient. An alternative form of chemical storage of surplus electrical energy, for example in the form of hydrogen, appears to be fundamentally necessary, to be reconverted to electricity when necessary ("Power to x to power" or "P2X2P"). Considering the low recovery efficiency (about 30%) for electricity, the energy-carrying chemicals produced from surplus power may become important in the transport and industrial sectors, for example replacing fossil fuels in transport and in industrial processes.

If Europe's future energy system is to be dominated by electricity production from intermittent renewables – as opposed to other low emission technologies such as nuclear, geothermal or CCS – major investments in new research, pilot and demonstration plants for P2X, and later X2P, will be necessary. Many such initiatives are ongoing or planned, but significant improvements in efficiency and costs are necessary. Research on a broad front, from materials science to large scale energy systems appears necessary. The need for improved relevant technologies is clearly recognised in current EU policies.

14. Hybrit, Fossil-free steel https://www.hybritdevelopment.se/en/

CARBON CAPTURE STORAGE AND UTILIZATION

In Carbon Capture and Storage (CCS), carbon dioxide from some industrial process – e.g. electricity production from coal, or steel production – is separated from the exhaust of the plant, transported, and deposited in some suitable geological formation, where it is expected to remain indefinitely. CCS is today only viable for large, stationary facilities such as power plants. CCS will reduce total emissions irrespective of the origin of the captured carbon, e.g. from biomass, cement production or fossil fuel. It is possible that emission reductions achievable in this manner may in the future outperform many other emission reduction strategies, both in terms of cost and in terms of practically viable speed of large-scale implementation. In the Carbon Capture, Storage and Utilisation (CCSU) concept, some or all of the carbon is to be used or utilized as feedstock to some process. For instance, methane or some other hydrocarbon to be used as fuel or for some non-energy product could be produced by combining hydrogen with carbon from the carbon dioxide.

CCS is not a new concept, and projects that have been running for many years, including the **ESFRI Landmark ECCSEL ERIC**, demonstrate there is no doubt that large quantities of carbon can be captured, transported and stored. Costs are currently dominated by initial capture and have been relatively high. However, as sources of feedstock to the chemicals industry will continue to be necessary, CCS costs are likely to decrease as technology evolves, and the cost-premium of dispatchable electricity sources may increase considerably with increasing dependence on non-dispatchable renewables. There seems little doubt that if the EU and the world wish to reduce CO2 emissions significantly and on a relatively short time scale, then CCS should be considered and supported much more than is currently the case, a view supported for example by the IEA[15]. This implies that major investments in research, pilot and demonstration plants, as well as large-scale implementation are strongly motivated.

15. IEA https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage

GAPS, CHALLENGES AND FUTURE NEEDS

Energy research may have been too heavily focused on single components, rather than on the analysis of complex energy systems where the different elements interact. Research Infrastructures investigating systems in practical use would be of significant benefit. One example of this is the use of **ENERGY IN BUILDINGS** and the supply of energy from buildings. The latter may relate to production of electricity, for example, or to exploiting the thermal storage potential of buildings to facilitate the use of intermittent electricity production from renewable sources. Similarly, projects related to the use of waste products from industry for energy production, as well as for improved efficiency and savings, have significant potential. Realizing such potentials may demand research Infrastructure initiatives, leading into pilot and demonstration activities on commercial scale.

POWER-TO-X addresses core research questions on electrolysis and plasma-chemical conversion, including catalysis, materials, membranes and efficiency on one hand, and the synthesis of fuels and base chemicals on the other hand. For P2X processes to be a major component in the future energy system, they must be adequately energy efficient and cost efficient. Major investments, from research to pilot and demonstration plants, will be necessary to achieve this, with R&D tasks ranging from basic research to questions of up-scaling towards demonstration of large plants combining production and use. Local infrastructures and expertise in electro-chemical and plasma-chemical conversion, physical separation of gases and chemical synthesis need to be combined and developed on European scale for creating efficient and effective integrated P2X solutions. This gap could be filled by an ESFRI distributed RI bringing together resources and testing facilities of European industries as well as governmental and non-governmental organizations.

It remains unclear if large-scale **CARBON DIOXIDE CAPTURE, STORAGE AND UTILISATION** will become an important part of the energy system, but there is a possibility that this is the case. Therefore, further major investments in relevant Research Infrastructure should be considered among the topics mentioned above.

NUCLEAR ENERGY

Worldwide electricity consumption is constantly increasing, regardless of progress in efficiency of transmission or reduction of energy needs in industry. Even though the global role of nuclear energy is decreasing in the electricity mix, it continues to have an important share: from 2000 to 2019[16] the worldwide percentage of nuclear electricity dropped from 14.6% to 10.4%, while the total electricity increased by 75% and the nuclear electricity production increased by 8.7%.

The strategic objectives in nuclear energy are safety aspects, spent fuel and high-level waste management and disposal, developing next generation reactors with more efficient fuel use (less waste), preparing the experimental phase of ITER, and continuing the engineering design of a fusion DEMOnstration reactor.

II CURRENT STATUS

NUCLEAR FISSION

Nuclear fission plays an important role to provide a stable, base load electricity in the EU (about 25% in 2018[17]). The main strategic objectives are safety aspects and long-term waste disposal. In the field of Accelerator Driven Systems which could be used for transmutation of long-lived actinides, a staged approach was adopted by MYRRHA, leading to the full realisation of the facility by 2036. MYRRHA is part of an overall approach[18] – Partitioning & Transmutation (P&T) – to reduce the amount of waste that requires geological repository. Moreover, by recycling and reusing the fissile materials and minor actinides contained in the spent fuel, P&T decreases the need of fresh raw materials. While recognizing the high scientific value of the project, the Forum decided not to award to MYRRHA the status of Landmark in 2021, expecting in the next few years a stronger case for implementation, especially since the creation of an AISBL – International non-profit Association under Belgian Law – in September 2021. While the approach rests on the two legs, Partitioning and Transmutation, the field of Partitioning[19] is more mature. Therefore, the MYRRHA infrastructure, the scientific quality of which was fully recognized by the SWG evaluation, is needed in closing the fuel cycle as an approach to the problem of radioactive waste.

In many countries, lifetime extensions of existing Nuclear Power Plants (NPPs) need experiments on materials under ionising radiation. Here, the **ESFRI Landmark JHR** plays a significant role. High-performance computing (HPC) of material properties is also needed, which has great potential for a cross-fertilisation with other materials science in general and, in particular, in the field of nuclear fusion (see below).

In view of the ageing of NPPs, as well as the nuclear phase-out by some, decommissioning and radioactive waste management – with the related safety, economic and environmental aspects – are increasing in European, and several countries are accumulating experience. This is a field that, in the future, could benefit from a dedicated RI.

16. Statistical Review of World Energy
https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

17. Nuclear Power in the European Union – World Nuclear Association
https://www.world-nuclear.org/information-library/country-profiles/others/european-union.aspx

18. Hamid Aït Abderrahim et al. Partitioning and transmutation contribution of MYRRHA to an EU strategy for HLW management and main achievements of MYRRHA related FP7 and H2020 projects: MYRTE, MARISA, MAXSIMA, SEARCH, MAX, FREYA, ARCA. EPJ Nuclear Sci. Technol. 6, 33 (2020)
https://www.epj-n.org/articles/epjn/pdf/2020/01/epjn190057.pdf

19. e.g. partitioning of spent fuel from the Experimental Breeder Reactor was performed at Idaho National Laboratory using pyro-processing method
https://inldigitallibrary.inl.gov/sites/sti/sti/5411188.pdf

In the Sustainable Nuclear Energy Technology Platform (SNETP)[20], within its ESNII branch, the use of process heat and cogeneration are relevant topics (NC2I branch). Therefore, the GEMINI initiative[21] was dedicated to this topic. Small Modular Reactors (SMR), delivering up to about 300 MWe, are a new field of development[22]. Besides improved safety features, SMR are getting serious attention for district heating, where a major impact on CO2 emissions can be expected[23]. Hydrogen production is another subject of R&D, with an interconnection with Concentrating Solar Power. This is clearly a development with great potential for new business opportunities for the nuclear industry. The role of nuclear energy is greatly affected by public perception of related risks and benefits. Therefore, more cooperation with Social Sciences is needed, offering a clear interconnection with this other ESFRI domain.

Therefore, it can be seen how the fission field can give a contribution to the goals of CO2 emissions reduction. Moreover, it has clear interconnections with HPC and material studies, as well as with Social Sciences, features that it shares with the fusion field.

NUCLEAR FUSION

The European fusion programme[24] has two main objectives, to prepare for the successful operation of ITER[25], the first fusion device to create net energy, and to design the first power-producing facility, so-called DEMO, scheduled to be operational by the mid of the 21st century. Construction of ITER is in full speed, with a first plasma by 2025 and the D-T operation by the end of 2035. In addition, EUROfusion coordinates the use of all the main European fusion research facilities.

Within EUROfusion, two different reactor concepts are explored: tokamaks and stellarators. The tokamak-line of research has in the past produced superior plasmas and, thus, five tokamaks[26] are currently in operation. The JET tokamak in the UK, the only one with the ability to operate with D-T mixture and, thus, pivotal in the scientific preparation of ITER, will remain at disposal of the EU community, as the UK will stay in Euratom. In the framework of the Broader Approach (BA) Agreement[27], EU and Japan have completed the construction of JT-60SA[28], a superconducting JET size tokamak with some novel technologies (e.g. the 500 keV negative neutral beam). It will be jointly exploited starting this year and will contribute to the many key physics issues of interest for ITER. In addition, to study the crucial issue of power and particle exhaust in a reactor, a dedicated device, the Divertor Tokamak Test (DTT)[29] facility will be constructed in Frascati, Italy, with first experimental plasma expected in 2026. EU is hosting and exploiting jointly with ITER the Neutral Beam Test Facility (NBTF) in Padua, Italy[30].

The stellarators are attractive since they have intrinsically a steady state plasma. However, the confinement properties of stellarators have been inferior to those in tokamaks. HPC optimization of the magnetic configuration led to the construction of the Wendelstein 7-X (W7-X)[31] stellarator in Greifswald (Max Planck institute for Plasma Physics). The first experimental campaigns, started in 2016, have even exceeded many of the initial goals, sparking hopes. Thus, even in the DEMO design, the option for a stellarator device is kept open.

The ongoing EUROfusion in Horizon Europe (2021-2025) has a strong component on the DEMO design with two main goals: i) to produce a substantial amount of electricity, and ii) to be self-sufficient in tritium[32]. For the operation of ITER, a flight simulator is under preparation. A strong emphasis is on theoretical/numerical work for extrapolation to DEMO through the E-TASC initiative (EUROfusion Theory and Advanced Simulation Coordination), opening up new possibilities for fusion plasma simulation and for related materials science.

A fusion reactor requires materials that tolerate neutron irradiation. Within the BA, commissioning of the first components of the neutron source prototype IFMIF-EVEDA LIPAc installed in Rokkasho, Japan is under way[33]. The EUROfusion programme supports IFMIF and proposes the **ESFRI Project IFMIF-DONES** as an interim step.

Therefore, the fusion program is based on an international collaboration and competition, involving several countries outside of the EU, and is based on a solid roadmap with well-defined objectives and clear interconnections with HPC and material studies.

CROSS-CUTTING ISSUES BETWEEN FISSION AND FUSION

Materials research is the most prominent common topic to fission

20. Sustainable Nuclear Energy Technology Platform (SNETP)
https://snetp.eu/

21. Gemini Initiative
http://www.gemini-initiative.com/

22. Exelon completes SMR feasibility study for Polish programme – World Nuclear News
https://www.world-nuclear-news.org/Articles/Exelon-completes-SMR-feasibility-study-for-Polish

23. Good riddance to fossil fuels! VTT develops a Small Modular Reactor for district heating
https://www.vttresearch.com/en/news-and-ideas/good-riddance-fossil-fuels-vtt-develops-small-modular-reactor-district-heating

24. The EUROfusion programme – EUROfusion
https://www.euro-fusion.org/programme/

25. ITER
https://www.iter.org

26. ASDEX-Upgrade (Max Planck institute, Garching, Germany), JET and MAST (CCFE, Culham, U.K.), TCV (EPFL, Lausanne, Switzerland) and WEST (CEA, Cadarache, France)

27. The Broader Approach agreement between Japan and EURATOM covers many other activities.
https://www.ba-fusion.org/ba/

28. Advanced Superconducting Tomawak JT-60SA
https://www.jt60sa.org

29. DTT DIVERTOR TOKAMAK TEST facility
https://www.dtt-project.it/

30. Neutral Beam Test Facility (NBTF)
https://www.iter.org/construction/NBTF

31. Wendelstein 7-X
https://www.ipp.mpg.de/w7x

32. Tritium, a « fuel » of the fusion reactor does not exist in nature and must be produced by the fusion reactor itself, if one considers an industrial deployment of fusion electricity.

33. IFMIF/EVIDA
https://www.ifmif.org/

and fusion. For fission it is a key element for the prolongation of NPP operation. For fusion, it is crucial for the construction of a fusion reactor. The field of experimental investigation and numerical simulation are cross-cutting fields, while another is the development of accelerators to be used in ADS for fission and in a neutron source for fusion material irradiation. Both fusion and fission need to involve specialists in Social Sciences and Humanities to create good contacts and paths of communication with society. Collaboration with social sciences is important to understand the public opinion towards a highly complex and emotional topic such as nuclear energy. The role of nuclear power in transitioning from the fossil fuels should be analyzed by socio-economic approaches combined with technological ones.

GAPS, CHALLENGES AND FUTURE NEEDS

Several gaps have been identified: i) decommissioning and waste disposal of aging NPPs would benefit from a dedicated RI; ii) experimental effort on SMR should be intensified; iii) for fusion, the issue of material development requires to go from the Preparatory Phase to the Implementation Phase of the **ESFRI Project IFMIF-DONES**. A clear future need concerns disposal of nuclear waste produced in power plants. This concerns both countries abandoning and countries continuing with nuclear power. So far only Finland is constructing geological deposition, and there is an obvious need for reducing the amount of long-term radioactive waste EU-wide. The MYRRHA infrastructure could address this need but, at the time of writing of this report, is still working to procure the necessary financial commitments from additional partners for its full implementation.

In general, it may be advantageous for the EU to enhance international cooperation and to make a stronger effort to attract private financial resources into energy R&D&I.

Research on nuclear energy for deep space exploration is another sector worth of consideration for the EU. So are various applications of nuclear technologies with cross-cutting aspects with PSE, like for instance antineutrino detectors sensitive to reactor power and fuel changes.

While the role of renewable sources will be crucial in the long-term, during the transition period it will be necessary to support a broad range of R&D&I covering different ways of energy production including nuclear.

As research on nuclear energy is linked to national policies on the use of nuclear generated electricity, the above considerations of the research goals in this area do not engage, in any ways, national financial or political commitments.

CROSS-SECTIONAL ENERGY RIs

Energy sector is very broad and covers many areas of Research, Development and Innovation (R&D&I) and has crucial impact on society, industrial production, buildings, mobility and environment. R&D&I in the energy sector is closely connected with several research areas and more and more with bioeconomy and biotechnologies. For purpose of Roadmap 2021 three general cross-sectional energy RIs were identified in the following areas: i) energy materials; ii) artificial intelligence/deep learning; and iii) environment.

Publicly funded R&D&I in the energy sector is characterized by the transfer of innovative technologies to the industrial sector giving considerable advantage to the industrial companies. Due to this fact and taking into account the construction and operational costs of RIs, it would be important to involve private companies in construction or modernization of RIs in the future.

CURRENT STATUS

SPECIAL MATERIAL FOR ENERGY SYSTEM

Energy technologies with their high and rapidly changing technical demands are particularly dependent on fast innovations in the structural and functional materials sector. The main research task in this context is to develop resource-efficient materials with increasing performance and reliability at lower costs – e.g. new materials for long-distance transportation of energy, improved construction materials for nuclear energy. At European level the topic is addressed in various cross-sectional aspects of the current key actions to the Strategic Energy Technology Plan (SET-Plan) with research, development and innovation as key pillars of SET-Plan implementation. It finds expression in the strategy papers of correspondent research and industrial platforms – e.g. EERA, EIIs, EMIRI, Joint Technology Initiatives, or EURAMET. In addition, there is a strong need to continue in development of techniques for sophisticated, scale-bridging and multi-method characterization for energy materials and components in their working environment (*in situ/in operando*). This is especially the case for electrochemical/catalytic, electronic materials and devices or for materials under severe radiation.

Despite the availability of quite a number of methods and facilities, large cross-sectional RIs and research platforms explicitly dedicated to R&D or energy materials still often lack coherence with regard to combining results from different methods. The future of characterization therefore is expected not only to include individual techniques which are pushed to their limits, but also to create coherent and synergistic strategies employing a range of cutting-edge characterization methods to address complex multiscale problems in materials and systems. For all energy systems, circular use of either special material or other raw material should be considered.

ARTIFICIAL INTELLIGENCE/DEEP LEARNING (DATA, SIMULATION AND MODELLING)[34]

An important task in energy sector is integrating different research and innovative activities with the objective of developing and applying scale bridging approaches. High-throughput screening and data processing by using of Artificial Intelligence/Deep Learning approaches are key to increase efficiency of R&D&I, the intelligent combination of data derived from R&D&I and quick exploitation of new results in practice. Energy networks and systems, from local to macroscopic scales, need detailed and large volume data handling and model-based processing. Quite a number of cross- disciplinary energy-relevant topics have to be addressed like, for example, new materials design; energy conversion processes; efficiency of energy production; energy transportation; systems design and operational/ lifecycle optimization. Further examples are process modelling for nuclear repositories, fusion reactor modelling or energy market modelling via high-resolution renewable energy production forecasts.

The European High Performance Computing Joint Undertaking (EuroHPC JU)[35], the European Technology Platform for High Performance Computing (ETP4EU), and the **ESFRI Landmark PRACE** (DIGIT) facilitate high-impact scientific discovery and engineering research and development across all disciplines. Nine Centres of Excellence (CoEs) for computing applications are now running[36]. The aim is to strengthen Europe's existing leadership in HPC applications and cover important areas like renewable energy, materials modelling and design, molecular and atomic modelling, climate change, Global System science, and bio-molecular research, and tools to improve HPC applications performance. The Energy oriented Centre of Excellence for computing applications (EoCoE, European Horizon 2020 funded project), working closely with associated experimental and industrial groups, has the mission to accelerate the transition to the production, storage and management of clean, decarbonized energy.

Distributed RI platforms such as DERlab[37] and ERIC-Lab[38] and a rising number of national living laboratories collecting and processing data of complex real energy systems have the potential to advance the digital real-time integration of distributed and volatile energy resources into energy systems.

ENVIRONMENT

Starting from the common challenge of monitoring and reducing the impact of energy production on environment, including energy-related CO2 emissions or safety issues, there are several strong links from energy to research questions tackled by RIs from the environmental field. First, there is the important task in energy sector to develop processes and technologies to substantially decrease or remove influence on environment (waste recovery - exhalation of pollutants, CO2 production, solid wastes including radioactive effluents, recovery of the area affected by intensive mining and questions referring to recycling and circular economy). Such research should be performed by common (distributed) RI involving researchers from both sectors (energy covering all needed technologies, from nuclear or geo-energy to underground CO2 storage etc.; environmental science covering e.g. climate-related observation and measurements, performed also from space). For example, the **ESFRI Landmark EPOS ERIC** (ENV) is active in the field of geology and therefore has strong links to geo-energy production and underground CO2 storage. Another example for this cross-sectional connection is the **ESFRI Project EMPHASIS** (H&F) which interacts with topics regarding bioenergy plant production. Climate-related observation and measurement platforms as **ESFRI Landmark ICOS ERIC** (ENV) and the **ESFRI Landmark ACTRIS** (ENV) are in direct line with energy research, as their task is to measure the environmental impact of the use of fossil fuels (and as well their future replacement by renewable energies).

34. A list of centres for excellence in HPC can be found at *https://www.hpccoe.eu/eu-hpc-centres-of-excellence2/*

35. EuroHPC *https://eurohpc-ju.europa.eu/*

36. BioExcel - Centre of Excellence for Biomolecular Research; COEGSS - Center of Excellence for Global Systems Science; CompBioMed - A Centre of Excellence in Computational Biomedicine; E-CAM - An e-infrastructure for software, training and consultancy in simulation and modelling; EoCoE - Energy oriented Centre of Excellence for computer applications; ESiWACE - Excellence in SImulation of Weather and Climate in Europe; MaX - Materials design at the eXascale; NoMaD - The Novel Materials Discovery Laboratory; POP - Performance Optimisation and Productivity)

37. DERlab *https://der-lab.net/*

38. ERIC-Lab *https://www.eric-lab.eu/*

CONTENTS

65 GEOSPHERE
66 CURRENT STATUS
66 GAPS, CHALLENGES AND FUTURE NEEDS
67 ATMOSPHERE
67 CURRENT STATUS
69 GAPS, CHALLENGES AND FUTURE NEEDS
69 HYDROSPHERE
69 **FRESHWATER**
70 CURRENT STATUS
70 GAPS, CHALLENGES AND FUTURE NEEDS
71 **MARINE**
71 CURRENT STATUS
71 GAPS, CHALLENGES AND FUTURE NEEDS
72 BIOSPHERE
73 CURRENT STATUS
73 GAPS, CHALLENGES AND FUTURE NEEDS
74 VISION AND PERSPECTIVES

PART2

LANDSCAPE ANALYSIS - SECTION1

ENVIRONMENT

ENVIRONMENT

Environmental Research Infrastructures are key to provide systematic and coherent datasets needed for research addressing climate, natural resources, health, food security, biodiversity, and sustainable use of the marine, freshwater and soils. However, they do not only cater to the scientific community but support the environmental monitoring activities conducted by agencies across Europe and serve as test-beds for development of technology and methodology.

Apart from being crucial for a systematic understanding of the environment, they are well positioned to give hard facts on the efficiency of the European Union and its Member States (MS) mitigation and adaptation actions. ESFRI have identified several Research Infrastructures that have become fundamental data providers as well as forefront exploratory research facilities addressing a multitude of Sustainable Development Goals (SDGs), the Unions ambitious climate agenda as well as its green and blue growth initiatives.

Environmental research as a scientific domain focuses on understanding how the Earth system works at various spatial and temporal scales. Environmental research requires comprehensive observations integrated with relevant experimental and modelling approaches which are essential for understanding and predicting the Earth's environmental system functions. A federated approach to IT resources and e-science facilities is also necessary together with liable data policies compliant with the FAIR principle. Environmental sciences are traditionally divided into four research spheres – **GEOSPHERE**, **ATMOSPHERE**, **HYDROSPHERE** and **BIOSPHERE** – forming a network of mutual interdependences. Each of the traditional areas of environmental research has its specificity as to the role in the natural system as well as research methods. Moreover, the assessment of interlinks between these 'spheres' also requires specific approaches. The role of Mankind becomes critical and drives most research priorities because it is twofold, being at the same time an agent affecting the Earth's system and a victim of its impact.

Environmental pressures play an important role in the most critical global challenges that humanity faces today (including those related to sustainable energy and food production, water supply, human health and well-being). The mitigation and adaptation to climate change, prevention of environmental pollution, conservation and sustainable use of key natural resources and ecosystem services are vital. Modern society is progressively vulnerable to the increased frequency of natural hazards (such as extreme weather, earthquakes, floods, hunger due to failed harvests or pandemic disease outbreaks) causing loss of life and having an enormous impact on society, and environmental catastrophes can shutter societal security and cause migration with related security problems.

This was reflected in latest strategic documents, including the United Nations 2030 Agenda for Sustainable Development (2015)[1], the European Green Deal (2019)[2], United in Science (2020)[3] and Making Peace with Nature (2021)[4], as well as national priorities of the EU Member States. Out of 17 Sustainable Development Goals calling for action to protect the planet and ensure future prosperity, three (SDG13 Climate action, SDG14 Life under water, SDG15 Life on land) are directly focused on sustainable management of natural resources while many others (e.g. SDG6 Clean water and sanitation, SDG7 Affordable and clean energy) strongly depend on them. Even the most generic goals (SDG1 No poverty, SDG2 Zero hunger, SDG3 Good health and well-being, SDG11 Sustainable cities and communities, SDG12 Responsible consumption and production) 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 achievement of these political goals, the new European research and innovation programme, Horizon Europe, was launched with a strong focus on Global challenges and European Industrial Competitiveness, together with five clearly defined research and innovation Mission areas.

The environmental RIs already play an important role in this process and support the scientific community and the society at large by:

- acting as centres of frontier research on grand environmental challenges and focal points for education and training of researchers contributing significantly to the European skills base and future leaders in the concepts of life and a sustainable planet;
- generating coherent, comparable, and sustained time-series of key environmental variables;
- providing accurate large datasets and new solutions (artificial intelligence) to share these data for increased scientific and technical knowledge that underpin the construction of tools supporting decision making and development of efficient regulations and policies;
- delivering essential data for more reliable communication to the public

1. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations (2015) https://sdgs.un.org/2030agenda

2. A European Green Deal. European Commission (2019) https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

3. United in Science 2020. World Meteorological Organization (WMO) (2020) https://public.wmo.int/en/resources/united_in_science

4. Making Peace with Nature. UN Environment Programme (2021) https://www.unep.org/resources/making-peace-nature

on events such as volcanic eruptions, earthquakes, poor air quality and extreme weather as well as information on biodiversity impacts;

- opening access to environmental big data from space-based and *in situ* observations as key driver for the development of new services and for promoting activities in the private sector; and

- developing new technologies, such as laser-based sensors, high resolution wireless networks and remotely operated autonomous systems, which leads to additional co-benefits.

The environmental RIs play a key role at the global scale 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 global data systems, such as Global Atmosphere Watch (GAW). They assist the European component of GEO in the development of the Global Earth Observation System of Systems (GEOSS) that will link 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. They are feeding in the European Union's flagship Copernicus programme providing validated information services in six areas (land monitoring, marine monitoring, atmosphere monitoring, emergency management, security, and climate change) and focus on operational monitoring of the atmosphere, oceans, and land services whose main users are policy makers and public authorities. Additional linkages are being developed with the INSPIRE Directive and on-going Joint Programming Initiatives.

In addition to targeted research on phenomena specific for the individual Environment sub-domains, a holistic research using cross-disciplinary approaches is needed to tackle the environmental and societal challenges. To assist with new research and innovation Missions, the environmental RIs aim at:

- addressing global and regional challenges by deepening the understanding of Earth system processes and improving the link between scientific understanding and policy making;

- achieving national and international objectives for a resilient society, sustain-

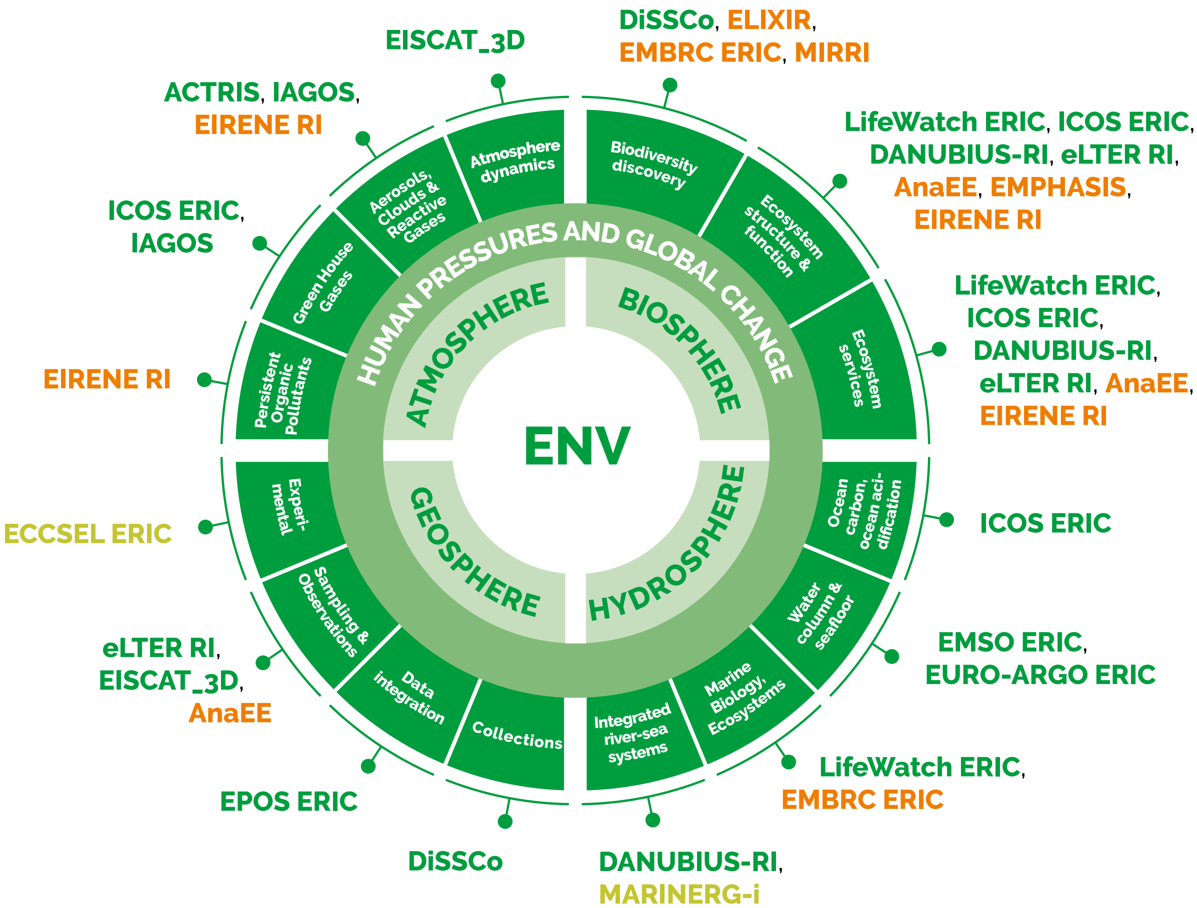

FIGURE 1.
The Landscape of the Environment domain.

able economies, and a healthy environment worldwide;

- fostering new economic opportunities, improving efficiency, and reducing costs to public sector budgets through innovation and collaboration.

The 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.

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GEOSPHERE: FROM SURFACE TO INTERIOR OF THE EARTH, FROM GEOHAZARDS TO GEORESOURCES

The RIs in the Solid Earth domain provide a fundamental contribution strengthening the research communities in their studies of highly interrelated natural processes connecting the solid Earths dynamics to natural resources, climate change, ecosystem services to enable fundamental scientific advancement 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 billions of years to microseconds: combining physical processes (e.g. plate tectonics), chemical processes (e.g. mineralogy) and biological processes (e.g. microbial interactions with minerals). Tectonics represents the mechanism that drives most Earth's processes: tectonic plates may diverge, converge, or slide laterally (transform), triggering earthquakes and causing volcanic activity. From the mountain formation to the ash and gas dispersion during a volcanic eruption, long-term and short-term observations as well as many underlying natural processes (e.g. seismic activity, ground deformations, magma rheology) combine and find application in tectonics, geodynamics, seismology, geology, geomorphology, soil science, atmospheric sciences, marine sciences, biological sciences and many other planetary sciences. Many of these interconnected processes have not yet been fully understood; therefore, broad Research Infrastructures are the basis for scientists to reveal answers to Planet Earth's complexity (**Figure 1**).

Monitoring of natural hazards (e.g. earthquakes, volcanic eruptions, rock falls, landslides, soil liquefaction, tsunamis, avalanches) and man-caused hazards (e.g. wildfires or forest fires, landslides, and groundwater depletion), but also the monitoring of natural resources have been identified as essential component for sustainable development. Solid Earth sciences RIs (**Figure 1**) are used to observe, monitor, and analyse the present in order to predict the future developments of the Earth's systems and to increase the predictive and mitigation capacities to protect planet Earth. Therefore, international collaboration is essential for solid Earth RIs given the fact that these problems do not respect national boundaries. Trans-national integration of measurements and calibrated data to develop a next generation of Earth System (model-) observations is crucial to enable research and societal applications.

In this process, RIs do:

- offer long-term, high quality and interoperable data, also used to calibrate satellites, validate or constrain earth system models to enable assessing, adapting and mitigating the risks caused by natural hazards and man-caused hazards for enabling an accelerated transformative change beneficial for biodiversity and societal resilience;

- make available monitoring infrastructures, experimental facilities and expertise to optimize 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, and for estimating and mitigating the risk of anthropogenic hazards which tend to increase, such as earthquakes possibly induced by the extraction of geo-energy resources;

- provide the monitoring and research background for an economic, viable and secure use of the underground taking into account considerations of long-term environmental sustainability.

CURRENT STATUS

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 seismology, near-fault observatories, geodetic data and products, volcano observations, satellite data, geomagnetic observations, anthropogenic hazards, geological information and modelling, multi-scale laboratories, and geo-energy test-beds for low-carbon energy. 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. Examples are the European seismology data repository[5], volcano observatories and geodetic data from GNSS network data[6]. EPOS has a strong participation in the coordination environmental research data through the EU initiatives ENVRI and ENVRIplus[7] and is actively engaged in set up of European Open Science Cloud (EOSC).

IIn addition to **ESFRI Landmarks EPOS ERIC**, other geosciences RIs and projects are operated globally; on-going work is conducted to ensure the required coordination and integration. These include:

- SoWa RI for comprehensive research and understanding of soil and water ecosystems in context of sustainable landscape use[8];
- Joint Research Centre – European Soil Data Centre (ESDAC) – Soil Atlas of Europe[9].

Large-scale geosciences RIs and projects are often operated globally. Examples are the International Ocean Discovery Program (IODP)[10] and the InterContinental Scientific Drilling Program (ICDP)[11]. These international programs have established activities for scientific exploration covering oceans and continents. Each is multimillion Euro program whereby partners across the globe operate and share drilling infrastructure platforms - ships, drilling rigs, repositories, open data management systems and analysis tools - to address issues like global climate dynamics, early development of life (and humanoids) and its adoption to extreme environments, dynamics of earthquakes and volcanos as well as catastrophic events such as meteorite impacts. In terms of scientific production, European partners are dominating these efforts. A continued strong participation in these, and other international programs, are vital for the European Earth science community.

An important global initiative for security and fast hazard response based on large infrastructure investments and with strong European participation from both the scientific and public sector is the GEOSS (Global Earth Observation System of Systems) initiative of the GEO (Group on Earth Observations). GEO is a worldwide network creating innovative solutions (e.g. Volcano observatories, EU MARSite -Near Fault Observatories/EPOS) to global challenges at a time of exponential data growth, human development and climate change that transcend national and disciplinary boundaries. The global collaboration of experts helps to identify gaps and reduce duplication in the areas of sustainable development and sound environmental management.

GAPS, CHALLENGES AND FUTURE NEEDS

The interactions between the researchers/research infrastructures, the industrial stakeholders and the public sector – such as the European geological surveys coordinated through EuroGeoSurveys network[12] – needs to be further strengthened as is now the case within the raw materials sector (i.e. EIT raw materials[13]). It should involve the accountability of data and data providers as well as the adoption of interaction strategies in which clear role of scientists is identified. Ethical issues in communicating science and geo-hazards to society must be addressed.

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.

The EU is now between 75% and 100% reliant on import of most metals (e.g. China supplies 98% of the REEs used in Europe)[14]. In 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 (transport, energy, ICT, home electronics, etc.). The situation is even more dramatic for critical metals, where the European Union strongly depends on geo-resources like rare earth elements. European collaborations like ERA-MIN and EIT Raw materials are set up to address this.

5. ORFEUS Observatories & Research Facilities for European Seismology
https://www.orfeus-eu.org/

6. EUREF Permanent GNSS Network
https://www.epncb.oma.be/

7. ENVRIplus
https://www.envriplus.eu/

8. SOWA Research Infrastructures
https://soilwater.eu/

9. European Soil Data Centre (ESDAC) – Soil Atlas of Europe
https://esdac.jrc.ec.europa.eu/content/soil-atlas-europe

10. International Ocean Discovery Program (IODP)
www.iodp.org

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

12. EuroGeoSurveys network
https://www.eurogeosurveys.org/

13. EIT raw materials
https://eitrawmaterials.eu/

14. Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions. COM(2020) 474 final, 3.9.2020
https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474&from=EN

Solid Earth RIs need to interact with on-going European initiatives in Geothermal Energy (e.g. ETIP-GeoThermal)[15] to support both technical development and data coordination to fulfil the implementation road map 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 safe management of high and medium grade nuclear waste in accordance with international and European legislation – e.g. Directive on the Management of Radioactive Waste and Spent Fuel (2011/70/EURATOM & 2013/59/EURATOM).

Furthermore, RIs should take into account the formation of new minerals during the Anthropocene, caused, for example, by mining or increasing "chemical" waste, leading to the creation of new environments with specific chemical conditions. These may cause a change of habitats for life of e.g. microorganisms inducing genetic changes and in turn inducing further changes of minerals by metabolic products.

Furthermore, the European Union must amplify its efforts to tackle environmental challenges like the climate crisis. Coordinated effort of RIs across various ESFRI domains and ENV sub-domains (**Figure 1**) is required to support implementation of the European Green Deal and Horizon Europe Missions (e.g. Soil Health Mission) and protect the environment, soils and biodiversity. Carbon Capture and Storage (CCS), for instance, is an important element for the long-term storage of Carbon dioxide from the atmosphere (ERA-Net ACT and the **ESFRI Landmark ECCSEL ERIC** (ENE). Green Infrastructures have been demonstrated to enhance nature protection and biodiversity beyond protected areas, to deliver ecosystem services such as climate change mitigation and re-creation, to prioritise measures for defragmentation and restoration in the agri-environment and regional development context, and to find land allocation trade-offs and possible scenarios involving all sectors.

15. Implementation Roadmap for Deep Geothermal – ETIP-DG https://www.etip-dg.eu

ATMOSPHERE: FROM NEAR GROUND TO THE NEAR SPACE ATMOSPHERE

The atmosphere hosts many physical and chemical processes and represents a major part of the environment to which life on Earth is sensitively responsive. The atmosphere is part of the larger connected global environment and is central for climate, weather, and transport of chemical species over large distances. Perturbation of the atmosphere impacts different thematic areas like climate change, air quality, environmental hazards, environmental risks, food security, and water cycle.

The research on the atmosphere is multidisciplinary, embracing atmospheric chemistry, physics, dynamics, and radiation; and it combines observations and modelling. It also covers the full altitude range from the planetary boundary layer near the surface across the tropopause and stratosphere up to the middle atmosphere – i.e. from ground to 50 km altitude and beyond (**Figure 1**). The atmospheric domain interacts with marine, terrestrial, freshwater, and solid earth systems but also with biological systems including humankind.

The atmosphere contains a wide range of trace species. The identification and quantification of their properties, atmospheric transport, transformation processes and lifecycles require highly interdisciplinary approaches. Both natural and man-made gases and aerosols may be transported from emission to receptor sites over long distances in the atmosphere across national borders and continents. Thus, atmospheric research and monitoring requires close international collaboration. Climate change poses a foremost scientific challenge because of large uncertainties in our current knowledge on climate change processes. Particularly, the understanding of climate feedback mechanisms requires considerable joint research where enhanced cooperation of existing RIs plays an important role and expansion of the current focus may be needed.

Atmospheric processes are multiscale in time and space, ranging from the sub-second, sub-micron microscopic scales to the decadal global scale characteristic of climate change. In this context, the atmospheric infrastructures should be sufficiently equipped to be able to inform across a similar range of scales.

II CURRENT STATUS

The European atmospheric landscape covers a wide range of actions ranging from the establishment of ESFRI long-term atmospheric RIs to EU-funded projects such as Integrating Activities (IA), Design Studies, and other projects. Based on this categorization, the current landscape includes:

- Long-term atmospheric observation platforms (**Figure 1**): the **ESFRI Landmark ACTRIS**; the **ESFRI Landmark IAGOS** (Airborne, lower atmosphere); the **ESFRI Landmark ICOS ERIC**; the **ESFRI Landmark EISCAT_3D** (upper atmosphere). There is a high level of interoperability between the infrastructures, especially between ACTRIS, ICOS and IAGOS (also demonstrated by the joint ATMO-ACCESS project described below). These long-term facilities are complemented by the following shorter-term on-going projects: the European atmospheric simulation chambers (IA-EUROCHAMP-2020, 2017-2021, now integrated within ACTRIS), and the balloon platforms for atmospheric observations (IA-HEMERA, 2018-2022). Some of the current ESFRI Projects have also matured from former integrated projects, e.g. the Integrated non-CO2 Greenhouse gas Observation System (InGOS) project in FP7 has been incorporated into ICOS, while the Svalbard Integrated Arctic Earth Observing System (SIOS) (Integrating all observations, terrestrial, marine and atmosphere at Svalbard) did not reach the pan-European dimension that is required to be an ESFRI Landmark and is therefore not listed anymore as ESFRI RI (but kept here as part of the Landscape Analysis).
- International atmospheric monitoring networks in support of the European

and international policies such as European Monitoring and Evaluation programme (EMEP)[16] established in support of the Long-Range Transboundary Air Pollution (UNECE LRTAP) Convention, the Global Air Passive Sampling (GAPS) and 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, Arctic Monitoring and Assessment Programme (AMAP), etc. Most of these networks were not formally established as RIs.

- European ERA NETs, such as the European Network for Observing our Changing Planet (H2020 ERA-PLANET)[17] with the overarching goal to strengthen the European Research Area in the domain of Earth Observation in coherence with the European participation to Group on Earth Observation (GEO) and the Copernicus, and associated IGOSP (Integrated Global Observing Systems for Persistent Pollutants) project focused on the integration of real-time monitoring data from various platforms, development of modelling tools and advanced global cyber-infrastructure for data sharing and interoperability.

- GEO Flagships and Initiatives such as the Global Observation System for Mercury (GOS4M)[18] and the Global Observation System for POPs (GOS4POP).

- Exploratory Platforms: Exploratory Platforms are needed to complement the observational long-term activities with short-term activities to address specific questions, ideally with close links. A good example for the response to this need is the incorporation of the laboratory based EUROCHAMP-2020 project with its atmospheric simulation chambers in ACTRIS.

- e-Infrastructures: the Infrastructure for the European Network for Earth System Modelling (IS-ENES)[19].

- Networking activities: Airborne platforms for field experiments (EUFAR).

The components of the Atmosphere sub-domain cover the full altitude range, from the surface up to the middle atmosphere, and are set to document the wide variety of trace species and processes involved in determining atmospheric composition changes, emissions, transport, removal, and feedback mechanisms (**Figure 1**). The **ESFRI Landmarks ACTRIS** and **ICOS ERIC** are crucial in providing data to Copernicus and Copernicus Atmosphere Monitoring service (CAMS). ACTRIS can make a substantial contribution to improve air quality and study the climatological effects of short-lived atmospheric constituents such as aerosols. The **ESFRI Landmark ICOS ERIC** is of paramount importance to reach the goal of climate neutrality. At the same time, it shows a lack of RIs supporting the research on chemical pollution of the atmosphere other than PM, trace, and greenhouse gases (e.g. POPs).

The European atmospheric research community is well recognised at an international level and in many specific research topics it has an undisputed leadership. Atmospheric RIs have a fundamental role to strengthening the EU position and leadership in this research area by providing unique information, services, tools, and reference methodologies that are used and applied by a very wide community also outside Europe.

One major user of Atmosphere RIs data products and services is CAMS. The **ESFRI Landmarks ACTRIS**, **IAGOS** and **ICOS ERIC** data are used by CAMS, for example, for Near-Real Time Model Validation, Monitoring Air Quality in Europe and for providing a forecast of air quality in Europe for European cities, also shown daily on EURONEWS.

ATMO-ACCESS is the organized response of distributed atmospheric research facilities – the **ESFRI Landmarks ACTRIS, ICOS ERIC** and **IAGOS** – for developing a pilot for a new model of Integrating Activities. The project will deliver a series of recommendations for establishing a comprehensive and sustainable framework for access to distributed atmospheric RIs, ensuring integrated access to and optimised use of the services they provide. ATMO-ACCESS gathers all ACTRIS components (including EUROCHAMP-2020), as well as the key observation and monitoring infrastructures for non-CO2 gases, first integrated into the FP7-InGOS project, and now combined in ICOS (ATMO-ACCESS is limited to the atmospheric dimension of ICOS for non-CO2 gas activities), and the digital services of IAGOS (IAGOS-Data Centre).

16. European Monitoring and Evaluation programme (EMEP) https://www.emep.int/

17. European Network for Observing our Changing Planet (H2020 ERA-PLANET) http://www.era-planet.eu/

18. Global Observation System for Mercury (GOS4M) http://www.gos4m.org/

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

GAPS, CHALLENGES AND FUTURE NEEDS

It is important to study not just components of the atmospheric system but observe them synergistically, to fully understand processes and linkages. A synergistic approach must include the use of *in situ* surface observations, together with columnar and vertical profiles, aircraft and satellite observations as well as laboratory and model studies to understand atmospheric composition and processes.

Long-term data records for atmospheric parameters, which are relevant for both air quality and climate research, are inadequate at the moment, and atmospheric contamination by legacy and emerging persistent pollutants has not been covered at all in existing RIs so far. Persistent Organic Pollutants (POPs) are chemicals of global concern due to their potential for long-range transport, persistence in the environment, ability to bio-magnify and bio-accumulate in ecosystems, as well as their significant negative effects on human health and the environment. The new **ESFRI Project EIRENE RI** (H&F) together with existing POPs monitoring projects and networks and existing atmospheric RIs should fill this gap[20].

Biocontaminants in the atmosphere are another gap that could possibly be covered by a Design study. Monitoring of the stratosphere is also crucial to study the properties of smoke injected from intense forest fires that have become more extreme recently. These observations are critical for assessing the impact of smoke on stratospheric dynamics and studying possible implications for geoengineering. Moreover, the geographical coverage by atmospheric observing infrastructures in the Mediterranean including North Africa and Eastern Europe is incomplete. A better integration of existing programs and projects in the atmospheric area will help to build and sustain the European component of GEOSS.

There is great interest in the use of cheap sensors with the potential to be used in much higher numbers than the usual costly and labour-intensive instrumentation. However, the sensors' precision and accuracy must be carefully evaluated, where the RIs can play a major role.

Air pollution is a major environmental risk to health. New variables such as the oxidative potential have recently been discussed as potential markers for health effects but are largely missing in RIs. As a consequence, interconnections with other domains (Health, Humanities) need to be better explored. The new **ESFRI Project EIRENE RI** (H&F) could play an important role here.

HYDROSPHERE: FROM FRESHWATERS TO MARINE WATERS

The hydrosphere is essential for human life and nature and plays a critical role in most natural processes. Water continues to be of huge global geopolitical importance, and it is central to many environmental challenges including climate change, usage, biodiversity, natural hazards, pollution, ecosystem services and desertification.

Approximately 97% of the hydrosphere is saline and found mostly in oceans and seas, with the remaining ca. 3% of freshwater in icecaps and glaciers, groundwater, rivers, lakes and swamps. Land use, including changing human occupation, agriculture, economic activities such as energy production and industry, greatly impact the status of water. While there are policies in place, the quality and the ecological status of waters, from mountain springs through to coastal zones and Europe's regional seas, are still threatened. Water availability is also becoming an increasing issue as the risk of water scarcity increases. With changing climate patterns, water ecosystems become more exposed to extreme hydrological events. These challenges require improved scientific understanding of all relevant processes to inform policy and to increase Europe's resilience to the impacts from climate change.

Within the future-oriented EU policy agenda, more systemic policy solutions are being formulated. For example, The EU is launching a Mission on Ocean, Seas and Waters under Horizon Europe[21]. This opens new opportunities for the RI community.

FRESHWATER: ICE, GROUNDWATER, LAKES, RIVERS, ESTUARIES

Environmental agencies across Europe collect vast amount of data on freshwater. Linking routine monitoring with high-resolution data from freshwater supersites and remote sensing data would benefit society directly as well as by supporting research in the area. Long time series, collected by research facilities, have been instrumental in understanding the coupling between the water cycle, the changing climate, environmental pollution, and ecosystems. It is of vital importance to ensure that such data series are continued. Experimental facilities for studying complex water-related phenomena – e.g. physical modifications of estuaries, behaviour of substanc-

20. Food safety: Persistent organic pollutants (POPs)
https://www.who.int/news-room/q-a-detail/food-safety-persistent-organic-pollutants-(pops)

21. Mission on Healthy oceans, seas, coastal and inland waters. Horizon Europe
https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/missions-horizon-europe/healthy-oceans-seas-coastal-and-inland-waters_en#latest

es and energy in mesocosms, etc. – allow physical models to underpin better systemic understanding, often in conjunction with mathematical models.

The multi-faceted water research in Europe is well captured by the overarching visions and agendas outlined by the upcoming Horizon Europe Water4All Partnership that builds on the research and innovation agendas of Water JPI[22] and, at higher Technology Readiness Levels (TRL), of Water Europe[23]. Large scale integrated systemic innovation pilots play a key role to enable successful innovation[24,25,26].

CURRENT STATUS

Much of the current science is done relying on access to existing water bodies, i.e. without specific and dedicated large-scale Research Infrastructures. The **ESFRI Project DANUBIUS-RI** supports interdisciplinary research in river-sea systems (**Figure 1**). It is the only physical pan-European Research Infrastructure devoted to support research on transitional zones between coastal marine and freshwater areas. The development of DANUBIUS-RI as a distributed environmental RI builds on existing expertise to support interdisciplinary research on River-Sea Systems, covering whole river basins and the coastal waters that they influence. Addressing the conflicts between sustainable development, environmental change and environmental conservation in River-Sea Systems, DANUBIUS-RI's mission is to achieve healthy River-Sea Systems and advance their sustainable use[27].

The **ESFRI Landmark LifeWatch ERIC** as the only e-RI, extends its area of interest to the whole freshwater environments (see section Biosphere).

There are European networks of basins for hydrological monitoring and research, such as the European Network of Hydrological Observatories (ENOHA). The HYDRALAB+ network supports the use of environmental hydraulic facilities. The **ESFRI Landmark AnaEE** (H&F); also offers access to experimental facilities in freshwater environments, applying an ecosystem services approach to key sectors including food security, human welfare and the wider bio-economy.

GAPS, CHALLENGES AND FUTURE NEEDS

Europe needs a dense, highly instrumented network of freshwater monitoring, as well as simulation and experimental platforms. Lake, river and ground 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. For the comprehensive analysis of the changes in the aquatic ecosystems, an integrated basin approach is necessary to understand the impact of different drivers and to find measures for sustainable water resources management. The **ESFRI Project DANUBIUS-RI**, with its structure consisting of the four Nodes (Observation/Measurements – Analysis – Modelling – Impact), is aiming to bridge the before mentioned gaps, at a basin-wide, river-to-sea approach. The Horizon Europe Water4All Partnership considers RIs as important enablers to support the implementation of its ambitious agenda.

22. Water JPI
http://www.waterjpi.eu/

23. Water Europe
https://watereurope.eu/

24. Water JPI - Strategic Research and Innovation Agenda 2025
http://www.waterjpi.eu/mapping-agenda/strategic-research-and-innovation-agenda-sria/waterjpi_sria2025_web.pdf

25. Water Europe - Strategic Research and Innovation Agenda
https://watereurope.eu/wp-content/uploads/2019/07/Water-Europe-SIRA.pdf

26. Water Europe - Atlas of the European Water Oriented Living Labs
https://watereurope.eu/wp-content/uploads/2019/07/Atlas-of-the-EU-Water-Oriented-Living-Labs.pdf

27. DANUBIUS-RI Science and Innovation Agenda 2019
https://danubius-pp.eu/www/wp-content/uploads/2019/11/DANUBIUS-RI_Science_Agenda_web_version_Dec2019.pdf

MARINE: FROM COAST TO DEEP OCEANS AND ICE CAPS

Approximately 10% (680 million) of the World's population currently lives on the coast and this number is expected to rise to one billion people by 2050[28]. Seas and oceans provide food, energy, and many other resources on which mankind depends and oceans have a fundamental influence on climate and are being significantly impacted by climate change (e.g. sea level, ocean acidification). Cumulative pressures from human activities has resulted in loss of habitat, biodiversity and ecosystem functioning and services[29].

Economic activity in the ocean continues to expand and in the EU in 2018 had a turnover of € 750 billion with 5 million people directly employed in the Blue Economy[30]. The OECD confirms that the Blue Economy will continue to expand but noted that ocean health, and its continuing deterioration due to climate change, pollution and over-exploitation, was an important constraint[31]. The UN Decade of Ocean Science for Sustainable Development 2021-2030[32] has commenced, led by the Intergovernmental Oceanographic Commission (IOC). This will see scientists work with policy makers, managers and service users to demonstrate how ocean science can deliver greater benefits for both the ocean ecosystem and for society. In tandem, the United Nations Environment Programme (UNEP) and the Food and Agriculture Organization (FAO) launched the UN Decade on Ecosystem Restoration 2021-2030[33]. As such significant input from the marine science community is required if it is to succeed with its goals of halting and reversing the decline in the health and productivity of our ocean and its ecosystems and to protecting and restoring its resilience and ecological integrity[34].

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28. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019) *https://www.ipcc.ch/srocc/*

29. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC (2013) *http://www.ipcc.ch/report/ar5/wg1*

30. The EU Blue Economy Report (2020) *https://blueindicators.ec.europa.eu/sites/default/files/2020_06_BlueEconomy-2020-LD_FINAL-corrected-web-acrobat-pro.pdf*

31. The Ocean Economy in 2030, OECD (2016) *http://dx.doi.org/10.1787/9789264251724-en*

32. UN Decade of Ocean Science for Sustainable Development 2021-2030 *https://www.oceandecade.org/*

33. UN Decade on Ecosystem Restoration 2021-2030 *https://www.decadeonrestoration.org/*

34. Global Ocean Science Report – The current status of ocean science around the world. UNESCO (2017) *https://en.unesco.org/gosr*

CURRENT STATUS

Marine RIs are diverse and range from fixed observatories, data centres to research vessels and autonomous vehicles that generate, analyse and apply *in situ*, remote sensed and modelled data and provide 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, biological and ecological research and for numerous established, and emerging, industries in the Blue Economy[35]. Key RIs for water-related research are fostered in ESFRI, as illustrated in **Figure 1**, while there are also other EU projects and initiatives supporting networks that are directly relevant for research:

- River-sea interaction, freshwater, water-ice: the **ESFRI Project DANUBIUS-RI**, the **ESFRI Landmark LifeWatch ERIC** as e-RI, HYDRALAB+, AQUACOSM (mesocosms).
- Open ocean mobile platforms: the **ESFRI Landmark EURO-ARGO ERIC**, EuMarineRobots.
- Open ocean and coastal fixed-point observatories: the **ESFRI Landmark EMSO ERIC**, Coastal/shelf seas observatories like JERICO.
- Research vessels and underwater vehicles: ARICE, EUROFLEETS.
- Data storage and standards, access: EMODnet and linked Copernicus Marine Service (CMEMS) for operational oceanographic services; EuroGOOS, SeaDataNet/ SeaDataCloud.
- Marine biology, omics and bio-informatics: the **ESFRI Landmark ELIXIR** (H&F), the **ESFRI Landmark EMBRC ERIC** (H&F), the **ESFRI Landmark LifeWatch ERIC** as e-RI, and the **ESFRI Landmark AnaEE** (H&F).
- Marine Renewable Energy: the **ESFRI Project MARINERG-i** (ENE).
- Carbon cycle: the **ESFRI Landmark ICOS ERIC**, and the **ESFRI Landmark LifeWatch ERIC** as e-RI.

GAPS, CHALLENGES AND FUTURE NEEDS

- The range of services offered by RI will have to evolve, will need to be tailored and will have to increase scientific knowledge and understanding not just in the scientific community but across society, policy and industry. This will enable individual citizens, society at large, policy makers and the business community to identify the impact they have had, and are currently having, on coasts, ocean and ice caps. Importantly these services should inform and demon-

35. The United Nations Decade of Ocean Science for Sustainable Development 2021-2030 – IOC (2018) *https://unesdoc.unesco.org/ark:/48223/pf0000261962*

strate how these end-users can remedy and reduce their impact. This will require a paradigm shift and collaboration across research communities with disciplines that traditionally would not have worked together to play a bigger part in meeting future challenges. RIs will have to work synergistically if they are to meet their end-user needs and enable the sustainable management of environmental resources[36,37].

As the coastal ocean is currently a key component of the UN Decade for Sustainable Development and has become a high priority on the worldwide environmental political agenda, Europe needs dense enough, well instrumented sites and regions to study, observe and monitor water of the coastal shelf. The comprehensive analysis of the changes in the coastal ecosystems requires an integrated basin approach to understand the impact of different drivers and to find measures for coastal preservation, management and planning. The long-term observation is needed to address transversal scientific and societal challenges acting at various spatio-temporal scales , and to understand large-scale processes that can significantly impact coastal and littoral areas. This could only be achieved at the pan-European level.

36. Navigating the Future V: Marine Science for a Sustainable Future. Position Paper 24 - European Marine Board (2019) https://zenodo.org/record/2809392#.YDFdWS9aZ0s

37. Oceans Beyond 2020: Draft Strategy Framework - JPI Oceans (2020) http://jpi-oceans.eu/draft-strategy-framework-beyond-2020

BIOSPHERE: BIODIVERSITY AND ECOSYSTEMS

Biodiversity is the diversity of biological systems at all levels, including genes, species and ecosystems. Biodiversity is part of our common natural heritage which underpins our health and quality of life, livelihood, food security and economies. Understanding Biodiversity is critical to ensure a sustainable Earth for the future. This includes knowledge about terrestrial, marine and freshwater ecosystems, its structural components, how they interact with each other, and with human societal activities (**Figure 1**). The biodiversity collapse is thought to be one of the biggest challenges humankind faces. Ecosystem services are essential to our current welfare and well-being.

The outcome of this research is also determinant to support policy making. IPBES, which interfaces research and policy, stresses in its 2019 Global Assessment for Biodiversity and Ecosystem Services[38], the importance in supporting primary research by countries. This should cover not only biodiversity, but also related areas like food, energy, health and genetic resources.

The goals set by the European Union Biodiversity Strategy for 2030[39] indicate the need to be on the path for biodiversity recovery by 2030, with the involvement of citizens, businesses, social partners and the research and knowledge community. The essential role of Biodiversity and Ecosystem Services in protection and restoration of wetlands, peatlands and coastal ecosystems, sustainable management of marine areas, forests, grasslands and agricultural soils, mitigation and adaptation to climate change or food security have been recognized. Green infrastructures contribute to lowering urban areas' extreme temperatures and reduction of natural disaster impacts. Some of the extensive policy EU instruments, like the Common Agricultural Policy (CAP) or the Common Fisheries Policy (CFP), include criteria of sustainable use of biological resources.

38. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES (2019) https://doi.org/10.5281/zenodo.3553579

39. EU Biodiversity Strategy for 2030 Bringing nature back into our lives. European Commission (2020) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0380

EU sets ambitious but concrete targets for the next decade. These include that at least 30% of land and sea should be protected, including 10% with strict protection. It also determines the restoration of land and sea, the naturalisation and increase of sustainable practices in agriculture, reversion of genetic diversity decline, increase in forestation, including in urban areas, among other actions. It also sets objectives for marine environments. freshwater ecosystems, reduction of pollution and combat to invasive alien species. The strategy is in line with the European Green Deal[40] and supports the role of Europe in the global landscape towards stopping biodiversity loss, in the context of the UN SDGs 14 and 15[41], and the Convention of the Biological Diversity[42], which had the Conference of the Parties in October 2021.

The implementation of the strategy needs a sound scientific basis. Only ¼ of the existing species on Earth were estimated to be known to science[43]. Many species will become extinct without being discovered, and their potential benefits in terms of food, medicine and ecosystem services will be lost. Some of the main drivers for scientific research are linked to main threats to biodiversity. This is the case of land-use change causing habitat destruction and the alien invasive species. Unhealthy and too close interactions between the humankind and wildlife resulted, among others, in the COVID-19 pandemics leading to major global societal and economic crisis. The loss of biodiversity decreases ecosystem services and affects ecosystem functioning and stability. Sustainable agriculture practices need to combine the promotion of ecosystem services, for example polli-

40. European Commission. 2020. The European Green Deal. European Commission (2020) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN

41. UN Sustainable Development Goals (SDGs) https://www.un.org/sustainabledevelopment/sustainable-development-goals/

42. UN Convention on Biological Diversity (CBD) https://www.cbd.int/

43. How many species are there on Earth and in the ocean? Mora, Camilo, et al. PLoS Biol 9.8 (2011) https://doi.org/10.1371/journal.pbio.1001127

nation, with promotion of wildlife and the reduction of fertilisers and pesticides. Life in oceans also depends on sustainable management of resources, and protection of coastal areas from effects of pollution. Plastics in marine environments are a real threat to wildlife but their adverse effects throughout the food chain and mechanisms through which populations are affected are largely unknown. This is an example of interdisciplinary research need linking all environmental domains to social sciences, health and food. Mechanisms of adverse effects of microplastics on the whole food chain are still a largely unknown area.

CURRENT STATUS

The European landscape for terrestrial and marine biodiversity and ecosystem RIs covers the complexity of the research agenda (**Figure 1**). The ESFRI RIs organised as distributed infrastructures are built on or closely connected to EU-funded projects such as Integrating Activities.

- Observatories and Monitoring Facilities: the **ESFRI Landmark ICOS ERIC** and the **ESFRI Landmark EMBRC ERIC** (H&F), (related IA ASSEMBLE Plus), the **ESFRI Projects DANUBIUS-RI** and **eLTER RI,** the IAs INTERACT and JERICO-S3, SIOS (Integrating all observations, terrestrial, marine and atmosphere at Svalbard).
- Facilities for *in situ* and *in vivo* experimentation: the **ESFRI Landmark AnaEE** (H&F), the IAs AQUACOSM-plus and HYDRALAB+.
- Biological collections, data infrastructures and reference data: the **ESFRI Project DiSSCo** (linked IA Synthesis PLUS), the **ESFRI Landmarks ELIXIR** and **MIRRI** (H&F), and the IA BiCIKL.
- e-Infrastructures for data, analysis and modelling: the **ESFRI Landmark LifeWatch ERIC**, and the IAs IS-ENES3 and SeaDataCloud.

It is important that capacities of ESFRI RIs are able to support the newly built European Partnerships in Horizon Europe. These aim to connect R&I programs from national to European programs, in which the RIs on biosphere and ecosystems can play a relevant role in several of the European Partnerships in food, bioeconomy, natural resources, agriculture and environment as well on health.

Within the framing of *Grand Challenges* that ranges from ecosystem conservation to preservation of ecosystem services, some RIs target ecosystems within the environmental domain. The **ESFRI Project eLTER RI** is tackling a broad spectrum of ecological challenges, based on observations that enable understanding ecosystems using an approach of ecological integrity, including the socio-ecological dimension. The **ESFRI Landmark AnaEE** (H&F) alternatively, provides experiments instead of observations, with stronger focus on agriculture and food security from a defined set of ecological and societal challenges and has a more anthropocentric approach.

The **ESFRI Landmark LifeWatch ERIC** has a cross-domain approach and a focus on the *Grand Challenges* of preserving biological diversity and of protecting ecosystem health. LifeWatch ERIC is an e-Infrastructure that enables knowledge-based solutions to environmental managers by providing access to a multitude of sets of data, services and tools about the role of biodiversity in ecosystem functioning and conservation. The focus is made in the construction and operation of Virtual Research Environments (VRE), backed by strong computational capacity and metadata catalogues. On another side, the **ESFRI Landmark ICOS ERIC** also has a cross-domain approach to enable understanding the carbon cycle and to provide necessary information on the land-ecosystem exchange of CO_2, CH_4 and N_2O with the atmosphere.

The digitization of biological collections and the connection to genomics is a game changer in the biodiversity research aiming to close the taxonomic gap, which still is a major limitation to biodiversity knowledge. The **ESFRI Project DiSSCo** is developing tools and resources to speed up digitization and virtual access to Natural History Collections (NHC). Only 10% of European NHC are digitally catalogued, and even a lower percentage are digitally imaged. The virtual access to collections is essential to help taxonomic efforts and speed up the description of the undiscovered biodiversity existing both in these collections and in nature.

GAPS, CHALLENGES AND FUTURE NEEDS

Some of the *Grand Challenges* related to biodiversity and ecosystems research still miss a counterpart support by the existing RIs. The above mentioned global and European strategic agendas indicate, for example, the need to increase protected areas, restore degraded ecosystems, reverse the decline of pollinators, increase biodiversity-rich landscapes on agricultural lands. Consequently, a call is made for intense research on conservation planning, ecological restoration, and ecosystem services, which are only partially covered by the existing RIs and in limited scales.

These needs extend to monitoring biodiversity and ecosystem changes, supporting the development and implementation of Essential Biodiversity Variables[44] as ecological data products underpinned on data and metadata standards, data quality, data preservation and open data policies. Another aspect that needs further attention is the environmental contamination and its interplay with a climate change, hazards and risks associated with toxic mixtures, especially endocrine disruptors. Testing platforms for elucidation of adverse outcome pathways are also required.

Urged by the biodiversity loss, the taxonomic gap needs to be overcome, in order to discover and describe the ¾ of the biodiversity still to be known. Rapid advances in genetic sequencing and ICT, including big data analysis of genetic sequences, and mass digitization can be integrated to provide more automated systems concerning genomics, species and ecosystem analysis.

Other challenges are the invasive species, for which the RIs need to adjust their data lifecycles in order to enable rapid alert systems and better monitoring and modelling. Observations and experiments need further scientific integration. Modelling can be a powerful tool for the conjunction of organismic and process-oriented approaches as well as multiple challenges perspectives in ecosystem analysis. However, most existing

44. Essential Biodiversity Variables. Pereira, H.M. et al. Science 339, 277–278, (2013) https://doi.org/10.1126/science.1229931

ecosystem models represent only facets and require further development.

The manifold connections to other fields, particularly Health & Food, but also Social Sciences and Energy are apparent. Human activities, energy production, construction, traffic or 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.

VISION AND PERSPECTIVES

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 as the urbanization, 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 disproportionally 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 improving human health since the 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 in 2050, biodiversity preservation strategy, sustainable food strategy, circular economy action plan or the overarching zero pollution ambition.

The political strategies must be accompanied by the research strategies aimed at improved understanding of the 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 recently developed within the H2020 HERA project[45]. Resulting research priorities included: (i) reduction of 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; or (v) promotion of intervention research. Among the top priorities was filling a gap in the landscape of RIs and building infrastructural capacities for assessment of environmental exposures and their health impacts (including new sensor technologies, laboratory capacities, data interpretation and modelling), as well as education, training and capacity building for improved understanding of combined environmental impacts (including toxic mixtures) on health. The new **ESFRI Project EIRENE RI** (H&F) will significantly contribute.

The identified needs have been addressed in the new European Research & 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, the research and innovation Missions were incorporated into the Horizon Europe covering Adaptation to climate change including societal transformation, Climate-neutral and smart cities, Healthy oceans, seas, coastal and inland waters, Soil health and food, and Cancer. None of these Missions can be carried out without the interdisciplinary research collaboration across the traditional domains, not just within the environmental sciences but at the interface between Environment, Health, Food, Energy, and Humanities.

The key implementation tools of the Horizon Europe are the European Partnerships bringing the private and public partners together to address some of Europe's most pressing challenges through concerted research and innovation initiatives. There are numerous candidate partnerships in the areas of Climate, energy and mobility, Food, bioeconomy, natural resources, agriculture and environment, or Health including the European Partnership for Chemicals Risk Assessment (PARC) which is meant to bridge the Environment and Health domains. 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

45.
Health Environment Research Agenda for Europe (HERA)
https://www.heraresearcheu.eu/

including Green deal. 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.

There are strong expectations on how the innovative research can help to find the best approaches and support achievement of the political goals. In collaboration with new Horizon Europe Partnerships the Landscape of the Environmental Research Infrastructures should be further developed to keep up with the 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. The RIs should better facilitate trans-disciplinary research and enable researchers to work in a more integrated manner across multiple domains. They should inspire new transformational approaches to addressing the environmental and societal challenges in their full complexity including ethical, political, socioeconomic, equity, sustainability, and communication aspects. The knowledge gained from such a holistic approach will help to define how to walk the delicate balance of utilizing natural resources with minimum impact on the environment and ensure that today's actions do not impede the well-being of future generations.

CONTENTS

78 THE H&F LANDSCAPE AND ITS EVOLUTION
78 HEALTH & FOOD SUBDOMAINS DIVERSITY
78 DEVELOPMENT, ADAPTATION, UPGRADING AND NEW RIs
78 INTRA- AND INTER-DOMAINS CLUSTERING
79 SCIENTIFIC IMPACT
80 SOCIO-ECONOMIC IMPACT
80 MISSIONS AND CHALLENGES

81 HEALTH
81 CURRENT STATUS

83 FOOD
83 CURRENT STATUS

85 GAPS, CHALLENGES AND FUTURE NEEDS
85 HEALTH CHALLENGES
85 HEALTH NEEDS
85 HEALTH EMERGING AREAS
86 FOOD CHALLENGES
86 FOOD NEEDS

PART2

LANDSCAPE ANALYSIS - SECTION1

HEALTH & FOOD

HEALTH & FOOD

The Health & Food Research Infrastructures are becoming truly a key pillar of Europe's endeavour in transition to a healthy planet encompassing healthy population living in balanced environment. Within the priority European Green Deal, Health & Food RIs focus on topics such as climate change, biodiversity, and food security[1], trying to ensure environment supporting conditions for healthy and diverse population that can cope with major challenges of health including civilisation disorders, healthy ageing, and also infection diseases, all of which affect European community development and economy.

Development of Health & Food RIs is flawlessly in line with the declaration of the European Commission to preserve and restore our ecosystem needs. In the Health & Food domain, Environment meets Health with all its major challenges. RIs are committed for solving challenges such as cancer or recently unexpectedly appearing pandemics and there is also a need to develop new effective and economic solutions for health challenges without compromising the environment.

With a turnover value of € 2.3 trillion and accounting for 8.2% of the EU workforce, the bioeconomy is a central element to the functioning and success of the EU economy[2]. The ESFRI Roadmap 2018 already highlighted the role of Health & Food RIs as research, innovation and skills hubs boosting the economic development and competitiveness in a global economy. Since 2018, the H&F RIs have all made significant progress – as Landmarks, they are mature and provide a comprehensive service portfolio and comprehensive knowledge to serve the Health & Food communities. RIs designated as Landmarks are expanding their memberships, their knowledge and service portfolio, establishing a strong record of accomplishment in services provided. ESFRI shall thus promote new ways of collaboration among existing RIs and advanced communities, mediate interactions between existing and aspiring RIs to create a fair and supportive milieu where needs of new user communities can be identified and new models of services created by encouraging the clustering of existing RIs for joint services towards advanced communities, building new ways for innovation.

A concrete step forward to be mentioned is the European Life Sciences Research Infrastructures (LS RIs)[3] group which has developed from its original formation as the Biomedical Research RIs within the CORBEL project[4]. Made up of representatives of the Biological and Medical Research Infrastructures, this group was brought together to establish a model to provide combined multi-RI services that support research spanning from fundamental science to clinical application. Along the way, the model has identified, developed and tested shared processes, which progressively resolved some service and expertise complexity.

To engage the scientific community in developing interdisciplinary research, new clusters among RIs from different sectors should develop including Health & Environment, Food & Environment, Health & Social Sciences, and naturally, Health & Food with agriculture should further proceed.

1. Political Guidelines for the Next European Commission 2019-2024
https://ec.europa.eu/info/sites/default/files/political-guidelines-next-commission_en_0.pdf

2. A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment (the updated Bioeconomy Strategy in 2018)
https://knowledge4policy.ec.europa.eu/publication/sustainable-bioeconomy-europe-strengthening-connection-between-economy-society_en

3. European Life Sciences Research Infrastructures
https://lifescience-ri.eu/

4. CORBEL Project
https://www.corbel-project.eu/home.html

THE H&F LANDSCAPE AND ITS EVOLUTION

HEALTH & FOOD SUBDOMAINS DIVERSITY

Regarding the RI's further development, numerous challenges need to be addressed including: food security – **ESFRI Project METROFOOD-RI**; resilient agriculture and agro-ecological transition – **ESFRI Project EMPHASIS**; biodiversity, the environment, and marine ecosystems – **ESFRI Landmark EMBRC ERIC**. The research data created by relevant ESFRI RIs, often managed by the **ESFRI Landmark ELIXIR**, need to be interoperable with other non-research datasets, such as crop yields, stock levels or geo-location environmental/ecological data. New machine learning and Artificial Intelligence (AI) approaches will increasingly allow for faster and more accurate analysis of datasets and at a greater scale. Data management and interoperability play an important role in connecting the two subdomains of H&F, which cover a very wide range of areas, spanning from fundamental biological science and medical research through biotechnological applications to *Agri-food* aspects involving also plants genetic aspects. This broad thematic diversity does not feature direct collaborations across the whole RI landscape of H&F. For instance, the **ESFRI Landmark AnaEE** is primarily collaborating with the **ESFRI Project EMPHASIS**, aiming at bringing innovative solutions for sustainable intensification of agriculture by integrating the study of plant phenomics and agro-ecology but also with the **ESFRI Landmark ELIXIR** because of common standards for life science data. On the other hand, the biomedically oriented **ESFRI Landmark MIRRI** interacts with the Food area, aiming to develop new, safe and healthy food products and the biological management of soils and crops, which connect the *Agri-Food* subdomain with the *Health* one.

DEVELOPMENT, ADAPTATION, UPGRADING AND NEW RIs

Over the last 18 years, within the framework of ESFRI and the ESFRI Roadmap process, national governments have worked in close partnership with the European Commission and the scientific community to catalyse the establishment of over 50 European RIs, a key pillar of the European Research Area (ERA). Many of them are mature and operate as Landmarks with established services for numerous research communities, showing a high degree of sustainability. As the whole European research landscape develops together with its research communities, it is now worthwhile to review the initially defined aims and missions of H&F ESFRI RIs and facilitate their further strategic development, refocussing, approach and mission adaptation, or their upgrade. The developmental adaption should follow the gap analysis as well as the development of needs of user communities that are changing, partly following the appearance of new research fields and opportunities or leaving some others. To this end, a continued and focused support of the existing and successful ESFRI RIs might allow them to serve the needs of new and emerging communities. Besides fostering interaction of the established H&F ESFRI RIs, a new RI strongly bringing together environmental aspects in human health appeared on the ESFRI Roadmap - the **ESFRI Project EIRENE RI** is filling the gap in environmental determinants of health, pioneering the needed knowledge hub on human exosome in EU. H&F ESFRI RIs foresee also interaction with the **ESFRI Project EBRAINS** which, although a new Digital Research Infrastructure, is based on biomedical knowhow of neuroscience, brain medicine, and brain-inspired technology.

INTRA- AND INTER-DOMAINS CLUSTERING

There is certainly a need to reinforce interactions and collaborations between RIs in Health & Food to exploit synergies and complementarities. The clustering approach of RIs with highly complementary approaches create new added values, allowing the research community to reach more complex and comprehensive goals while acknowledging and allowing that some RI resources and competencies will remain truly unique outliers in the RI ecosystem. One example builds on the Alliance of Medical Research Infrastructures (AMRI)[5], which could be extended to other existing and future ESFRIs. Such clustering could be also used for refocusing the individual RIs to increase their quality and effectiveness. It is also evident that further intra-domain interactions will be needed to fully address diverse challenges such as cancer or infection diseases as it could be also observed during the recent pandemics crisis. The solutions should consider also inter-domain interactions to include for instance Social & Cultural Innovation, and Environment.

Areas for different RIs interactions are numerous and H&F proceed to develop knowledge and service clusters for research areas including the following examples.

- Human disease challenges, including infections, cancer, rare diseases, metabolic, neurological and other disorders influencing human well-being and ageing.
- Ageing connected to environmental impact on human health, an inter-domain interaction to setup a new directions regarding exposomes and environmental medicine.
- Foods and diets constitute an age-related and geographically diverse exposure matrix that affects health and environmental outcomes across the EU. It is needed to uniquely combine population health and environmental sustainability, the biological and social drivers of food consumption, and foods and diets within the diverse European food systems. Interdisciplinary and multi-stakeholder data, research facilities and innovative tools should become interconnected to synergise the research potential of the heterogeneous European Health & Food land-

5. Alliance of Medical Research Infrastructures (AMRI) https://www.esfri.eu/alliance-medical-research-infrastructures

scape. To accomplish this, an interdisciplinary effort is needed, including complementary RIs – e.g. the **ESFRI Project METROFOOD-RI**, **ESFRI Landmark ELIXIR** and others.

- Reinforcement of advanced drug discovery, from identifying and characterizing the drug targets, to screening biological activity of compounds to understanding the drug metabolism and biological effects. This requires the European researchers to access technologies and expertise for structural biology, chemical screening, genetics, understanding mechanisms of action at the cellular level as well as at the level of the complex organism using advanced tissue and animal models – e.g. the **ESFRI Landmarks EATRIS ERIC**, **EU-OPENSCREEN ERIC**, **INFRAFRONTIER**, **INSTRUCT ERIC**, **ECRIN ERIC**, and the new **ESFRI Project EIRENE RI.**

- Advancing the marine biology towards environment and medicine by connecting genomics data, with models and image data of marine microorganisms. The **ESFRI Landmark EMBRC ERIC** supports fundamental and applied research towards sustainable solutions in the food sector, as well as in health and the environment, where it collaborates with other Food and environmental RIs.

- Use of advanced phenotyping technologies including imaging to comprehensively understand plant biology and soil health under changing climate as well as mammals physiological processes in health and disease – e.g. the **ESFRI Landmarks Euro-BioImaging ERIC** and **INFRAFRONTIER**, the **ESFRI Project EMPHASIS**.

- Healthy soils and healthy crops for healthy, safe and sustainable food – e.g. the **ESFRI Project METROFOOD-RI.**

An overview of the Landscape of the Health & Food domain is given in **Figure 1.**

SCIENTIFIC IMPACT

H&F RIs have increased research and service performance as well as its quality. Their workflows have improved and analyses have been more efficient. Integrated Standard Operation Procedures (SOP) were established, data are better accessible and are being standardised. Besides this, RIs have developed various training and education programs, thus providing users with the necessary skills

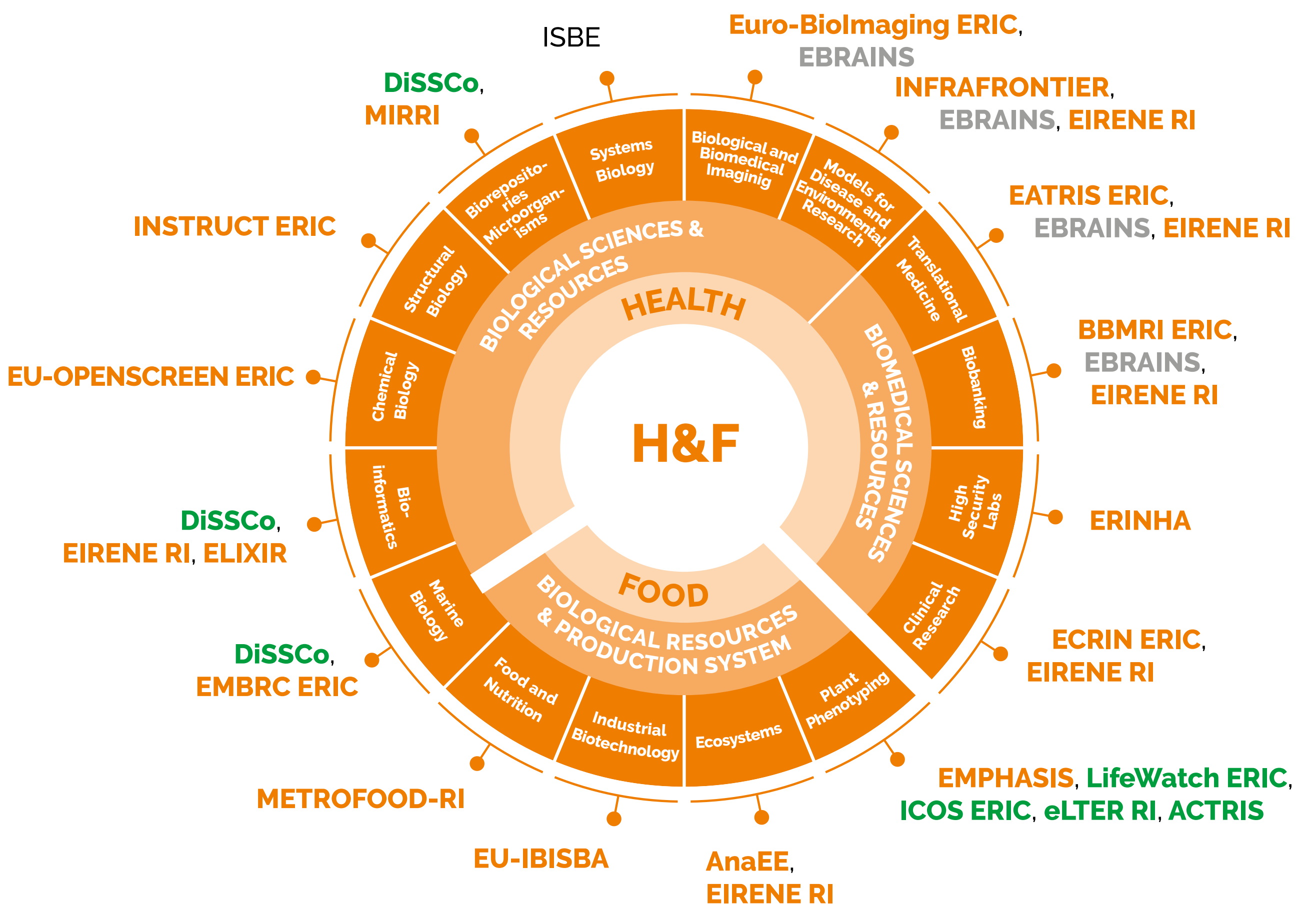


FIGURE 1.
The Landscape of the Health & Food domain

and competences in a wide range of H&F scope. The RIs disseminate the service-related knowledge, relationship capital (i.e. the benefits of working together such as facilitated knowledge-sharing and cooperation), policy influence (i.e. increased awareness of the benefits of Open Science) and bioinformatics resource uptake. It is becoming clear that the overall economic impact is large and further increases. The RIs have built and established knowledge platforms and cutting-edge technologies for every user in open-access regiment. They especially support excellent research that could not be performed without the existence of RIs. The added-value of the pan-European Health & Food RIs steadily increases with the growing number of users, which could be virtually anywhere in Europe. Thus, ERA becomes true reality. Without additional large investments in an individual European country, the 'European User' can find a high-quality solution. Such organisation allows working on complex scientific tasks to solve large European challenges and to improve research efficiency. The impact of the H&F RIs has also expanded internationally through a number of cooperation agreements and building global consortia with related RIs and institutions worldwide.

The European Commission estimates that there are more than 500,000 individuals in Europe involved in some way in life science research and H&F RIs serve substantial part of these user communities, from basic research experts in life sciences and medical professionals to environmental and food domains researchers. The access and service of H&F RIs go beyond the European border and many of them providing services to scientists worldwide directly or through the establishment cooperation agreements and joint initiatives.

SOCIO-ECONOMIC IMPACT

H&F RIs enable leading research to happen while societal and socio-economic benefits impact European society well beyond the RI site. Health & Food RIs influence also industry as a significant share of activities is beneficial also for the private sector. The H&F RIs work to increase awareness of their services exemplified by **ESFRI Landmark ELIXIR**, which makes public data available to a number of small and medium sized enterprises that have built their business model around these resources.

Technology development is another good example of the socio-economic impacts of Health & Food, in which every RI develops or establishes new technologies and methodologies to move the research possibilities to cutting-edge, which is then used by researchers or even by the private sector. Thus, for instance, by promoting integrative methods, the **ESFRI Landmark INSTRUCT ERIC** provides peer-reviewed access to state-of-the-art, structural biology technologies and enables excellent science and technological development for the benefit of all life scientists, with strategic relevance and major impact for pharma and biotech companies. The **ESFRI Landmark EU-OPENSCREEN ERIC** offers its shared resources to users from academic institutes, SME's, industrial organizations, and facilitates collaborative development of novel molecular tools. **ESFRI Landmark EMBRC ERIC,** the specialized RI for marine biological resources, provides access to marine resources and cutting-edge services and facilities that allow users from both academia and industry to study the ocean and develop innovative solutions to tackle even societal issues. The **ESFRI Landmark INFRAFRONTIER**, which created the 3rd largest mouse repository holding more than 6,000 mouse mutants, setups and capitalises the revolutionary technology of genome editing based on the CRISPR/Cas9 technology, which allows to create precise models of human diseases and propose future corrective treatments for many human diseases.

The **ESFRI Landmarks AnaEE,** as an example from the *Agri-Food*, enables moving beyond past and current scale- or approach-specific experimental approaches by combining state-of-the-art distributed experimental and analytical platforms with modelling and simulation, of direct relevance for the challenges facing European ecosystems. The **ESFRI Project EMPHASIS** builds facilities, resources and services for plant phenotyping across Europe, aiming to better understand plant performance and translate this knowledge into application.

According to WHO publication *Ecosystems and human well-being: health synthesis: a report of the Millennium Ecosystem Assessment*[6] ecosystems are the planet's life-support systems for the human species and all other forms of life. The causal links between environmental change and human health are complex because they are often indirect, displaced in space and time, and dependent on a number of modifying forces. Thus, preventing the decline in the world's ecosystems should improve the situation regarding malnutrition, infectious diseases, maternal mortality, exposure to unsafe drinking-water and, most importantly, poverty.

MISSIONS AND CHALLENGES

In Health & Food, each RI has its own specific mission and dedication to particular challenges but there are also common missions. The **ESFRI Landmark EATRIS ERIC** main mission is condensed in a short statement "Increasing value, reducing waste", and tackles improvement of new therapeutics development as only 40% of drugs are effectively used worldwide and billions of euros are spent each year to develop new drugs. The mission of new therapeutics and vaccine development also requires the technologies and services provided by the **ESFRI Landmarks EU-OPENSCREEN ERIC**, **INSTRUCT ERIC** and **INFRAFRONTIER**.

One of the most prominent missions is dedicated to cancer which, after cardiovascular diseases, is the leading cause of premature deaths in the EU. In 2016, one quarter (26% corresponding to 1.3 million people) of the total number of deaths in Europe were due to cancer and it was predicted to kill 1.41 million in 2019. The **ESFRI Landmarks INSTRUCT ERIC**, **Euro-BioImaging ERIC**, **BBMRI ERIC**, **EATRIS ERIC**, **ECRIN ERIC**, **INFRAFRONTIER** and **ELIXIR** will strategically contribute to the new European mission[7] aiming at '*Conquer-*

6.
Ecosystems and human well-being: health synthesis: a report of the Millennium Ecosystem Assessment. WHO
http://www.millenniumassessment.org/en/Synthesis.aspx

ing Cancer' as their services are essential in the multiple facet aspects of cancer-related projects, going from understanding to prevention and treatment of cancer.

Another very integrative mission of the H&F RIs is that of protecting human health by increasing Europe's preparedness for and capability to respond to highly pathogenic infectious threats, for which all RIs of the Health subdomain clustered to provide an effective organization of service provision to address health emergencies.

The RIs of the H&F domain aim to contribute to other Missions of the Horizon Europe Framework Program[8]. With respect to the '*Caring for Soil is Caring for Life*, the **ESFRI Project EMPHASIS** has a major role in providing access to services that are key for understanding plant performance and translate this knowledge into application. These are complemented with services and technologies of the **ESFRI Landmarks MIRRI** and **AnaEE** which, together with the **ESFRI Landmark EMBRC ERIC**, would also contribute to the '*Healthy oceans, seas coastal and inland waters*' mission.

HEALTH

As Health & Food RIs grow and expand, they are developing and adopting policies that safeguard their operation, including standardization, integration with national facilities, implementation of GDPR, and adoption of cloud services to be able to cope with data storage and analysis.

Health & Food RIs have developed intra-domain clustering in the area of data storage and usage across the ESFRI RIs. Since March 2019, the Life science RIs have been working within EOSC-Life[9] to share working best-practices in data management that will enable and prepare the LS RIs to use EOSC[10] tools and services. The complexity and scale of the data being captured and managed by the LS RIs are already astounding and ever increasing and this, along with complex metadata, presents specific issues of data management. Moreover, this would facilitate interdisciplinary research in the area of health-environmental-food that is needed for the health and well-being of 450,000,000 European citizen-consumers and their global counterparts.

Another complementary cooperation shows the Alliance of Medical Research Infrastructures[5] which includes the cluster of the **ESFRI Landmarks EATRIS ERIC**, **BBMRI ERIC** and **ECRIN ERIC**, providing a broad spectrum of services with a strong focus on patient benefit and improvements in societal well-being. The clustering initiatives support the consolidation of the European landscape of infrastructures towards translational-to-clinical research that share common user communities and are highly complementary in scientific scope and mission.

II CURRENT STATUS

The Health subdomain is very rich regarding the number of research areas, portfolio technologies, and connected services, and the developmental dynamics, which is especially remarkable under the current situation caused by the SARS-CoV-2-based pandemics. The Covid-19 actions of RIs proved a striking example of concerted tackling of an urgent problem. The *RIs against COVID-19 webpage*[11] lists the RIs working, individually or collectively, on the COVID-19 pandemics. Involvement of these RIs shows their crucial importance but also uncovers developing scientific challenges that could be defined as follows:

- interdisciplinary collaboration,
- thematic versus permanent clustering, intra- and inter-domains,
- development, adaptation and enrichment and new RIs,
- Health & Food diversity,
- cross-domain and inter-sectorial clusters.

Within the Life Sciences, RIs have established closed interconnections over the past years[3], signed several inter-RI collaboration agreements and joined forces in the framework of several EU-funded Projects, including CORBEL, EMBRIC, EOSC-life, RI-VIS, and also ERIC Forum. For future development, it will be critically important to reinforce cross-RI activities, especially the implementation of joint user projects, by providing adequate funding to the RIs. Life Science RIs have also worked together with ERIC Forum to provide information and participate in consultations for the Horizon Europe Framework, and have contributed to

7. European Mission on Cancer
https://ec.europa.eu/info/horizon-europe/missions-horizon-europe/cancer_en

8. Horizon Europe
https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en

9. EOSC-life
https://www.eosc-life.eu/

10. EOSC Portal
https://www.eosc-portal.eu/

11. RIs against COVID-19 pandemic
https://www.esfri.eu/covid-19

several publications that will shape the future European Research Area.

In light of this, the medical RIs – the **ESFRI Landmarks EATRIS ERIC**, **BBMRI ERIC**, and **ECRIN ERIC** – have been jointly intensifying their engagement of specific communities of practice, notably: patient engagement, research and development in rare diseases, and cancer. In 2019, the **ESFRI Landmark EATRIS ERIC** signed a collaboration agreement with the European Patients Forum (EPF)[12] which, in 2020, has been extended to the European Patients Academy (EUPATI)[13].

Huge development appeared also in the field of rare diseases, especially in the context of the European Joint Programme on Rare Diseases (EJP RD)[14]. Combined, rare diseases patients count more than 30 million people in Europe; thus the policy and RI attention to developing diagnostic and therapeutic solutions for them is an important welfare and economic incentive. The **ESFRI Landmarks EATRIS ERIC** is co-leading one of the four pillars and the sustainability planning for the whole programme. The **ESFRI Landmarks ECRIN ERIC**, **BBMRI ERIC**, **ELIXIR** and **INFRAFRONTIER** are also involved as project partners. Interestingly, INFRAFRONTIER partners exceed the activities in modelling the rare diseases beyond the European border joining the world-wide Research Infrastructure of International Mouse Phenotyping Consortium (IMPC)[15].

Also in the cancer field, one of the Missions in Horizon Europe, RIs of the Health subdomain are a strategic asset able to provide unique services for understanding the molecular bases of cancerogenesis – e.g. **ESFRI Landmarks INSTRUCT ERIC** and **Euro-BioImaging ERIC** – and finding new treatments – e.g. **ESFRI Landmarks INSTRUCT ERIC** and **EU-OPENSCREEN ERIC**. The **ESFRI Landmark INFRAFRONTIER**, providing open access calls to create models for various cancer types interlinks with EurOPDX consortium[16] to develop a new platform for cancer research and patient treatment. Future development of RIs activities in the cancer field will require further harmonisation, standardisation, and especially utilisation of human samples with **ESFRI Landmark BBMRI ERIC** to foster cancer treatments.

Several other areas which are developing in the European scientific landscape, will be reinforced upon engagement of ESFRI RIs. The aim of the One Health EJP[17] is to create a sustainable European One Health framework by integration and alignment of medical, veterinary and food institutes through joint programming of research agendas matching the needs of European and national policymakers and stakeholders. The overarching goal of the European Human Biomonitoring Initiative (HBM4EU)[18] is to generate knowledge to inform the safe management of chemicals and so protect human health. Innovative Medicine Initiative (IMI)[19] is a joint initiative (public-private partnership) of the DG Research of the European Commission and the European Federation of Pharmaceutical Industries and Associations (EFPIA). The EU Joint Programme – Neurodegenerative Disease Research (JPND)[20] is the largest global research initiative aimed at tackling the challenge of neurodegenerative diseases. The Joint Programming Initiative on Antimicrobial Resistance (JPIAMR)[21] is a global collaborative organisation and platform, engaging 28 nations to curb Antimicrobial Resistance (AMR) with a One Health approach.

The current development of the H&F RIs brings also a new interdisciplinary RI the **ESFRI Project EIRENE RI** on the roadmap. This RI fills the gap in the European infrastructural landscape and pioneers bridging the topic of environmental impact and human health with the topic of human exposome, i.e. environmental determinants of health. This effort will lead to improved understanding of an impact of exposome on the European population, characterization of the risk factors behind development of chronic conditions, and discovery of novel tools for their prevention and treatment. It also brings together the leaders of the EU and US Environment & Health research to advance new scientific developments and establish a large-scale interdisciplinary research providing harmonized workflows covering all processes between the data and sample collection and knowledge provided to the end users accessible to academic researchers, private companies, public authorities and citizens.

12.
European Patients Forum (EPF)
https://www.eu-patient.eu/

13.
European Patients Academy (EUPATI)
https://eupati.eu/

14.
European Joint Programme in Rare Diseases (EJP RD) is a H2020-funded project (2019-2023), bringing over 130 institutions from 35 countries to create a comprehensive, sustainable ecosystem allowing a virtuous circle between research, care and medical innovation.
https://www.ejprarediseases.org/

15.
International Mouse Phenotyping Consortium (IMPC)
https://www.mousephenotype.org/

16.
EurOPDX consortium
https://www.europdx.eu/

17.
One Health EJP
https://onehealthejp.eu/

18.
European Human Biomonitoring Initiative (HBM4EU)
https://www.hbm4eu.eu/

19.
Innovative Medicine Initiative (IMI)
https://www.imi.europa.eu/

20.
EU Joint Programme – Neurodegenerative Disease Research (JPND)
https://www.neurodegenerationresearch.eu/

21.
Joint Programming Initiative on Antimicrobial Resistance (JPIAMR)
https://www.jpiamr.eu/

FOOD

The Food Challenge is multifaceted and complex. We are facing a challenge in securing food supply to a global growing population. Population projections estimate that by 2050 the world population will increase to 9.6 billion and 12.3 billion people in 2100[22]. The ability to feed the world's growing population is dependent on the capacity of food supply to meet future food demand, and food demand is expected to increase anywhere between 50% and 100 % by 2050[23]. New disruptive technologies and strategies must be developed and adopted to be geared towards increasing food production while minimizing environmental impact, carbon footprint, and emission of greenhouse gasses. Such new technologies development should help contribute to sufficient supply of affordable food for European citizens and help facilitate the transition set out in the EU's Farm 2-Fork Strategy for fair, healthy, and environmentally friendly food systems. The Strategy is also central to the Commission's agenda to achieve the United Nations' Sustainable Development Goals (SDGs), particularly goals related to food and nutrition security. In the same way, the Food 2030[24] is an EU research and innovation policy that aims to apply a holistic system-based principle to meeting the SDGs, and to future proofing our food systems under four main priorities: Nutrition, Climate, Circularity, and Innovation. This systemic approach views the way food is produced and how it affects health, well-being and the environment as a circular issue comprising all elements of food production, processing, packaging, logistics, and distribution, healthy people, and recovered waste streams.

A significant part of the food challenge is our food consumption patterns and their impact on our physical health and health systems. To effectively realize the transition to healthy and sustainable diets, interdisciplinary linkages between domain specific RIs are urgently needed to address the health and food challenges in an integrated way, including the modification of current eating habits of European citizens. Worldwide increases in calorie consumption combined with a sedentary lifestyle with low physical activity is emerging as an increasing problem with harmful impacts. Incidences of metabolic syndrome, type 2 diabetes and related lifestyle-related non-communicable diseases are increasing worldwide, escalating the healthcare costs. Moreover, there is also expected increase of aged population, those aged over 65 years are anticipated to account for over 22% of the global population by 2050. When considered together with an increased life-expectancy and a need for extended active working years, the need for nutritional solutions to both maintain and enhance the quality of becomes increasingly apparent. The dietary habits will not only effect on human health but it will also influence the agricultural system, which will meet also changes in environmental conditions due to the climate change. At a global scale, adoption of more plant-based diets may participate on reduction of development diseases and global mortality. However, several studies, including a major review by the Food and Agriculture Organization (FAO) of the United Nations, predict a substantial increase in meat consumption in the next decades[25]. Most of this increase will occur in low and middle income countries. In essence, understanding the interconnection between diet, environment and agricultural production is essential to be able to define possible scenarios and set the boundaries for a sustainable agriculture at a global scale.

In order to meet the increase in animal and crop production that will be required to feed the projected future population, enhanced productivity on existing agricultural lands through genetic selection, improved fertilizer and irrigation methods and adopting new methods like precision farming will be necessary. Intensive and large-scale agriculture should be achieved without negative impacts on air and water quality, biodiversity, carbon footprint and infectious disease transmission. This could be in part facilitated by AI & robotic, for monitoring and modelling of the environmental effects on food production and its application in precision agriculture.

CURRENT STATUS

The **ESFRI Project EMPHASIS** will provide RI for the quantitative measurement of plant properties (plant phenotyping) under diverse environmental scenarios. This is crucial for the characterization of phenotypic variability, which is at the base of plant breeding, and the subsequent identification of the genes controlling plant traits. Ecosystem services, central to food security and human welfare, are at the core of the **ESFRI Landmark AnaEE**. These services are instrumental for analysing factors affecting different aspects of the ecosystem, from the use of land and nutrient input, to changes in the production of food, of raw material and of bio-energy, to climate change at global and local scales, to loss of biodiversity, tackling pollution problems, etc. Several of these global change drivers have the potential to disturb critical ecosystem processes, eventually leading to tipping-points and catastrophic changes in ecosystem functioning. The **ESFRI Project METROFOOD-RI**, Infrastructure for promoting Metrology in Food and Nutrition, tackles services to various stakeholder in the field of food quality and safety. It provides high-quality metrology services in food and nutrition, comprising an important cross-section of highly interdisciplinary and interconnected fields throughout the food value chain, including *Agri-food*, sustainable development, food safety, quality, traceability and authenticity, environmental safety, and human health. By providing RIs for the study of the interactions between agriculture and environment, the **ESFRI Landmark AnaEE, EMPHASIS** and **MET-**

22. World population stabilization unlikely this century. P. Gerland et al. Vol. 346, pp. 234-237 (2014) DOI: 10.1126/science.1257469
https://science.sciencemag.org/content/346/6206/234

23. The future of food demand: understanding differences in global economic models. H. Valin et al. Volume 45, pp. 51-67 (2014)
https://www.researchgate.net/publication/258883059_The_Future_of_Food_Demand_Understanding_Differences_in_Global_Economic_Models

24. Food 2030
https://ec.europa.eu/info/research-and-innovation/research-area/environment/bioeconomy/food-systems/food-2030_en

25. World agriculture towards 2030/2050: the 2012 revision
http://www.fao.org/3/a-ap106e.pdf

ROFOOD-RI contribute to the definition of possible strategies for the development of a sustainable agricultural system.

The food system is also highly dependent on manifold functions of microrganisms that are involved in a myriad of processes, from plant nutrition to food processing. The **ESFRI Landmark MIRRI**, although primarily involved in the biomedical area, makes available a broad range of high-quality microorganisms, their derivatives, associated data, services and expertise, which are key assets for researchers and bioindustries to deliver the maximum value and impacts from their projects, technologies and products targeting different Sustainable Development Goals. MIRRI can contribute to deliver the impacts of the '*SDG 2 | Zero Hunger*', especially in what concerns to promoting sustainable food production systems and the access to safe, nutritious and sufficient food.

Progress in plant breeding and innovation in agricultural practices will be at the basis of the increase in agricultural production in the next future. The introduction of molecular techniques is accelerating the breeding process and recent advances in genomics, together with the development of plant phenotyping, are facilitating the identification of key genes controlling productivity and nutritional quality. In this context, the **ESFRI Project EMPHASIS** plays a pivotal role in the development of different types of plant phenotyping platforms for the quantitative measurement of plant traits in high throughput, to enhance plant breeding and enable resilient agriculture. Several efforts are being made also to understand how a changing climate is going to affect yields and the nutritional characteristics of the edible part of crop plants. This requires monitoring of the effect of the environment on plant growth under a variety of experimental conditions.

The transformation of the food system is likely to involve a move towards greater reliance on plant-based food sources in our diet, at least in some countries. This will require a refocusing of breeding efforts in order to improve both the nutritional and technological characteristics of plant proteins, and reduce the presence on antinutritional factors in plant raw materials. The transition will also require piloting and up-scaling facilities to for the processing of raw materials including plant, algae, marine life, fungi and micro-organisms. The **ESFRI Landmark INSTRUCT ERIC** on the use of structural biology to support plant and animal sciences, the **ESFRI Landmark ELIXIR** on life sciences large-scale data and knowledge management, and the **ESFRI Project METROFOOD-RI** will be functional in achieving these goals. A continued development of the marine biotechnologies, which is central to the **ESFRI Landmark EMBRC ERIC**, towards Blue Growth can contribute to deliver the long-term strategy to support sustainable growth in the marine and maritime sectors. Of course, achievement of the UN Sustainable Development Goal to "halve per capita global food waste at the retail and consumer level, and reduce food losses along production and supply chains by 2030" could contribute greatly to addressing the food challenge. As some 1.3 billion metric tons, or one-third of all the food produced, is thrown away (United Nations' Food and Agriculture Organization), it is estimated that recovering just 25% of that wasted food could feed 870 million hungry people – effectively ending world hunger.

The Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI)[26] brings together 24 countries who are committed to building an integrated European Research Area addressing the interconnected challenges of sustainable agriculture, food security and impacts of climate change. The Joint Programming Initiative a Healthy Diet for a Healthy Life (JPI HDHL)[27] brings together 26 countries that align research programming and fund new research to prevent or minimize diet-related chronic diseases. The joint health and environmental challenges require fostering innovative research at the cutting edge of these domains.

26. Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI) https://www.faccejpi.com/

27. Joint Programming Initiative a Healthy Diet for a Healthy Life (JPI HDHL) https://www.healthydietforhealthylife.eu/

GAPS, CHALLENGES AND FUTURE NEEDS

ESFRI RIs by definition are built on a foundation of scientific excellence and their continuous effort and investment in developing new technologies and resources of high-quality and standards allows to tackle the highly complex challenges.

HEALTH CHALLENGES

For the *Health* subdomain, challenges include the following items.

- Develop and implement platforms and tools to address pandemics including tools for diagnostics, early intervention, development of cures and prevention approaches – e.g. vaccines.
- Tackle antimicrobial resistance.
- Develop research and service platforms for neurodegenerative diseases as well as ageing and environmental impact (exposomes).

  Fostering complementary research activities among health-environment-food interdependencies would allow to fill the current gaps and facilitate innovation in the food-nutrition-health axis.
- Boost RIs complementary services and expertise addressing all phases of cancer research to fully support Mission on Cancer.
- Facilitate precision medicine, stratified and personalised treatments and healthcare, tailored also to rare disease subgroups or individuals, providing multi-scale facilities as test-beds for pharmaceutical and biopharmaceutical (therapeutics) manufacturing.

  This stratification should take into account the paediatric aspects, including methodologies and tools covering paediatric specific pharmacology, formulation, devices and innovative biological-driven drug discovery tools as well as data science applications.
- Develop tailored healthcare interventions and robust models for prevention and treatment, bridging the gap between genomic information and clinical practice.

HEALTH NEEDS

The emerging picture is complex and indicates that *Health* challenges cannot stand in isolation. They have to be framed in the entire science and innovation landscape, taking in consideration the following needs.

- Excellent science, technologies and high-quality data to develop effective preventions, including screening technologies, diagnostic opportunities, and treatment requests.
- Development of treatments for diseases, which requires a full understanding of their molecular bases, the design of new therapeutics and investments into the testing facilities within preclinical development, empowering their translation.
- Build complex inter- and cross-disciplinary research models, technologies, with bridges between scientific disciplines, enterprises and the society, bringing together leading science, state-of-the-art technologies, healthcare providers, relevant industry sectors.
- Empowering state-of-the-art technologies, such as 3D tissue models which can replace certain organ parts, and single and intra-cell technologies, to improve our knowledge about how different cell types communicate and collaborate within an organ.
- Enabling research approaches that will combine genetics, environmental, and societal challenges.
- Training of novel bioinformatics experts to integrate and interact with *health care*.
- Climate change, extreme weather, dramatic changes in ecosystem services, environmental pollution and exposure to harmful chemicals represent a new combination of issues that require an integrated approach at the pan-European level.
- Enabling a suitable environment to facilitate research on human health and well-being at all stages in development, including ageing, nutrition and behavioural studies, and their connections to the Social Sciences and Humanities.

HEALTH EMERGING AREAS

As the societal needs of Europe evolve, ESFRI should consider a strong clustering program, creating an interdisciplinary environment for new emerging areas.

Synthetic biology. Connection to health, future therapies, food & agriculture. Programmable bacteria/microbiota.

Future therapies. Fostering translation of new technologies and genetic findings to enable efficient disease correction and cure. Gene-therapies: genome editing, personalized medicine including cancer and rare diseases.

Infections threats and their impact. Multi-sectorial RIs providing capacity and expertise to diagnostics and prevention/treatments of infection. Revealing gaps and possible future developments.

Biomedical engineering and electronics. An interpectoral collaborative platform or a new RI could advance biomedical research and innovation especially with regards to clinical use in the area including new sensors and various medical devices, and embedded electronics such as: Wearable devices and implantable technologies; Nanorobotics; Brain-computer interfaces (BCIs).

Biotechnologies to interconnect classic Health RI with preclinical-to-clinical technologies. 3D-bioprinting and technology for biomedicine to bridge the gap among biological science, medicine, and biomedical engineering.

Intra-domain, inter-domain and cross-sectorial clusters to fill existing gaps. Chemistry-preclinical development interface, a RI platform to facilitate and speed up translation into medicinal practice.

RI platform for assessment and management of human health as environmental medicine in strong connection to healthy ageing, e.g. to initiate a trans-disciplinary infrastructure that would support studies of the environmental factors, including the working conditions and circadian misalignment, on human health; more studies need to be supported in this area in order to identify scientific connections, provide mechanisms and pinpoint individuals at the highest risk.

Linking dietary behaviour to both health and environmental impact regarding the research on physiological and behavioural determinants would generate unique scientific data that would allow to understand the impact of the nourishment on human health.

Data. The complexity and scale of the data being acquired and managed by the Health subdomain RIs is already astounding and ever increasing and this, along with complex metadata, presents specific issues of data management that need to be framed within EOSC architecture.

Furthermore, the rules and guidelines of how to collect and properly use patient data need to be further developed. The challenge of data, management and stewardship for precision medicine is to some extent met within the H&F ESFRI RIs. Ethical, legal and social implications are included and taken care of by clinical and health-focused RIs. However, multiple gaps still exist, both at level of data sharing among different communities, as well as of unifying data collection.

Artificial intelligence has also been identified as an infrastructure to generate opportunities and combine data from different resources. There is an obvious connection with the DIGIT domain.

FOOD CHALLENGES

In the *Food* subdomain, the following gaps and challenges need to be addressed.

- A gap regarding the focus on animals in agriculture and food sub-domain. A new infrastructure or an upgrade of existing efforts are needed at EU-level in the field of food, nutrition and processing.
- Concerted effort to continue bringing together national facilities at the pan-European level in the field of animal genetic resources, phenotyping and breeding, animal health is needed to contribute to address the challenge to produce safe, healthy and sustainable food.
- Large farm animals, poultry and fish, often in relation to adaptation to climate change and higher feed efficiency.
- World-class facilities for the integration, conservation and coordination of national and international animal genetic stock and potential stock lines for adaptation to climate change.
- Integration of facilities for bioimaging, digital imaging, genomics, proteomics and metabolomics along with field and veterinary facilities with farm-scale experimental platforms for animal studies and phenotyping, including aquaculture and animal disease facilities.
- To bring together pilot-scale facilities, demonstrators and up-scaling facilities to enable access to the production and processing of materials, chemicals (e.g. antibiotics) and energy, using biological resources, including plant, algae, marine life, fungi and micro-organisms.
- High-quality metrology services in food and nutrition, comprising an important cross-section of highly inter-disciplinary and inter-connected fields throughout the food value chain, including agri-food, sustainable development, food safety, quality, traceability and authenticity, environmental safety, and human health.
- Integrated approaches including e-Infrastructures are needed to systematically predict, diagnose, prevent and treat plant and animal disease, and to device effective responses to mitigate the impact on agri-ecosystems.
- Tools for the monitoring of food consumption patterns, to measure their impact on our physical health and health systems, on agriculture and the environment would be instrumental for the development of a sustainable food system.

FOOD NEEDS

Fulfilling the following needs should help to tackle *Food* subdomain-specific challenges whose solutions should be solved within the already established RIs.

Sustainability and improving plant health and ecosystem functioning. The Food subdomain RIs need also to focus on system approaches for effective management of pests and harmful alien species to ensure a European food security system. It should be well balanced with a sustainable agro-ecological transition and ecosystems services while developing practical solutions to predict, prevent and protect agricultural and forestry ecosystems from native and alien pests (introduced in EU Member States) through integrated agro-ecological approach to plant health.

Reducing greenhouse gas emissions in ecosystems, especially in agriculture. There is a need to reduce the environmental and climate footprint of European agricultural crop production. The aim is quantifying the potential of promising agricultural practices (improved fertilization methodologies, water management, and microbiological-targeted amendments) on crops to improve or maintain ecosystem services delivery (C sequestration, reduction of GHG emissions, maintaining water quality, high quality food production), in EU, and under future climate.

Ecosystem carbon storage. European forests constitute a sink for 450 million tons of CO2 per year, plus in addition 5 million tons stored in woody biomass and 30 million tons in forest soils. Wetlands, 21% of the European surface are also important for CO2 sequestration. However, forests are currently impacted by global change, and extended drought periods make their resistance to perturbation decrease, and less resistant to pathogens. Only 50% of wetlands are considered in good state. Improving the health of wetlands, and the adaptation of forests to global change pressures will result in preserving this important CO2 sink. Moreover, sustainable amendments can be tested in agriculture to sequester carbon (negative emission technology).

Energy and climate-smart food systems. These systems as well as sustainable agricultural production systems can become viable solutions for development and bring significant structural change in rural areas relying on clean energy solutions.

Prevent biodiversity loss. Global loss of biodiversity is threatening the security of the world's food supplies and the livelihoods of millions of people. Land-use changes, pollution, overexploitation of resources, and climate change are the biggest drivers of this biodiversity loss.

Digital platform technologies. Increase the availability of digital platform technologies (e.g. 5G; robotic, artificial intelligence) with increasing opportunities for crop breeding and production. The development and implementation of novel technology including machine learning (needed e.g. for smart farming), of common standards to enable use and reuse of data from agriculture, and data sciences from sensors to prediction models and decision support, would be functional to the sustainable intensification of agriculture.

A topic which could be considered as an additional challenge is related to the development of animal vaccines and treatments for crops. This requires to exploit the integration of services in both the *Health* and the *Food* domains and include an effort to integrate new chemistry-based Research Infrastructure. The Health domain provides the tools for characterizing diseases (virus, bacteria, etc.) and for designing treatments. The *Food* domain could provide facilities for testing them and giving feedback for their optimization. The possibility to set up a RI in Vaccine Development is currently pursued by Transvac-DS[28].

With the addition of the **ESFRI Projects EU-IBISBA** and **METROFOOD-RI** many of the challenges in the landscape in this thematic area could be tackled, especially if the Health & Food RIs would interact to develop together solutions addressing the health status of people in connection to sustainable food production.

28.
TRANSVAC infrastructure
https://www.transvac.org/transvac-ds

For each of the above mentioned fields, it is paramount to embrace the principle that Health & Food RIs hold the keys for the full and successful implementation and/or development of pan-European and national efforts to improve Health & Food RIs, expanding their capabilities to respond to current and future demands.

Furthermore, a Chemistry-specialised Research Infrastructure, so far not presented in the ESFRI landscape would be highly needed for the whole H&F domain to solve major challenges in Europe.

Significant innovations and new developments often occur at the boundaries of research areas. It is envisaged that the development of the EOSC, providing an open science ecosystem for research data following FAIR principles, will foster the critical role of H&F RIs and their capability to connect their efforts with other domains, where they have the potential to pioneer new ways of working and realise true interdisciplinary.

CONTENTS

95 ASTRONOMY & ASTROPARTICLE PHYSICS
95 CURRENT STATUS
97 GAPS, CHALLENGES AND FUTURE NEEDS

98 PARTICLE & NUCLEAR PHYSICS
98 CURRENT STATUS
100 GAPS, CHALLENGES AND FUTURE NEEDS

101 ANALYTICAL PHYSICS
101 CURRENT STATUS
102 GAPS, CHALLENGES AND FUTURE NEEDS

PART2

LANDSCAPE ANALYSIS - SECTION1

PHYSICAL SCIENCES & ENGINEERING

PHYSICAL SCIENCES & ENGINEERING

Research Infrastructures have a profound impact on research excellence, organisation of research and structuring of Physical Sciences and Engineering communities. RIs are scientific and technological hubs, which fully engage scientists to create, design, and exploit facilities to advance science, industrial innovation and manufacturing, with overall benefit to society.

The successful European RI landscape is the result of a long-term coordinated strategy to pool efforts and resources through international collaborations with inclusive, open, and excellence-based access policies. PSE RIs enable innovative research and technology development at a European and global scale, with a solid coverage of Astronomy & Astroparticle Physics (A&AP), Particle & Nuclear Physics (P&NP), and Analytical Physics (AP), and a growing systematic impact in new areas. PSE RIs are core research centres for producing excellent science culminating in several Nobel prizes for Physics and Chemistry. The common practice of RIs towards global cooperation enables even greater exchange of knowledge, skills and scientific advances. This way they can very efficiently address and solve scientific challenges, often combining multiple simultaneous probes and messengers within a complementary methods approach.

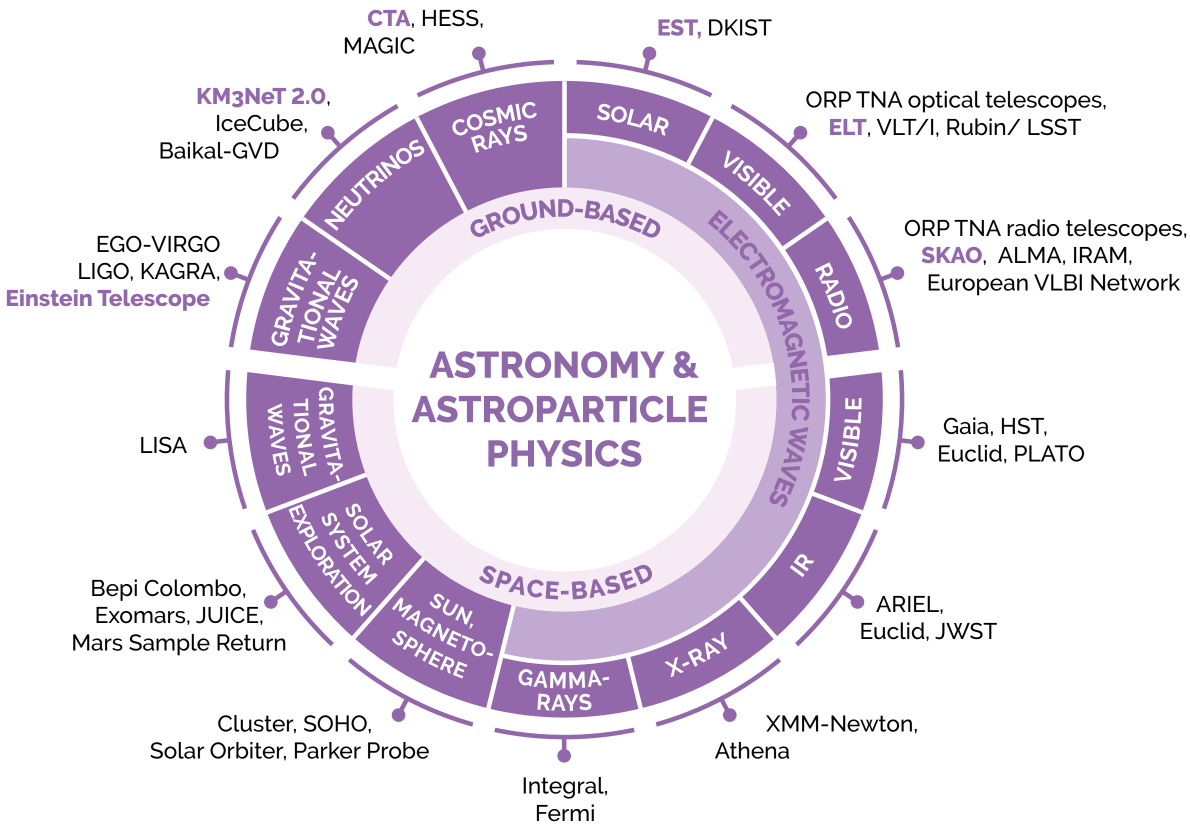
RIs have demonstrated their instrumental role to scientific communities and society during the COVID-19 pandemic, providing technologies, services and analytical skills, routinely available to PSE researchers, to support a prompt and well-coordinated response to a complex emergency. RIs have responded rapidly to new challenges, drawing on their strengths as science pillars, knowledge hubs and providers of reliable open data. Analytical facilities such as synchrotrons, neutron sources, lasers and electron microscopes were agile to rapidly establish access procedures for experiments on the structure and functioning of the virus. The COVID emergency accelerated the broader trend in the ability of RI to deploy their competences and capacities to address urgent societal issues, including the five Missions identified for Horizon Europe. Continued fostering of scientific and technological innovations is essential to develop the RIs and their co-operation beyond the state-of-the-art. It is also critical to create strategies for outreach to increase public awareness of the crucial role of RIs in helping Europe to reach the goals of these missions.

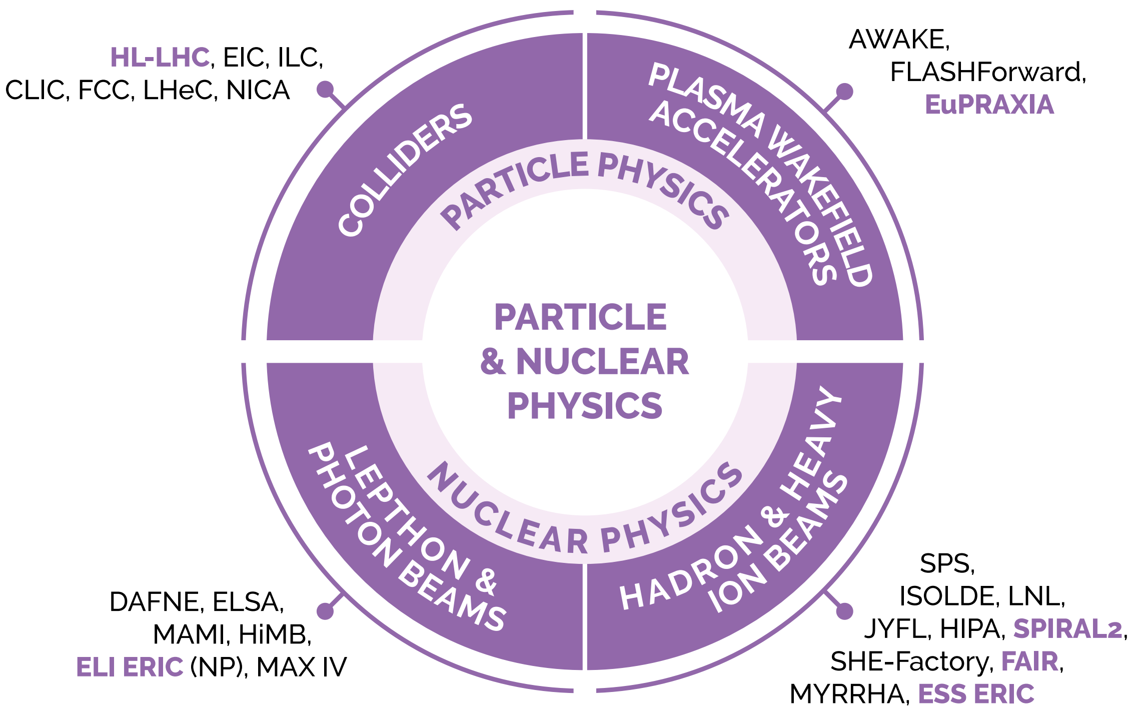
THE PSE LANDSCAPE AND ITS EVOLUTION

PSE RIs enable understanding the physical structure of nature and its interactions over an enormous range of distances, energy and time, from the Big Bang to now, and from subnuclear scales to the whole observable Universe.

The landscape contains a variety of RIs in terms of advanced technologies and services for research and innovation. In **ASTRONOMY & ASTROPARTICLE PHYSICS**, data-sharing methods are extremely advanced and the remotely collected observational data represent an invaluable asset that can be accessed worldwide for research and educational scopes. In **PARTICLE & NUCLEAR PHYSICS** the exploitation of colliders and accelerators is organized under the umbrella of large international collaborations with researchers physically accessing the facilities to perform the experiments. For **ANALYTICAL PHYSICS**, the successful model of synchrotrons gives access to a very large number of diverse users moving to the facilities to carry out approved-for-access research. Integration of large-scale analytical facilities with complementary material synthesis, characterization and numerical simulation services facilitates the close engagement with researchers across universities, institutes and industry.

An overview of the RIs currently forming the European landscape is shown **Figure 1**. This is an updated version of the last Roadmap data on RIs based in Europe or participated by European countries, running international open access programmes for users.


ASTRONOMY &
ASTROPARTICLE
PHYSICS
GROUND-BASED
SPACE-BASED
ELECTROMAGNETIC WAVES
COSMIC RAYS
SOLAR
VISIBLE
RADIO
VISIBLE
IR
X-RAY
GAMMA-RAYS
SUN, MAGNETO-SPHERE
SOLAR SYSTEM EXPLORATION
GRAVITA-TIONAL WAVES
GRAVITA-TIONAL WAVES
NEUTRINOS
CTA, HESS, MAGIC
EST, DKIST
ORP TNA optical telescopes, ELT, VLT/I, Rubin/ LSST
ORP TNA radio telescopes, SKAO, ALMA, IRAM, European VLBI Network
Gaia, HST, Euclid, PLATO
ARIEL, Euclid, JWST
XMM-Newton, Athena
Integral, Fermi
Cluster, SOHO, Solar Orbiter, Parker Probe
Bepi Colombo, Exomars, JUICE, Mars Sample Return
LISA
EGO-VIRGO LIGO, KAGRA, Einstein Telescope
KM3NeT 2.0, IceCube, Baikal-GVD


PARTICLE
& NUCLEAR
PHYSICS
PARTICLE PHYSICS
NUCLEAR PHYSICS
COLLIDERS
PLASMA WAKEFIELD ACCELERATORS
LEPTHON & PHOTON BEAMS
HADRON & HEAVY ION BEAMS
HL-LHC, EIC, ILC, CLIC, FCC, LHeC, NICA
AWAKE, FLASHForward, EuPRAXIA
DAFNE, ELSA, MAMI, HiMB, ELI ERIC (NP), MAX IV
SPS, ISOLDE, LNL, JYFL, HIPA, SPIRAL2, SHE-Factory, FAIR, MYRRHA, ESS ERIC

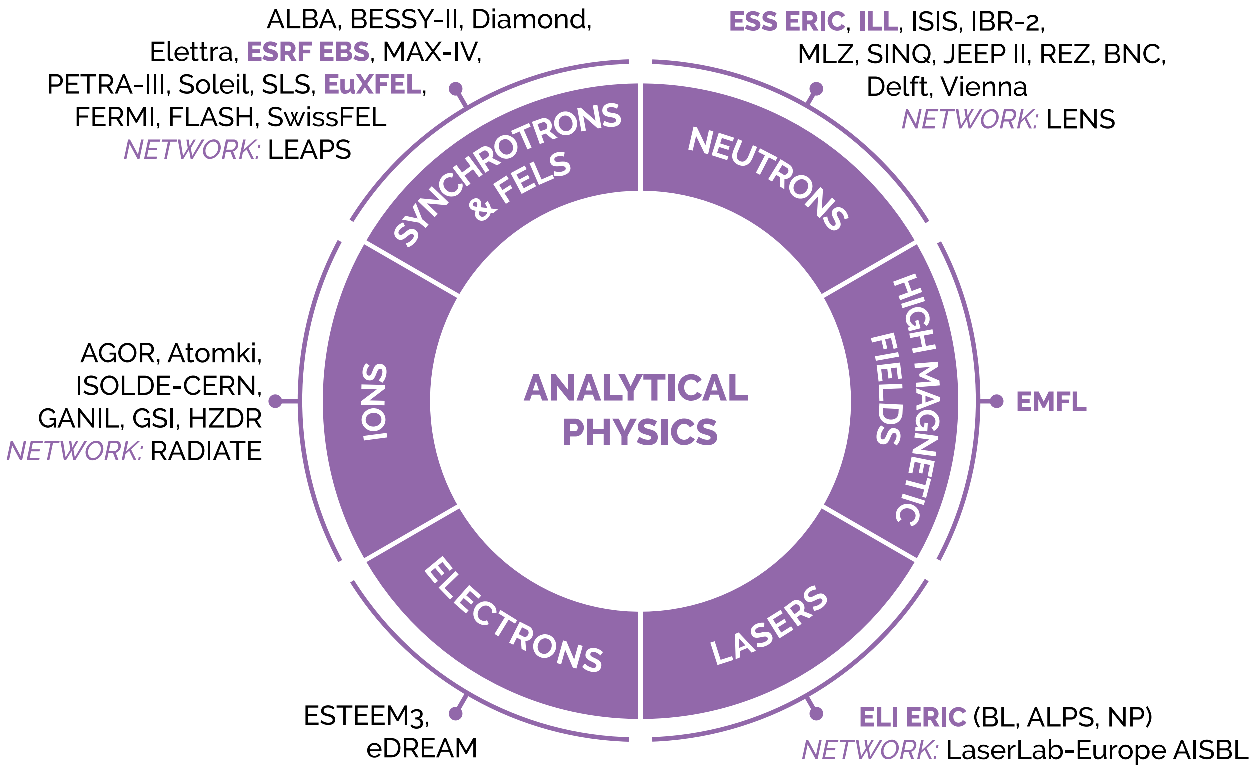


FIGURE 1.
The Landscape of the Physical Sciences & Engineering domain

Key questions that the PSE RIs help to answer for the progress of human knowledge are:

- What is the origin of the Universe and its constituents 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 mission of the PSE RIs. However, gaps remain in the landscape that should be filled to satisfy the scientific needs to answer these questions. **Table 1** provides a view of the vision and gaps against the relevant ESFRI PSE programme, with non-ESFRI large scale international RI's programmes also contributing to address some of the questions.

	VISION	GAPS & CHALLENGES	ESFRI RIs
ASTRONOMY & ASTROPARTICLE PHYSICS	Understand the Universe and its constituents, their origin and evolution	Integration of multi-messenger information Temporal domain Search for life High angular resolution/adaptive optics	CTA ET ELT EST KM3NeT 2.0 SKAO
PARTICLE & NUCLEAR PHYSICS	Understand the fundamental particles and interactions that govern the Universe and search for new physics beyond the standard model	High field (High Tc) superconducting magnets High gradient acceleration with breakthrough technologies Sources for high intensity and high quality muon beams High performance detector for photons and charged particles High intensity rare isotope beams	EuPRAXIA FAIR HL-LHC KM3NeT (ORCA) SPIRAL2
ANALYTICAL PHYSICS	Solve grand societal challenges by exploring frontiers of fundamental physics and materials science	Higher brilliance and stronger fields Higher temporal and spatial resolution *In situ* and *in operando* experiments Detector technology	ELI EMFL ESRF EBS ESS ERIC European XFEL ILL

TABLE 1.
Research drivers of the PSE subfields against the ESFRI RIs programme

PSE RIs share technologies, tools and practices that go beyond thematic disciplines and constitute a solid basis for effective cooperation. Sharing technologies increases the efficiency of the RIs while lowering their overall cost.

The data and data analysis chain – FAIR principles (Findability, Accessibility, Interoperability, and Reusability), big data, open data, open software, deep learning, etc. – and enabling technologies for interoperability and digitalization are exemplars. However, despite the Big Data challenges pressing on the field, a common limitation is that funding of the data and computing infrastructure is not always included in the RI initial cost estimate. The large experiments of Particle & Nuclear Physics, through their needs for massive data transfer, storage and processing, drive the field of Big Data. The complexity of the data structures requires development of sophisticated data analysis approaches based on artificial intelligence methods. Quantum computing, although still far from practical implementation, offers the potential to solve specialized tasks much more effectively than conventional methods. At the Analytical Physics facilities, the brilliance increase enables higher throughput of samples with higher resolution by employing faster and larger detectors. The rapid growth of the data produced at these RIs creates needs for strategies to transfer, store and treat Big Data. Also, the increasing number of multidisciplinary users demand new fast and reliable tools for analysis of large datasets. Use of artificial intelligence as well as standardisation in the hardware and software will aid progress toward this goal.

Technologies developed specifically for the needs of RI often *spill-over* to other fields, finding widespread cross-disciplinary applications with a large impact on society and citizens. Particle & Nuclear Physics requires accelerators at the forefront, new types of detectors with increased resolution and sensitivity, and highly efficient systems for acquisition, storage and processing of some of the largest data-streams ever encountered. These front-line technologies ultimately find their way into numerous applications in medical imaging and therapy, advanced detection and diagnostic methods, environmental science, computing etc. The methods of Particle & Nuclear Physics are closely related both in terms of science and in technology, but have significant overlaps with many other fields in astroparticle, astronomy, material science, real-time chemistry and biology. Closer cross-disciplinary exchanges are burgeoning and should be further reinforced. The selection of common tools in **Table 2** shows the crossing between thematic areas.

COMMON TOOL & KEY TECHNOLOGY	ASTRONOMY & ASTROPARTICLE PHYSICS	PARTICLE & NUCLEAR PHYSICS	ANALYTICAL PHYSICS
Adaptive mirrors	●		
High field and superconducting magnets		●	●
High gradient acceleration		●	●
Intelligent systems, instrument and stability control	●	●	●
Detectors	●	●	●
Cryogenics	●	●	●
Big and FAIR data	●	●	●
Deep learning, Artificial Intelligence	●	●	●

TABLE 2.
Tools and key technologies common to the subfields

The PSE RIs provide FAIR datasets of high reproducibility and quality as well as advanced data analysis methods and computational resources, contributing to drive the European Open Science Cloud (EOSC) and to make it workable. As demonstrated in astronomy, a global implementation of a FAIR disciplinary framework and openly available data, the so-called astronomical Virtual Observatory, enables exploitation of the data produced by the Infrastructures by any scientist around the world, and provides access to premium scientific data also to citizen scientists. RI services, however, should evolve to cope with the new needs of FAIR data, effective Interactive Remote Access (IRA), and mission-originated demand for research. This evolution requires significant strengthening of the skilled human resources available at RIs, to make IRA and mission-driven research possible. Boosting in-house science capability can better support the wider research community. New access schemes, different from the traditional model of users' originated projects, should be developed. The model of remote observation, common in Astronomy, could be more widely applied to the other domains. In the case of analytical facilities, protein crystallography has shown that robotized beamlines and mail-in samples can tremendously improve the throughput in standardized measurements. On the other hand, in certain highly specialized experiments, users and their hands-on expertise will still be needed to be present at the facility. Nevertheless, IRA technologies, from real-time on-line remote connection to augmented reality technologies, should be implemented to make the user control of remote experiments as effective as possible. This would improve the productivity of RIs while guaranteeing efficient training for young researchers. Increasing human resources at RIs can be pursued in various ways. A further increase in PhD students carrying out their research program at RIs, and Post-Doctoral positions at RIs, would reinforce the RIs as research and knowledge hubs in cooperation with universities and industries. RIs can play an increased role in preparing and training skilled young scientists and technology developers, as innovation-ready employees of industry and civil services.

REINFORCING RI COLLABORATION THROUGH NEW MODELS

Interconnection of RIs can occur spontaneously via clustering and joint offering of services such as common developments of protocols for FAIR data and services. The EOSC will be an element of evolution of the landscape. Interoperability of RIs is a new organizational and technological frontier enabling overarching research programmes beyond the measurement or observation session model and widening the portfolio of services for the users community. Clustering is powerful in enabling synergies between the ESFRI RIs, including sharing of technologies and best practices. A framework should be established to encourage such endeavours under Horizon Europe, beyond the current cluster projects.

The Astronomy ESFRI & Research Infrastructure Cluster project (ASTERICS, 2015-2019) successfully gathered the Astronomy & Astroparticle ESFRI RIs. Enhancing their performances beyond the state-of-the-art, it demonstrated the power of building synergies and common endeavours between the ESFRI RIs. ASTERICS was succeeded in 2019 by the European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures (ESCAPE) – one of the five EOSC-related Clusters, which includes the European Organization for Nuclear and Particle Research (CERN), and the European Southern Observatory (ESO). ESCAPE also brings on board other world-class established astronomical observatories, such as those operated by ESO (e.g. APEX, ALMA, the Paranal and La Silla observatories) and other Research Infrastructures including the European Gravitational-Wave Observatory (EGO-Virgo) and the Joint Institute for VLBI ERIC (JIVE), and the European Virtual Observatory teams.

Along with clustering of thematic RIs, a new model of multiple exploitation of broadly thematic RIs to pursue scientifically focused goals is proposed by the Analytical Research Infrastructures in Europe (ARIE)[1] position paper, where the alignment and exploitation of the wide range of services available at the RIs enable to meet the five Horizon Europe Missions, *i.e. climate change, cancer research, climate-neutral and smart cities, healthy oceans, seas, coastal and inland waters,* as well as *soil, health and food.* There are seven European networks under the ARIE umbrella representing about 120 national and international research facilities, including all the thematic ESFRI Projects and Landmarks: the League for European Accelerator based Photon Sources (LEAPS)[2] brings together the European accelerator based light sources, the European Distributed REsearch Infrastructure for Advanced Electron Microscopy (e-DREAM) collects the major actors in electron microscopy, LaserLab-Europe[3] coordinates the laser infrastructures, the League of advanced European Neutron Sources (LENS)[4] the neutron facilities, EMFL the high magnetic field facilities, and INSPIRE the proton and RADIATE the ion facilities. These networks thrive to create common tools for data, expand user communities, advance the technologies, and access models including industrial use. This is a joint effort undertaken within the networks and, under the ARIE umbrella, crossing the networks.

A pioneering approach towards the exploitation of complementary techniques was proposed by the NFFA-Europe model, now the newly funded NEP (NFFA-Europe Pilot) project for nanoscience, and the CERIC ERIC model in material and life science. NEP provides a rich catalogue of services and instruments to researchers who can access the theoretical and experimental facilities needed for their project. Thematic infrastructures, intrinsically distributed and multidimensional – highly specialized academic laboratories, large clean room facilities, large fine-analysis installations – that are already part of the landscape will most likely evolve into more structured and integrated organisations with the potential of extending PSE resources and methods to other fields of research such as life sciences.

Recent studies assess the overall economic impact of research carried out at RIs. This is complex as the technological innovations or scientific discoveries enabled by the PSE RIs extend over long time scales, up to decades after the invention or the finding[5]. Indicators have been proposed to guide the studies of economic impact of research at RIs. One of the most recent studies was carried out by the Centre for Economics and Business Research (CEBR) for the European Physical Society and published in 2019[6]. According to this report, physics-based industries generate more than 16% of total turnover and 12% of the overall employment in Europe, thus representing a net annual contribution of at least 1.45 trillion Euro[7]. Evaluation of the wider impact of RIs on society and economy should include the returns on discoveries and technology that sometimes find applications well beyond the initial targets, apart from the easier evaluation of the returns on RIs construction budgets that, in a variable measure from 40% to 60%, flow back into industries and companies of the partner countries through the procurement of supplies and services. The large innovation potential of technical solutions, for example, in detector and accelerator technologies, data handling, or remote control, is often exploited also for commercial applications and act as boosters for new applications and new practices.

RIs play key roles in training, higher education and communication to society and citizens. As hubs of knowledge and centres of excellence, RIs are crucial for advancing skills by giving access to cutting-edge facilities and providing opportunities for students and young researchers to specialise and develop their careers in stimulating environments. Collaboration platforms with European universities and research organisations are an important instrument to strengthen the link between education and research while stimulating the competitive excellence profile of the RIs through a beneficial and sustained injection of young, motivated researchers. The constructive links between RIs and universities are also apparent from the provenance distribution of the users, which in large percentages are M.Sc. and PhD students, and the European RIs serve many thousands of international users.

The overall evaluation of the users community size provides numbers as high as 30,000 for the Particle & Nuclear Physics area, at least 30,000 for Astronomy & Astroparticle Physics[8], and 40,000 for Analytical Physics. PSE users very positively adopted the access modes developed to mitigate restrictions to mobility, actively collaborating to implement interactive remote participation in the actual conduct of experiments. That prepares the ground for a transformative usage of the RIs enforcing the resilience of the transnational access paradigm.

To strengthen the public perception of the RIs value in everyday life, well-structured plans for communicating the unique scientific achievements enabled by the RIs are developed, explaining clearly the returns in knowledge, technology and education for the benefit of society.

1. Analytical Research Infrastructures in Europe - A key resource for the five Horizon Europe missions, Joint Position Paper. Pre-release 8 July 2020 https://www.lens-initiative.org/wp-content/uploads/2020/07/ARIE-PosPaper-2020-07-07-14.00.pdf

2. League for European Accelerator based Photon Sources (LEAPS) https://leaps-initiative.eu/

3. LaserLab-Europe https://www.laserlab-europe.eu/

4. League of advanced European Neutron Sources (LENS) https://www.lens-initiative.org/

5. STFC Impact Report 2018 https://stfc.ukri.org/files/stfc-impact-report-2018/

6. The Importance of Physics to the Economies of Europe - A study by CEBR for the period 2011-2016 (2019) https://www.eps.org/page/policy_economy

7. CERN Courier July/Aug 2020 https://cds.cern.ch/record/2722711/files/CERNCourier2020JulAug-digitaledition.pdf

8. Data from the astronomical facilities is open to the global community after a proprietary period, hence the relevant user community is the global astronomical community. The minimal number of potential users from the A&AP community is derived from the number of authors of the articles published in the 7 main journals of the field on one year (private communication from the Astrophysical Data System, the reference bibliographic database for astronomy).

ASTRONOMY & ASTROPARTICLE PHYSICS

Astronomy & Astroparticle Physics (A&AP) seek to understand the Universe and its components: from its still mysterious beginnings to its growing complexity, with the formation and evolution of galaxies, stars and planetary systems, until the emergence of life. The main science questions addressed by the RIs can be summarized as follows:

- understand the origin of the Universe and its main constituents;
- understand the extreme conditions the Universe hosts;
- understand the formation of galaxies and their evolution;
- understand the formation of stars and planets;
- search for planetary systems in our galaxy, study the Solar System and extra-solar planets, search for life and understand the conditions enabling life.

The domain relies on a combined approach of observations, theoretical work and modelling, and more and more on laboratory experiments. The level of precision necessary to constrain models requires high-performing space, ground-based and underground observatories, mostly built and managed through international collaboration, and exploited in synergy. Observations of our Universe extend beyond the historical optical domain, to the whole electromagnetic spectrum from radio waves to gamma-rays, and new messengers such as gravitational waves and neutrinos. Multi-messenger astronomy, with its multi-wavelength, multi-instrument approach, is the new frontier to study the phenomena of the Universe and their evolution. Underground physics laboratories investigate the rarest phenomena to discover dark matter and the nature of neutrino mass.

Gravitational wave astronomy is developing. On-going observation of gravitational waves is completed by the first identifications of their source by the detection of electromagnetic and neutrino counterparts, opening a new window for observation. It exemplifies the potency of international and interdisciplinary collaboration, relying on the joint exploitation of VIRGO (EU) and LIGO (USA) data which enables the study of the direction of the signals, whereas the astronomy community mobilizes its telescopes to identify the electromagnetic and neutrino counterpart of the gravitational wave events.

The study of planets from our Solar System through telescope observations, planetary probes and sample return missions, has built up a multidisciplinary field spanning from astrobiology to geology. In recent decades the knowledge of planetary systems outside our own Solar System vastly expanded, with – as of May 2021 – more than 4,300 exoplanets detected from ground and space observations, indicating that our galaxy alone holds 100 billion planets. With the **ESFRI Landmark ELT** and other forthcoming facilities able to probe the atmospheres of these planets, a new direction in comparative climate science could yield new insights about our own planet's climate.

The usage of data from multiple telescopes and instruments is now part of the astronomers' daily life. Another example of a significant result obtained by international collaboration involving several instruments is the imaging of the central black hole of a galaxy by the "Event Horizon Telescope", a very long baseline array which comprises millimetre and submillimetre-wavelength telescopes separated by distances comparable to the diameter of the Earth, including IRAM telescopes in France and Spain, APEX and ALMA in Chile, in which European participation is secured by ESO.

The key contribution of space missions is illustrated by the map of the positions of 1.7 billion galactic stars and the radial velocities of 7 million of them by the Gaia satellite, which is triggering a number of follow-up observations with ground-based instruments. Solar Orbiter, launched in February 2020, will provide an unprecedented detailed close look at the Sun.

The science drivers of Astronomy & Astroparticle Physics merge with those of Particle & Nuclear Physics, linking the physics from the infinitely large to the infinitely small, giving a holistic rationale for the overall Research Infrastructure investment in the Physical Sciences and Engineering field. This is exemplified by the extension of the Astronomy & Astroparticle Physics community gathered in the ASTERICS cluster to Particle Physics in ESCAPE.

II CURRENT STATUS

European Astronomy & Astroparticle Physics continue to occupy a world-leading status as a result of a strong portfolio of intergovernmental, multi-national and national Research Infrastructures available to the community. The community is strongly organised at the European and national levels, with two bodies dealing respectively with the Astronomy & Astrophysics and the Astroparticle Physics strategy, ASTRONET[9] and APPEC[10]. ASTRONET, which started as an ERA-NET, is now a self-sustained group of funding agencies and associated bodies. The last update of their Infrastructure Roadmap was in 2015; they are establishing a new Science Vision and Infrastructure Roadmap up to the 2030s, which is expected to be published in 2021. The Astroparticle Physics European Consortium APPEC, which was created in 2012 following the preparatory work of the ASPERA ERA-NET, launched its European Astroparticle Physics Strategy 2017-2026[11] in January 2018.

These European-level community-driven roadmaps coupled with the planning processes convened by ESO and ESA, have provided strategic coherence and continue to be 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. The ALMA millimetre/sub millimetre array in the Atacama Desert (Chile), the largest such facility in the world, is in full operation. The International LOFAR Telescope (ILT) and the Joint Institute for VLBI ERIC (JIVE) in the European Very Long Baseline Inter-

9. ASTRONET https://www.astronet-eu.org/

10. APPEC https://www.appec.org/

11. European Astroparticle Physics Strategy 2017-2026 https://www.appec.org/roadmap

ferometry (VLBI) Network are pathfinders for the **ESFRI Landmark SKAO** 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 CTA**. The current status of the ESFRI Landmarks and Projects in the Astronomy & Astroparticle Physics domain is summarized in **Table 3.**

	ESFRI ENTRY	NAME	STATUS (AS OF DECEMBER 2020)
LANDMARK	2006	ELT	Currently in construction in Chile's Atacama desert. The first set of instruments are passing their Preliminary Design Reviews. Stands to be the first 25-40m class telescope available.
	2006	SKAO	Dual location established in Australia and South Africa. International treaty signed in March 2019, being ratified. SKA Observatory intergovernmental organisation launched, and Construction Proposal and Observatory Establishment and Delivery Plan published, in February 2021.
	2008	CTA	Two hosted sites chosen, ESO Paranal (Chile) and IAC La Palma (Spain). Large Size Telescope in pre-production in La Palma. ERIC agreement signature foreseen in 2021.
PROJECT	2016	EST	Significant technological progress and well organised community. Promising but not yet confirmed stakeholders' commitment.
	2016	KM3NeT 2.0	Two Mediterranean sites, Capo Passero (Italy, ARCA) and Toulon (France, ORCA). First phase of building ORCA completed - the detector is taking data. Upgrade of the ARCA infrastructure progressing. Actions to prepare legal entity (ERIC) underway. Aims at higher luminosity than IceCube.
	2021	Einstein Telescope	Two potential sites to host the facility. Initial steps of the project underway.

TABLE 3.
Current status of the ESFRI Projects and Landmarks for Astronomy & Astroparticle Physics

Transnational access to national or multinational astronomical facilities – medium-size optical telescopes and radio telescopes – is organised through the H2020 programme OPTICON-Radionet-Pilot (ORP), which followed the successful EC-funded OPTICON and Radionet networks starting in March 2021 and will continue to develop synergies among activities in the communities (**Table 4**).

OPTICAL TELESCOPES	Australia, *Siding Spring*	AAT
	Chile, *La Silla*	MPG/ESO 2.2m, REM
	France, *Pic du Midi*	TBL
	France, *Saint Michel*	OHP 1.93m/1.2m
	Greece, *Helmos*	Aristarchos
	South Africa, *Sutherland*	SALT
	Spain, *La Palma*	CAHA 2.2m/3.5m, INT, LT, NOT, TNG
	Spain, *Teide*	TCS
	USA Hawaii, *Mauna Kea*	CFHT
	Distributed	LCOGT
RADIO TELESCOPES	Chile, *Llano de Chajnantor*	APEX
	France, *Plateau de Bures*	IRAM Interferometer
	Germany, *Effelsberg*	Effelsberg
	Italia, *Sardinia*	SRT
	Spain, *Pico Veleta*	IRAM 30m
	Sweden, *Onsala*	OSO
	The Netherlands, *Westerbork*	WSRT
	United Kingdom, *Jodrell Bank*	eMERLIN
	USA Hawaii, *Mauna Kea*	JCMT
	Distributed	EVN, LOFAR

TABLE 4.
Medium-size telescopes and radio telescopes available for transnational access in ORP, with their location.

GAPS, CHALLENGES AND FUTURE NEEDS

The lifetime of present-day scientific instrumentation and large telescopes exceeds the natural evolution timescales of the science cases that motivated them in the first place. The original science case often evolves in substantial ways by the time the facility becomes scientifically productive. Thus proposed new projects usually have broad science cases covering several fields of (astro/particle) physics that ensure their continued interest over their expected operational lifetime. The programme of development of new facilities is principally on track, but timelines get longer as the cost and complexity of projects increase.

The evolution of Astronomy & Astroparticle Physics projects clearly goes towards internationalisation in the construction as well as the operation of Research Infrastructures. ALMA and the **ESFRI Landmark SKAO** have been the first global astronomy infrastructures. Moreover, RIs may work in close collaboration and international networks can be set up to deal with key subjects, for instance, for the follow-up of gravitational events. Ground-based observations can play an essential role in the scientific exploitation of space observations.

The development of time-domain astronomy will be boosted in particular by the advent of the 10-year Legacy Survey of Space and Time (LSST), a US-led project with participation from several European countries. The novel multi-messenger paradigm incorporates follow-up observation and interpretation of transient phenomena alerts by a network of telescopes and underground or underwater/ice detectors. Particularly relevant projects for the observation of gravitational waves are the Laser Interferometer Space Antenna (LISA) selected by ESA as its third Large Mission, foreseen to fly in the early 2030s, and the **ESFRI Project Einstein Telescope (ET)**, which is proposed as the European Third-Generation Gravitational Wave Observatory with a significant increase in sensitivity.

The study of the planets from our Solar System and other planetary systems in our galaxy, and the conditions enabling life, builds up as an inter/multidisciplinary field, using a variety of techniques, complementary ground- and space-based observations, the Solar System studies including landers and sample return. A key topic for the future is the search for early life signature in exoplanet studies, the expansion of astrochemistry to this field and the development of astrobiology.

State-of-the art back-end instruments are essential to ensure the optimal science return of RIs. Instrument development can lead to technological advances shared with the private sector. The long time span of RIs requires instrument suites to be developed with complementarity and technological advances in mind. For instance, the lessons learnt from the on-going development of the first generation of the **ESFRI Landmark ELT** instruments will have to be taken into account for the next one. Several generations of cameras are also expected for the **ESFRI Landmark CTA**.

PARTICLE & NUCLEAR PHYSICS

Particle & Nuclear Physics (P&NP) deal with the smallest building blocks of Nature that constitute our present world and Universe and the interactions among them. The energies required to produce fundamental particles are so large that their study requires some of the largest accelerators and detectors ever built. Dedicated accelerator facilities are necessary to probe hadronic and nuclear structure. The research relies on intense international collaboration and pooling of resources on a regional or global scale to be able to build and operate the necessary Research Infrastructures.

The scientific landscape confronting Particle & Nuclear Physics at the turn of the 2020s is both exciting and challenging. It holds the perspective of revealing some of the deepest mysteries and secrets of Nature and transforming the understanding of the world.

In **Particle Physics**, the discovery of the Higgs Boson completed the Standard Model (SM). Yet, in spite of the astonishing success of the Standard Model, we also know that it cannot be the full story since it provides no explanation for Dark Matter and Dark Energy, which are now known to constitute about 95% of the energy content of the Universe. Measuring the coupling strengths of the Higgs boson to known particles with great precision, and to itself, could provide important clues to new physics beyond the SM and to cosmological riddles, such as the stability of the Universe. Searches for feebly interacting particles in accelerator experiments with high intensities and in underground experiments may provide clues to new physics. The study of the elusive neutrinos raises fundamental questions to which the SM cannot answer, namely the origin and the structure of the neutrino mass matrix. Resolving these issues may also help answering why the Universe is dominated by matter.

At the confluence of Particle & Nuclear Physics, the exploration of the Quark Gluon Plasma and of the phase diagram for strongly interacting matter gives access to study, under earthly conditions, the properties of the matter prevalent in the early Universe at times before the first millionth of a second after the Big Bang.

Nuclei are complex objects and a quantitative description of **Nuclear Physics** from first principles is still a challenge. A major direction involves the use of unstable particles ('rare isotope' beams) to study reaction mechanisms and nuclei far from stability. This is of increasing relevance for understanding nucleosynthesis in stars, responsible for generation of elements. Super heavy elements discovered recently, including the heaviest one Oganesson (proton number 118), were produced in nuclear physics laboratories. Nuclear Physics contributes with precision measurements to the search for dark matter and for new physics beyond the standard model. Fundamental and applied research in nuclear physics are playing an important role in the development of carbon free sources of energy and advanced cancer diagnosis and treatment.

II CURRENT STATUS

The current status of the ESFRI Landmarks and Projects in the Particle & Nuclear Physics domain is summarized in **Table 5**.

In Particle Physics, Europe currently has the global lead at the *energy frontier* based on the exploitation of the Large Hadron Collider (LHC) at CERN that delivers beam energies an order of magnitude higher than anywhere else. The LHC is currently being prepared for a substantial upgrade to higher luminosities (HL-LHC) by 2027, delivering about an order of magnitude more collisions. Similarly, the large experiments (ALICE, ATLAS, CMS, LHCb) are undergoing significant upgrades to be able to handle the challenges following from the higher collision rate and increased data rates. The upgraded facility will be unique on the world scale for attacking the physics that lies beyond the Standard Model (BSM) and exploring new phases of matter. On the technological side the HL-LHC has led to the development of new high magnetic field superconducting magnets (11 Tesla), R&D that will be further strengthened in the coming years at CERN and in Europe.

CERN is contributing importantly to the study of accelerator-based neutrino physics via its 'neutrino platform' helping develop novel detectors for use mainly in the DUNE project in the US that will study neutrino oscillations at the so-called 'intensity frontier'. A similar experiment is HyperK in Japan. Neutrino properties are and will be studied also through a number of experi-

	ESFRI ENTRY	NAME	STATUS (AS OF DECEMBER 2020)
LANDMARK	2006	FAIR	Under construction in Darmstadt. Expected to be operational 2026
	2006	SPIRAL 2	Under commissioning at GANIL
	2016	HL-LHC	Under construction at CERN. Expected to be operational in 2027
PROJECT	2016	KM3NeT (ORCA)	Under construction
	2018	IFMIF-DONES	Under development
	2021	EuPRAXIA	Two potential sites to host the facility. Initial steps of the project underway.

TABLE 5.
Current status of the ESFRI Projects and Landmarks for Particle & Nuclear Physics

ments, exploiting neutrinos produced in the upper atmosphere or coming from space, in large stopping volumes of either ice (IceCube in Antarctica) or water (the **ESFRI Project KM3NeT 2.0** in the Mediterranean and Baikal-GVD in the Baikal lake). China is active in the study of neutrinos from the reactors now preparing for the JUNO experiment. A number of other experiments focus on determining neutrino masses directly (e.g. KATRIN) and on the nature of neutrinos (e.g. GERDA/LEGEND, CUORE/CUPID, SuperNEMO, etc.) through searches for neutrinoless double beta decay in low-background environment realised at deep underground facilities.

Candidates for new particles (Dark Matter, WIMPs, Axions etc.) are also sought in specialized experiments at the underground facilities utilizing detector media such as liquid xenon and argon (e.g. XENONnT, DarkSide) or in solid state (e.g. COSINUS, DAMA, EDELWEISS, Sabre) looking for scattering of (unseen) exotic particles on nuclei.

The study of strongly interacting matter (SIM) and its phases, using heavy ion collisions, is at the border of Particle & Nuclear Physics. The ALICE experiment at LHC, operating at the highest center-of-mass energies in the world, is under substantial upgrade and plans for further upgrades exist. At GSI-FAIR, the planned Compressed Baryonic Matter (CBM) experiment will search for the critical point in the phase diagram of SIM. At JINR the NICA facility is entering the commissioning phase with the Multi-Purpose Detector (MPD).

Likewise, the study of the nucleon properties and bound quark structure is in strong international focus. The DOE has approved the Electron-Ion-Collider (EIC) as the next large accelerator project in the US, focusing on understanding the partonic structure of nucleons at medium and high-x. Europe has proposals (e.g. LHeC) for much higher energy accelerator configurations and detectors that could probe (at smaller x) the gluon content of nucleons and study possible gluon saturation and condensation phenomena.

Rare isotope beams allow synthesizing nuclei far from the stable nuclei that exist. Such nuclei play important roles in reactions in stars and their properties must be determined in experiments on Earth in order to accurately simulate astrophysical processes. Several major new facilities are in the commissioning phase, the **ESFRI Landmark SPIRAL2**, or under construction, the **ESFRI Landmark FAIR**, and will become operational in the coming years. In the US, FRIB is under construction. CERN has been upgrading the ISOL (Isotope Separation On-Line) facility with a new superconducting post accelerator (HIE-ISOLDE), SPES@LNL and ISOL@Myrrha is under development in conjunction with the prototype accelerator driven fission reactor.

The extension of the periodic table of stable nuclei with new superheavy elements and the search for an island of stability will make further advances with the GSI-FAIR facilities, SPIRAL2 and the SHE-factory at JINR.

Nuclear structure experiments require high-resolution and high efficiency gamma-ray detectors, such as the pan-European AGATA multi detector. Such detectors also find applications outside basic science, for example in environmental and medical areas.

Non-ESFRI facilities and projects of relevance for the Particle & Nuclear Physics thematic area are reported in **Table 6**.

	NAME	STATUS (AS OF DECEMBER 2020)
OTHER MAJOR FACILITIES OF INTEREST (NON-ESFRI)	LNGS	Operational, Gran Sasso National Laboratory
	NICA	Under commissioning, JINR
	HIE-ISOLDE	Operational, CERN
	SHE-Factory	Operational, JINR
	Baikal-GVD	Operational, Russia
	IceCube	Operational, Antarctica
	IBR2	Operational, JINR
POTENTIAL FUTURE FACILITIES	ILC, CLIC, FCC	Proposed and under discussion
	EIC	Approved (US). Expected start-up 2035
	LHeC	Proposed, CERN

TABLE 6.
Other facilities and projects of relevance for Particle & Nuclear Physics landscape

GAPS, CHALLENGES AND FUTURE NEEDS

The search for physics beyond the Standard Model will remain the central quest for Particle Physics. The recent European Strategy for Particle Physics Update (ESPPU)[12], adopted by CERN's member states in 2020 identifies a Higgs factory as the next future accelerator goal for Europe in order to explore in detail the properties of the *Higgs particle*. Such a facility could either be based on a linear or a circular collider design. The Japanese high energy physics community has proposed to host the International Linear Collider (ILC). China has also expressed ambitions in this direction with a circular collider. CERN will study the feasibility of a new hadron collider at the energy frontier (100 TeV) based on extremely high magnetic fields (16-20 T) in a 100 km tunnel possibly starting with electron-positron collisions. Already, R&D efforts in magnet research, superconducting RF and High Temperature Superconductivity (HTS) are being boosted with a potential for dramatic technological spin offs that can benefit society in multiple ways.

Complementary to the energy frontier, new physics can be probed by experiments searching for extremely rare phenomena. There are several proposals (i.e. SHIP, LDMX, ALP, etc.) targeting feebly interacting particles in the low mass region that could reveal new particles with possible cosmic relevance. They require very intense particle beams or lasers. The direct dark matter searches in underground laboratories will require detectors with much larger target mass (e.g. DARWIN). In the longer-term, new detector technology capable of directionality have to be developed.

In accelerator technology, developing further new and compact acceleration schemes, such as laser and electron or proton induced wakefields in static plasmas are potential game changers. A broad European consortium to that end has been established, now evolved as the new **ESFRI Project EuPRAXIA**. The large field gradients (> 1 GV/m) that can be achieved could—if the technologies are developed and standardized—revolutionize the field from the research machines to the work-horse accelerators that are already so important for material and biosystems studies and medical therapy, making them more compact and cheaper. Likewise, the development of a muon collider demonstrator in Europe would be a major new element in accelerator technology opening new scientific doorways.

Advanced and reliable innovative detectors are a cornerstone of research in Nuclear Physics and Particle Physics and propagate over time to detection and imaging systems for use in many other areas of science and society. New Quantum sensing devices are under development that will increase precision of measurements considerably. Overall detector technology has a very high societal spin-off value and potential for technology transfer.

12. European Strategy for Particle Physics Update (2020)
https://home.cern/sites/home.web.cern.ch/files/2020-06/2020%20Update%20European%20Strategy.pdf

ANALYTICAL PHYSICS

Analytical Physics (AP) Infrastructures explore the frontiers of science ranging from fundamental physics to applied materials science using high-brilliance beams of electrons, neutrons, ions or photons, or high magnetic fields. They offer a variety of analytical techniques based on particle and field interactions with matter. They enable the manipulation and characterization of materials and processes at multiple length scales, from atoms to industrial-scale products and living beings, and in ultrafast timescales down to the attoseconds range. They serve academia, industry and society with strong links to other ESFRI facilities especially in the sectors of energy, environment, health and food. They find use in physics, chemistry, materials science and engineering, environmental research, life sciences, and in the field of cultural heritage.

The AP facilities offer solutions to analyse minute concentrations and chemical speciation of elements in soil, water, plant, animal, and human cells as well as in microbes, allowing the discovery of ways to fight pollution and increase food safety. Micro and nanoscale imaging with different modalities enable the study of cells, their organelles, and their interaction with pharmaceutical products with unprecedented resolution and accuracy. Resolving the structure of proteins and other macromolecules via crystallography has given us the key to understand the biological function of these complex systems. Protein folding dynamics can be revealed by ultrashort X-ray pulses from Free Electron Laser (FEL) sources. CryoEM has emerged as a powerful alternative to crystallography in this field.

The action to reduce greenhouse-gas emissions relies on new technologies and materials, for which the AP RIs offer characterisation in real time and *in operando* conditions. They work together in the fields of clean energy and climate action to lead the research on rechargeable batteries, fuel cells, hydrogen storage, photovoltaics, catalysis, the circular economy, and other means of cleaner energy production and green industrial processes. They also provide non-destructive analyses of samples for our material cultural heritage and to understand the evolution of life and species on Earth.

High-performances, innovative and state-of-the-art nanotechnologies are also essential to address several of the global challenges identified by Horizon Europe and by the European Green Deal. Nanotechnologies are indeed involved in Clean Energy, Climate Action, Eliminating Pollution but also Cybersecurity or Advanced Biomedical Technologies, Key Digital Technologies and Advanced Computing. Universities and research centers possess top-level skills, with extremely high capabilities in developing new nanotechnologies, facing basic and applied research challenges and serving large communities of users from several different scientific fields. However these skills are often distributed among several tens of centers and their overall performances and capabilities are strongly limited by the lack of structured communication and organization.

The AP scientific case has strong links to other fields of PSE. For astronomy, samples returned from planetary exploration or comet missions are studied using AP facilities, giving crucial information on geology, atmosphere and climate within the planets in our Solar System and beyond, even helping to understand the origin of life. Extreme conditions created by the brightest particle beams ever created by humankind reveal processes and the structure of matter in the interior of giant planets. The AP RIs work strongly together with Particle & Nuclear Physics in research and development of accelerator, beam, laser and detector technologies. The co-operation in technology development, especially in Big Data science, across all fields in PSE, is an increasingly important key to success of the AP RIs.

II CURRENT STATUS

The current status of the ESFRI RIs in the field is given in **Table 7.**

Major modifications have occurred in the landscape of neutron sources recently. Within Europe, there are now ten such facilities in operation. Two have recently been closed, i.e., the Berlin-based BER-II and the Saclay-based ORPHEE reactors. The start of the **ESFRI Landmark European Spallation Source ERIC** in Lund (Sweden) is currently foreseen for 2023. ESS will be a gamechanger, far beyond an incremental improvement of the existing sources. It offers up to 100 times the brilliance of current spallation sources, making it the world's most powerful neutron source. The League of Advanced European Neutron Sources (LENS) brings the European neutron infrastructures together and provides transnational user programs.

	ESFRI ENTRY	NAME	STATUS (AS OF DECEMBER 2020)
LANDMARK	2006	ELI	In the transition from construction to operational phase, the two ELI pillars Beamlines and ALPS transformed their governance from an AISBL (ELI-DC) to an ERIC
	2006	European Spallation Source ERIC	Under construction
	2006	European XFEL	In operation with three undulator beamlines
	2006	ILL	In routine operation
	2008	EMFL	In routine operation
	2016	ESRF EBS	New storage ring started operation in 2020 and four new beamlines are being constructed during 2020-2022

TABLE 7.
Current status of the ESFRI Projects and Landmarks for Analytical Physics

Synchrotron light sources and **free-electron lasers** (FELs) are brought together within the League of European Accelerator-based Photon Sources (LEAPS), a strategic consortium that ensures and promotes the quality and impact of the fundamental, applied and industrial research carried out at these facilities.

There are nearly 15 operating synchrotron light sources in Europe. The advent of Multibend Achromat (MBA) technology has allowed synchrotron storage rings to decrease the horizontal emittance down to the diffraction limit and thus created the 4th generation of synchrotron light sources. The development started from the MAX-IV Laboratory and was followed by the **ESFRI Landmark ESRF EBS** (Extremely Brilliant Source). There are several plans to upgrade national synchrotrons, e.g. the Diamond Light Source, Petra-III, SOLEIL, and the Swiss Light Source, using different implementations of the MBA technology. This allows the synchrotrons to perform even better for nanoscale materials analysis, operando studies of processes, and enable new uses of coherence properties of the light.

FELs provide ultrashort pulses of very intense highly coherent radiation from a laser-like radiation process with a peak brilliance typically 5-6 orders of magnitude higher than that of a synchrotron light source. These properties make them excellent facilities for studying structural and electron dynamics at the atomic and molecular scale covering the fs-ps time domains. These techniques are often combined with lasers operating at other wavelengths in order to study pump-probe dynamics. There are 9 FEL's in Europe providing light from the infrared to the hard x-ray range.

Laser RIs and research centres in Europe are coordinated through Laserlab-Europe AISBL. The evolution from a long-standing EU funded network, Laserlab-Europe, to a legal organization maintains a stable and sustainable network of national facilities. This transition strengthens the leading role of Europe in laser research through joint research activities and offers a sustainable centralized access to state-of-the-art laser systems and is open to worldwide collaborations.

The **ESFRI Landmark ELI** is currently moving from construction to operation of three sites with complementary capabilities: i) ELI-Beamlines, for novel laser-plasma-accelerators delivering particles and photon sources with extremely high energies; ii) ELI-ALPS, for generation of ultrashort light pulses down to attosecond time domain with applications in atomic and molecular physics; iii) ELI-NP, for nuclear photonics applications with petawatt-class laser systems and a high-energy narrow-bandwidth gamma source. ELI will be the gateway to new regimes in fundamental physics and will promote the advent of new laser technologies.

There are over 100 high-end **Electron Microscopy** (EM) instruments in Europe with 15 leading laboratories and some SMEs forming a networked infrastructure ESTEEM3[13]. It is the primary European portal for EM and provides access to state-of-the-art TEM instrumentation and methodologies for industry and academy. It provides expertise and infrastructure for solving complex problems in physics, materials technology, engineering, and chemistry.

13. ESTEEM3 https://www.esteem3.eu/

Within the ARIE network, the eDREAM consortium of partners from ESTEEM3 has formed. Both consortia explore possibilities for creating a complementary pan-European Research Infrastructure for advanced EM providing sub-10 meV energy resolution and 50 pm spatial resolution. The recent development of direct electron detectors enabled faster frame rates and higher resolution for physical sciences applications and facilitated the exponential growth of use of cryo-EM for structural biology.

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. A sensitivity enhanced by several orders of magnitude is provided by implantation of radioactive ion beams (e.g., at ISOLDE-CERN) into a sample followed by the detection of the emitted radioactive decay products, providing unique information about the structural and functional properties of the host lattice.

The **high magnetic field** activities in Europe are organised under the **ESFRI Landmark EMFL**, with a common user access program, outreach, training, and technical developments. Maximum field strengths are increasing, with two hybrid magnets designed to exceed 43 Tesla (T), and bringing fully superconducting magnets into user operation, non-destructive pulsed magnets up to the vicinity of 100 T at Toulouse and Dresden, while in Toulouse, a semi-destructive pulsed field installation now offers fields of 100-200 T. All EMFL facilities have recently been fully renewed or upgraded, are internationally competitive and have complementary specificities. Two of them (Nijmegen and Dresden) are directly coupled to a THz FEL, allowing unique joint operation.

GAPS, CHALLENGES AND FUTURE NEEDS

The Analytical Physics RIs aim to use the most advanced methods of physics to meet the goals of the five Horizon Europe missions. All AP facilities boost their technologies to increase the beam brilliance or field density to improve the characterisation sensitivity as well as the resolution in time and space.

Short-pulse, high-power lasers and their secondary sources of particles and radiation aim at highly efficient and high repetition rate laser systems to drive laser-plasma based particle accelerators and x-ray sources. Addressing these new needs in laser technology is becoming a challenging task in order to further enlarge the user community in areas with high industrial and societal impact. The laser RIs interact strongly and have a strong impact on Particle & Nuclear Physics through common development of accelerator technologies.

Radically novel electron microscopes aim at three-dimensional imaging of materials' functional properties. Developments are also needed in sample preparation, *in situ* microscopy and sub-1-Kelvin microscopies, as well as in low dose imaging of biological and other beam-sensitive materials. Next generation CryoEM, enabled by improved technologies for electron beams and detectors, will operate at much lower voltages, making them much more widely available and less damaging to biological samples.

The future unavailability of neutron sources poses a major threat as older sources are closing down while existing sources are unable to cope with the demand and the ESS is still under construction. Therefore, there will be a strong need to continue to support the existing national sources. Several centres are working on the development of accelerator-based compact neutron sources that can play a strong role in particular applications. Furthermore, the future policies strongly endorse initiatives to seek an optimal way to harmonize neutron and X-ray studies, for example, in the framework of LENS and LEAPS.

In ion beam facilities, there is a growing interest in the use of radioisotopes in materials research, and institutes like ISOLDE-CERN and GSI are making efforts to accommodate this. Large-scale ion beam infrastructures are complemented by stand-alone ion-beam based techniques like atom probe tomography and helium microscopy and this synergy will be further pursued.

For high magnetic field facilities coordinated development across RIs (CERN, NS, etc.) is needed to develop even higher static and pulsed magnetic fields and to improve the required materials (superconducting, copper alloys, reinforcement) and enabling a wider portfolio of measurements in the short time scales of pulsed fields.

To fully exploit the potential of nanotechnologies, Europe needs to capitalize on the top-class competences available and investments already made, by streamlining the landscape of upstream research that is currently very fragmented, through a stronger organization. This would enable Europe to build a world-class nanofabrication ecosystem for fundamental research with exceptional performance, able to face the upcoming global challenges.

In conclusion, significant scientific and technological breakthroughs are expected from the Analytical Physics infrastructures by exploiting new ways of open cooperation with other fields of PSE and users from different fields of science, new thematic user access modes, as well as the close involvement of industrial research and development.

CONTENTS

107 EMERGING DRIVERS
107 SUPPORTING COMPARATIVE RESEARCH AND OPEN SCIENCE
107 BIG DATA
108 NEW FORMS OF INTERDISCIPLINARITY
109 CURRENT STATUS
111 GAPS, CHALLENGES AND FUTURE NEEDS
111 RIs FOR HUMANITIES
112 RIs FOR SOCIAL SCIENCES
112 BIG DATA
113 INCREASING THE GLOBAL REACH
113 SUSTAINABILITY AND GEOGRAPHICAL COVERAGE

PART2

LANDSCAPE ANALYSIS - SECTION1

SOCIAL & CULTURAL INNOVATION

SOCIAL & CULTURAL INNOVATION

Research Infrastructures that support research across and within the Social & Cultural Innovation domain are among the first known infrastructures: libraries, museums and archives are the most obvious examples of this legacy. In today's digital age, Research Infrastructures in the Social Sciences and Humanities (SSH) aim to enhance research into the historical, social, economic, political and cultural contexts of the European Union, providing primarily data, tools and knowledge to support strategies at the European as well as at the national level.

The data collected and provided by SCI RIs contribute as tools and basis to research that offers new insights into Europe's cultural heritage, its creative industries, education, health and well-being of its citizens, as well as the workings of democracies, social and economic policies and societal trends in and across Europe. These insights are fundamental to understanding European society and to answer to emerging challenges moving forward.

Many SSH Research Infrastructures bring together information and data from different countries over a long period of time and as such contribute to a better understanding of cultural and societal challenges in Europe or to address the UN Sustainable Development Goals. Enhancing democratic governance and citizens' participation, safeguarding and promoting cultural heritage, and responding to multifaceted economic, technological and cultural transformations are objectives of the Horizon Europe Pillar II Cluster 2[1]. And the UN has set ambitious goals[2] to erase poverty and hunger, bring quality education to all children, advance gender equality and reduce inequalities, and to foster peace, justice and strong democratic institutions. Evidence based and impact oriented SSH research lays the foundation to work towards these objectives and Research Infrastructures are essential especially in areas where information from different sources, countries and over time needs to be collected and made available to the research communities.

The value of SSH research, however, is not limited to such direct societal and cultural challenges. Climate actions, affordable and clean energy, responsible consumption and production, sustainable cities and communities or good health and well-being depend inherently on transforming human behaviour. The ability to reach the climate objectives, to take the example of the biggest current challenge in the world, is not a simple technological challenge. The ability of governments to act depends very much on political support for measures to reduce carbon emissions and to change our personal lives. In order to address these challenges, requires therefore a sound understanding of historic, social and political processes. Similarly, to fight a global pandemic does not only require developing vaccines, it requires an understanding of everyday social interactions or how to create acceptance for new vaccines or, how much balance is needed between reaching health related objectives to reduce infections but at the same time avoid several long-term negative economic and social consequences.

The SSH community reflects the importance and need of understanding society and cultural identity, and the community is also substantial in size: according to available data, SSH area accounts for over 40% of the students in Europe. Eurostat[3] reports that 34% of the students are in Social Sciences – including journalism, business and law – and 10% in Arts and Humanities.

Data from Social Sciences and Infrastructures that create, collect, assemble and curate relevant information are fundamental to the further development of the social science research community of Europe. The data literacy and research potential of the next generation of Social Sciences is nurtured using the resources of networked social science data archives and cross-national surveys. Public statistics and official administrative data, major scientific surveys, and increasingly data collected through digital processes represent essential sources of knowledge for the Social Sciences. The research outputs of Europe's social scientists have an impact on Europe's politics and map the social and economic conditions of the continent. Developing better measures of well-being and progress is supported, at the international level, by the Organisation for Economic Cooperation and Development (OECD), its Global Science Forum (GSF)[4] and the European Commission (EC)[5], with important contributions arising from the Social Sciences.

Research in the Humanities provides a better understanding of our society, both diachronically through historical and archaeological research to answer questions of how we became what we are, how we developed our cultural identities, by which mechanisms this was driven, and how we can elaborate this knowledge for shaping the future development of our society; and synchronically, for example, by monitoring the media to detect what is currently happening in our society, how we react to the

1. Horizon Europe https://ec.europa.eu/info/horizon-europe_en

2. UN Sustainable Development Goals https://www.undp.org/content/undp/en/home/sustainable-development-goals/

3. Eurostat – Tertiary education statistics https://ec.europa.eu/eurostat/statistics-explained/index.php/Tertiary_education_statistics#Fields_of_study

4. OECD Global Science Forum https://www.oecd.org/sti/inno/global-science-forum.htm

5. What is the 'Beyond GDP' initiative, European Commission https://ec.europa.eu/environment/beyond_gdp/index_en.html

major challenges, and how societal challenges in our neighbourhood can be addressed. Furthermore, Humanities make essential contributions to understand the intellectual and cultural foundation of humanity in general and the European societies in particular, by analysing its literature and the philosophical bases of economic, political and religious thinking and beliefs, as well as by anthropological research. As diversity increases in the European population, Humanities will have a major role to play in proposing methods to manage diversity and resolve conflict, both within and between societies. Humanities RIs also serve society by providing resources for the research into education, language learning, sign language, communication and gestures, etc.

There is economic impact from this knowledge, as well as a solid base for developing politics and society at large. The increased availability of digital resources in the Humanities and Social Sciences, and the development of advanced digital methods for research, have prompted remarkable changes in the scale and scope of research in these disciplines. In the area of the Humanities, collaboration between the RIs and the GLAM sector – galleries, libraries, archives and museums – will lead to an enhanced impact on culture and society as advanced tools are now being developed. In the Social Sciences, the turn towards doing research with existing data, instead of data designed and collected specifically for research, requires new infrastructures to use and access data, and in collaboration with other disciplines also to analyse such data.

Further drivers of SSH research and SSH Research Infrastructure needs are impact assessments and the push towards Open Science. In addition to scientific impact, which is at the core of Research Infrastructures, SSH research creates impact by enhancing evidence-based public policy, through a deeper engagement of citizens in the understanding of culture and cultural heritage in increasingly diverse societies, through contributions to resources and tools for handling citizens' needs, and through creating collaboration among multiple stakeholders. SSH Research Infrastructures strengthen this process through new tools, technologies and services[6]. The strong push towards more Open Science by policy-makers and funding agencies in many disciplines has also important consequences for the Research Infrastructure landscape. There is a common understanding that a lot of research data and information is a public good, but this requires institutions to allow storing and finding this information or accessing it in terms of data or also accessing publications in open publications formats.

6. See for example the Social Impact Open Repository that allows researchers to upload qualitative and quantitative testimonies of the social impact of their research, making use of specific indicators
http://sior.ub.edu

EMERGING DRIVERS

SUPPORTING COMPARATIVE RESEARCH AND OPEN SCIENCE

Some information and data for SSH research in Europe is still collected in a rather punctual and isolated way. While this leads to interesting and valuable scientific outputs, the ability to do high value SSH research increases exponentially if such information and data is more easily available from a single point or at least a smaller number of points even if they arise from different sources, different countries and different points in time. This allows to understand cultural and societal processes in comparison and to detect broader trends.

Not accidentally, many SSH Research Infrastructures therefore aim at collecting data or making data available that allows *comparisons* over different instances and events, countries or over time. Current SSH infrastructures do this in different ways. The **ESFRI Landmark ESS ERIC** collects high quality data from many countries and on many aspects of human life and behaviour through opinion surveys, the **ESFRI Landmark SHARE ERIC** gathers information on health, ageing and transition between work life and retirement of older European citizens, the **ESFRI Landmark CLARIN ERIC** gives access to more than 700,000 resources from many countries expressed in many different languages and relevant tools to treat them. As an example, CLARIN provides access to parliamentary debates so that parliament discussions may be compared across countries and across time. The **ESFRI Project EHRI** connects information from many different resources to perform Holocaust research, and the **ESFRI Landmarks DARIAH ERIC** and **CESSDA ERIC** aim at making information from different sources easily available. Such Infrastructures make an important contribution to sharing existing information and knowledge and through that contribute substantially towards reaching more Open Science.

As regards in particular the cultural part of Humanities, the data collected and provided by the existing RIs or other repositories and libraries, function as the basis for initiating the actual research. Therefore, they are primary material for the actual research that leads to the knowledge, understanding and interpretation of the past as well as of the cultures, their diversity and common traits. History, archaeology, literature, film, music and art history are some representative examples in Humanities that may benefit from the collected data, without, however, being totally dependent on them. Collaboration and interdisciplinarity play a crucial role to their future as well to as to the future of cultural heritage.

BIG DATA

Big data is seen as an important driver in the fields of Social Sciences and Humanities. The speed and versatility of electronic communication and the growth of digital media and tools, as well as their accessibility and linkage, is underlying the success of the five ESFRI Landmarks in the SCI domain. From large-scale databases to virtual museums, the tools that these developments have fostered are changing the way in which research is carried out. From the old model of *theorise/hypothesise/collect data/test/refine/conclude*, scientific enquiry has now become much more data-driven and, at the same time, more theory- and method-dependent. The ability to rapidly access large bodies of texts in different languages, to examine music archives, to compare three-dimensional images, to analyse census and survey data from around the world provides research possibilities that were inconceivable 20 years ago and redefine parts of Social Sciences and Humanities research.

The term *Big Data* started to be used to describe assemblages of data – data files, datasets, databases or data streams – that, in terms of their volume, their variety, and the velocity of creation, pose severe challenges for many conventional analytical and computational methods in SSH. The amount of digital content is estimated to over 33 Zettabytes (ZB, 10^{21} bytes, 10^{12} GB) in 2018 and it is growing fast every year, expected to be at 175 ZB in 2025[7]. *Big Data* technologies, tools, and services that turn this information overload into information gains are the next opportunity for competitive advantage. Language Technology (LT) is an example of such a core *Big Data* technology and the translation technology segment will continue to dominate the European LT market. RIs in LT are indispensable in breaking new ground. It must be noted that even though the amount of SSH data may be relatively less big than in other domains, for example astronomy, they are far more complex.

A common characteristic of *Big Data* in SSH is that they have significant research value in terms of the information contained either in its own right or when linked to other sources. They can, for example, be used to extract information about preferences (opinion mining and sentiment analysis), or undiscovered relations between people, and therefore provide important snapshots of human activities and orientations. When data are collected over time, such collections will also contain information about how culture and society develop. Data generated by social media interactions can be used to gauge the mood of users, their political affiliations, or to document popular interpretations of significant events – e.g. migration, riots, and virus outbreaks. Biosocial data, such as a genome-wide scan linked to longitudinal life course survey data, represent a special form of *Big Data*, with the potential to demonstrate the links between our health, well-being and lifestyles. These data are evidence bases as well as indicators of the effects of public policies. The treatment of

7. The Forum for Europe's Language Technology Industry
https://www.lt-innovate.org/sites/default/files/LTIpresentation_European_Data_Forum100413_0.pdf

Big Data is obviously also taken up by other, more technical, scientific domains, but it is important for society that the domain of SCI continues to play an important role in this, so that future solutions will take the human aspect into account.

Very closely linked to *Big Data* is their use in *Artificial Intelligence*. Currently, we are witnessing the development of technologies that will transform our world. Therefore, even if a major part of the development is seen as belonging to the technical domain, the development of algorithms is a very important field for SSH right now and in the future. The contribution from Research Infrastructures will be from Social Sciences as well as from Humanities (tools for analysis etc.), and will enable researchers to investigate the questions arising from the changes where humans and computers become more integrated. Therefore, the European Commission has also taken this up as a central activity, witnessed in a long range of documents and communications, such as the White Paper[8].

8. Artificial Intelligence - A European approach to excellence and trust – European Commission White Paper (2020) *https://ec.europa.eu/info/sites/default/files/commission-white-paper-artificial-intelligence-feb2020_en.pdf*

NEW FORMS OF INTERDISCIPLINARITY

Recently there has been an increase in the value and practice of interdisciplinary SSH research.

INTERNAL INTERDISCIPLINARITY

The traditional fragmentation of the area is being overcome: Social Sciences and Humanities make way for promising interactions. Disciplinary boundaries seem to be gradually fading to make room for integrative and transversal research methods concerning the entire field of Social Sciences and Humanities. On the one hand, a large body of digitised texts allows Humanities to use quantitative methods that were previously confined to the Social Sciences and Information Technology. On the other hand, a linguistic turn within the Social Sciences, makes room for new types of discourse and conversation analysis. Media Studies, which connect the Social Sciences and Humanities, are an articulate example of that evolution. There is a need for the extension of Media Studies even further to the scientific study of the production and dissemination of phenomena such as fake news, and its interaction with other social problems and challenges that were highlighted even further during the COVID-19 crisis with its geopolitical ramifications. In particular, the scientific study of the web, which has become an integrated part of society, culture, business, and politics, is a burgeoning field of research activity, with enormous potential for contributing to societal challenges related to the evolution of communication, solidarity or security issues. This internal interdisciplinary collaboration between Social Sciences and Humanities Research Infrastructures is also supported by the SSHOC cluster project funded by the European Commission under the Horizon 2020 programme.

EXTERNAL INTERDISCIPLINARITY

The increase of the interaction between SSH and other sciences is one of the most salient features of the recent period. There is now a more acute perception that many causal chains that are the object of natural sciences have their determinants in human action and behaviour. Nevertheless, interdisciplinary research that allows gaining insights into the interaction of behavioural, socioeconomic and political developments on the one hand and technical, environmental or biological changes on the other hand is still rare. Such research, however, would be essential to address some of the sustainable development goals such as clean energy, clean water and sanitation, sustainable cities, responsible consumption and production chains (including food, nutrition and health areas that are particularly important for major SDG goals) climate action or the protection of our ecosystems. Also, the combination of social indicators and bio-medical or genomic information would allow to better understand how bio-medical and social factors interact. The evolution of collective behaviour, especially in many Western societies, towards the use of public transport, car sharing or less polluting individual vehicles over the last 30 years is a major move away from the trend of extreme individualism and the association of the idea of freedom with possessing an automobile. This development has been accentuated by recent developments in the way of managing research. Horizon 2020 and Horizon Europe, which are not structured by disciplinary fields, but by societal challenges – e.g. health and well-being, climate changes – are the paradigmatic examples of this transformation of the research system in Europe.

Substantial European financing has been allotted to these areas during the 2018-2020 period of H2020. The research encouraged during the COVID-19 crisis was also an excellent example of 'external interdisciplinarity' between natural and Social Sciences, because social and economic choices, behaviour and mobility across the world shaped the response to the COVID-19 crisis, from the political, medical and sanitary point of view. In the post-pandemic period, SCI RIs will have specific opportunities to cooperate with the H&F and other fields.

Another example of interdisciplinarity is seen with hybrid Research Infrastructures, aggregating data arising from different domains or, alternatively, new forms of collaboration and interchange between existing infrastructures. A good example of this hybridization is provided by the **ESFRI Project E-RIHS** which combines material science methods with interpretative schemes of history of art to rejuvenate the field of heritage studies.

II CURRENT STATUS

The digital aspect of the currently most prominent SCI ESFRI Landmarks and ESFRI Projects is outlined below to testify the progress in the use of digital techniques throughout SSH research methodologies.

Scientific databases are a crucial part of the pan-European Infrastructures and more generally in the global science system. Effective access to research data, in a responsible and efficient manner, is required to take full advantage of the data and the possibilities offered by the rapidly evolving digital technology. Accessibility to research data is an important condition for maximising the research potential of new digital technologies and networks. An open and democratic access policy not only provides scientific advantages to the whole academic community, it also provides greater returns from public investments in research activities.

An Infrastructure provides a technology platform, creating a whole range of tools and services that make and represent new knowledge, new resources, for a range of stakeholders generating opportunities for growth, challenge and engagement, for sustainability and for the innovative catalysis of ideas. Creating meaning and knowledge work are central to these mechanisms for sharing, with a foundational interoperability as standard. Research Infrastructures widen participation and strengthen the European Research Area.

The **ESFRI Landmark CESSDA ERIC** is a distributed Research Infrastructure that brings together social science data archives across Europe, with the aim of promoting the results of social science research and supporting national and international research and cooperation. CESSDA brings important added value to national data archives through providing a central data catalogue, a platform to jointly develop new user friendly tools and services, training especially in research data management, building trust in data through ensuring data quality and standards on how to archive and re-use data. CESSDA also plays an important role to integrate social science data archives into the European Open Science Cloud (EOSC) in the coming years.

The **ESFRI Landmark ESS ERIC** is an academically driven long-term cross-national survey that has been conducted across Europe since its establishment in 2001. Every two years, face-to-face interviews are conducted with newly selected, cross-sectional samples to chart and explain the interaction between Europe's changing institutions and the attitudes, beliefs and behaviour patterns of its diverse populations. Based on open calls and a scientific evaluation procedure, the core module is complemented with changing rotating modules to allow new topics to be included into the study. In total 10 rounds of data have been collected with up to 30 European countries participating in each round, round 11 is in the fieldwork phase in 2021. ESS had more than 170,000 registered users and ESS data has been downloaded 130,000 times by 2021 and therefore ESS is one of the most widely used Social Science projects worldwide.

The **ESFRI Landmark SHARE ERIC** is a Research Infrastructure for studying the effects of health, social, economic and environmental policies 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). Starting in 2004, 480,000 face-to-face interviews with 140,000 individuals have been collected in 29 countries over 8 waves by now. SHARE has more than 12,000 users from many different disciplines by 2021.

The **ESFRI Landmark CLARIN ERIC** via CLARIN's Virtual Language Observatory (VLO) provides easy and sustainable access to digital language data – in written, spoken, video or multimodal form – and advanced tools to discover, explore, exploit, annotate, analyse or combine them, wherever they are located. CLARIN makes these data, tools and services available to scholars, researchers, students and citizen-scientists from all disciplines, especially in the Humanities and Social Sciences, through single sign-on access. CLARIN offers long-term solutions and technology services for deploying, connecting, analysing and sustaining digital language data and tools. CLARIN supports scholars who want to engage in cutting edge data-driven research, contributing to a truly multilingual European Research Area.

The **ESFRI Landmark DARIAH ERIC** aims to enhance and support digitally-enabled research and teaching across the Arts and Humanities. DARIAH is a network of people, expertise, information, knowledge, content, methods, tools and technologies from its member countries. It develops, maintains and operates an infrastructure in support of ICT-based research practices and sustains researchers in using them to build, analyse and interpret digital resources. By working with communities of practice, DARIAH brings together individual state-of-the-art digital Arts and Humanities activities and scales their results to a European level. It preserves, provides access to and disseminates research that stems from these collaborations and ensures that best practices, methodological and technical standards are followed.

The ESFRI Landmarks CLARIN ERIC and DARIAH ERIC have collaborated on the relaunch of the Digital Humanities Course Registry.

The **ESFRI Project E-RIHS** supports research on heritage interpretation, preservation, documentation and management. It connects researchers in the humanities and natural sciences and facilitates a trans-disciplinary culture of exchange and cooperation. E-RIHS will enable the provision of state-of-the-art tools and services to cross-disciplinary users and communities. It aims at the advancement of knowledge about heritage and the division of innovative strategies for its preservation. E-RIHS joined the ESFRI Roadmap in 2016, and is currently working towards reaching the Implementation Phase.

The **ESFRI Project EHRI** joined the ESFRI Roadmap in 2018 and is currently transforming itself from a project into a permanent organisation that will help secure the future of trans-national Holocaust research, commemoration and education. EHRI will undertake all the necessary legal, financial and strategic work to have this permanent organisation fully operational by January 2025, the 80th anniversary of the liberation of Auschwitz.

The **ESFRI Project GGP** 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. The GGP survey focuses on inter-generational and gender relations between people, expressed in care arrangements and the organization of paid and unpaid work. GGP is run by social scientists and National Statistical Offices.

The **ESFRI Project GUIDE** is a pan-European comparative birth cohort survey including a sample of new born infants as well as a sample of school age children. Both cohorts will be surveyed using a common questionnaire and data collection methodology at regular intervals until the age of 24 years. The Research Infrastructurewill be an important source of high quality longitudinal statistical evidence to support the development of social policies which will enhance the well-being of children, young people and their families across Europe.

The **ESFRI Project OPERAS** is a distributed Research Infrastrusture enabling Open Science and upgrading scholarly communication practices in the Social Sciences and Humanities in line with the European Open Science Cloud. OPERAS' aim is to make Open Science a reality for research in the SSH and achieve a scholarly communication system where knowledge produced in the SSH benefits researchers, academics, students and more generally the whole society across Europe and worldwide, without barriers.

The **ESFRI Project RESILIENCE** is an interdisciplinary scientific Research Infrastusture for all 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 at the same time its impact extends significantly to the non-academic community: an innovative approach for building a European response to the challenges of diversity of religion.

An overall representation of the Landscape of the Social & Cultural Innovation domain in provided in **Figure 1**.

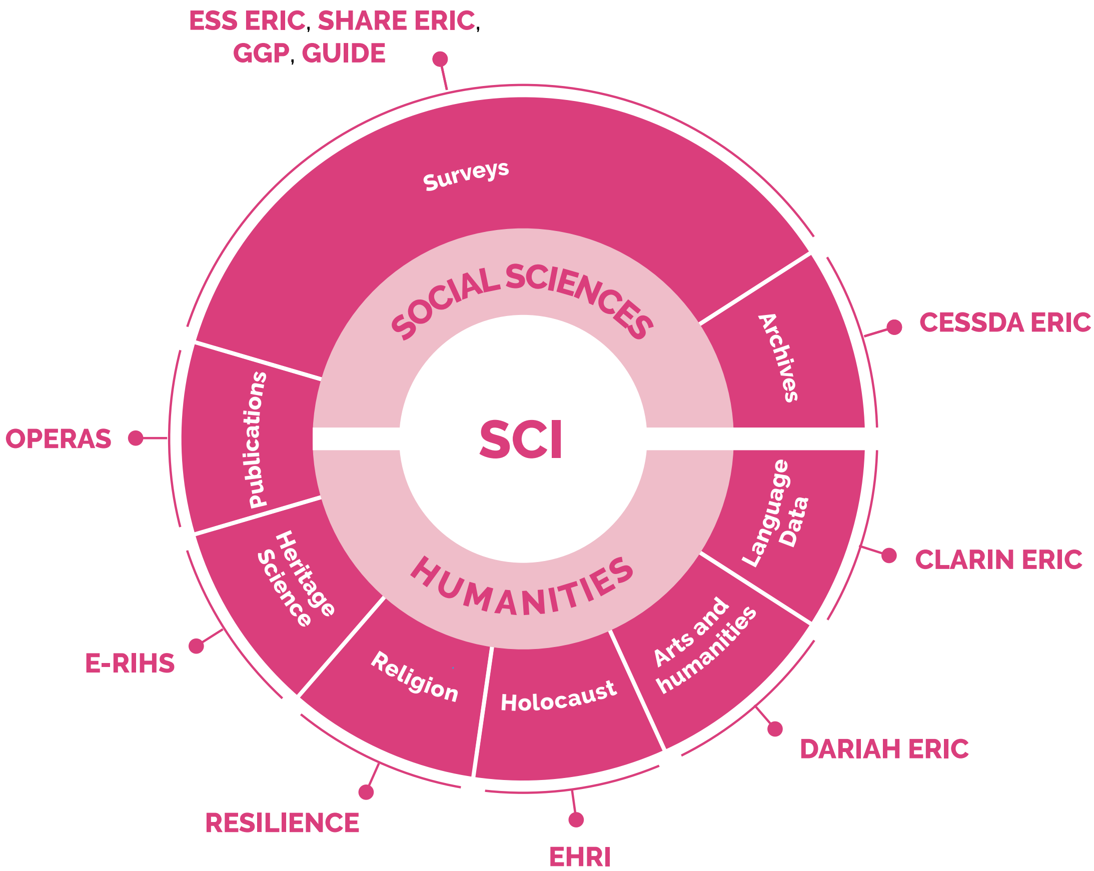


FIGURE 1.
The Landscape of the Social & Cultural Innovation domain

GAPS, CHALLENGES AND FUTURE NEEDS

Several strong SSH RIs already exist and they create a solid foundation to fill existing gaps in three main areas:

- The landscape is still very *fragmented*: for some scientific communities, strong RIs already exist that facilitate research in their domain. Other communities lack such infrastructures and hence have a much weaker information base to advance research in their field. Also the geographical coverage of RIs varies a lot, which creates inequalities in the availability of good foundations in doing research between European countries. Such gaps need to be filled either through expanding the scope of existing RIs or through allowing new RI to emerge and grow. For Social Sciences and Humanities it is especially important to allow also for medium-sized RIs to emerge and develop[9].

- The addition of *big and new forms of data* requires new environments to access, process and analyse such data also in the SSH domain to gain new knowledge on social and cultural processes. Such data from the administration, private companies or internet transactions are used increasingly in research in many SSH domains.

- *Connectivity* will be a main challenge of RIs infrastructures in the future. This needs to happen in different ways. While existing information sources are often FAIR in themselves nowadays, we are far away from having an entire information system that is FAIR in all aspects of FAIR. This is the case within the SSH domain but especially between different domains. Many existing resources are not easily findable if researchers don't know where to search. Many data sources, especially around big data are not easily accessible or not accessible at all. And using information available from different sources for research requires developing joint standards and procedures how to make data interoperable. To do so is not mainly a technical process, it requires bringing together entire communities to reflect and agree on such standards.

9. Four Golden Principles for Enhancing the Quality, Access and Impact of Research Infrastructures. LERU (2017 *https://www.leru.org/files/Four-Golden-Principles-Full-paper.pdf*

RIs FOR HUMANITIES

For the Humanities some strong digital RI initiatives have been initiated. However, clearly they are far from showing full coverage of all humanities disciplines. There is still an enormous amount of historical and contemporary cultural data that has not been digitized and not all available digitized data have been annotated and curated in such a way that they can be incorporated in the RIs. These can be historical manuscripts, papyri, books, movies, music, paintings, artefacts, monuments, landscapes etc., but also the knowledge about such cultural objects. There are also still vast amounts of contemporary items – political speeches, newspapers, literature, new art forms, audio-visual materials, collections of child language or language learners' language, social media data – that need to be incorporated. And new text, video, multimedia and social media data are being created constantly.

The study of contemporary materials is however often hampered by copyright and privacy restrictions. The Freedom of Information Act has made possible the access to public information like parliamentary records, but efforts need to be invested in lifting such restrictions for research when it comes to non-public data.

An additional challenge is that an enormous amount of diverse materials is widely distributed across Europe and beyond. Much effort will still be needed to include them. Some data are even difficult to access from outside local communities, and sometimes they are at risk of deterioration. An important challenge for RIs is to increase the awareness of their existence and services, and to provide users – researchers, teachers, museums and citizens – access to such data and heritage wherever possible in terms of rights. Moreover RIs should provide users access to the state-of-the-art analysis carried out by experts and researchers, also by exploiting digital media and archives.

Already existing technologies and expert knowledge from material science, physics and chemistry need to be used to better analyse, understand and preserve cultural heritage objects. New digital techniques also enable the creation of digital copies of historical objects and environments allowing new types of research without harming the original objects and historical environments can be digitally recreated and studied.

By combining new digital technologies, digitised Humanities resources and expertise from Humanities experts (including the citizens) to enrich, link and analyse the data new ways of doing humanities research and new research questions can be enabled. This new way Humanities scholarship involves collaborative, transdisciplinary, and computationally engaged research, teaching, and publishing.

Finally, new tools and services need to be developed in order to fully exploit the potential of the Humanities RIs for understanding society, culture, thinking etc. and for enabling new types of research and teaching, and supporting citizens with special needs, for evidence-based policy making and for contributing for some societal challenges like the energy transition and climate change but also for challenges like fighting fake news or explaining the value of COVID-19 vaccinations.

RIs FOR SOCIAL SCIENCES

The SSH infrastructure landscape is still fragmented. While some fields have comparative data and information already easily available to support research in their domain, similar data collections are missing in many other fields. To create a Research Infrastructure environment that allows a less fragmented understanding of how democracies and societies or economic and cultural processes function or can be transformed will be one main challenge for the SSH Research Infrastructure landscape. Collaborative projects therefore continue to emerge in the field of SSH to create a solid information base, either through collecting new information or through making existing information available - or both. Some more specific gaps can be identified in the Social Sciences.

Access to new forms of data for research. This includes administrative or private sector data or internet transactional data. There is an important trend in social science research to use data that has not been designed for research purposes. A lot of data already exists in the public and private sector because of digitalised administrative procedures or through the digitalization of everyday life that is highly valuable for social science research. A lot of this data is personal data that increases further in value if such information can be linked across data sources. However, using such data creates specific challenges beyond computing power, as such data is far from being FAIR. Often, findable metadata on such sources is non-existent and it will be essential in the coming years to create a comprehensive institutional and legal environment to use, link and re-use such data for research while respecting data protection and privacy rights. Only few countries have started to provide such an environment and existing data archives may have to expand their focus and develop new tools and processes around remote or secured access to support making such data available for research.

Understanding political and socio-economic dynamics. Existing comparative surveys allow well to study social conditions and to some extent developments. Other fields lack comparative or long term information to the same extent. For example how challenges to democracies and the process of political representation and political participation developed over time, or trends in socio-economic or gender inequalities or migration that can create political contestation and have an impact on well-being can still be studied only in a fragmented way. Research Infrastructures that collect, integrate and provide political, social and economic data and information within and across countries as well as over time in a comprehensive way are lacking. To have a profound understanding of these processes, however, would be essential to support achieving many of the UN Sustainable Development Goals such as peace, justice and strong institutions, no poverty and reduced inequalities, decent work and economic growth or gender equality and quality education.

Linking nutritional behaviour to environmental and agricultural sustainability. From a social science point of view this is an interesting question. It is based on three synergistic scientific challenges, which cannot be solved in isolation: the nutritional health challenge (as in overweight and obesity reduction), the environmental challenge (as in the protein transition) and the consumer well-being challenge (consumer engagement). Social inequality is an important determinant for unhealthy nutritional behaviour. The environmental challenge (taking into account the diversity of Europe) and consumer engagement require multiple stakeholder coordination and bargaining between agro-food businesses, citizen-consumers and governments and public agencies, which require political engagement and regulatory processes, and collaboration with SSH disciplines need to be developed.

BIG DATA

The development of high-speed data connection together with storage capacities and information processing software has provided access to substantial amounts of data for some fields, as well as new ways of analysing analogue resources of cultural heritage. The disciplines in Social Sciences and Humanities are thus confronted with a momentum that is transforming to a great extent the entire profession of the researcher. Research Infrastructures in this area must enable the creation and manipulation of large and very heterogeneous bodies of data, of a qualitative or quantitative nature, opening up new research possibilities and encouraging interdisciplinary work. RIs contribute to the valorisation of scientific and cultural heritage.

Accelerated data storage and processing capabilities delivered via the web have generated renewed opportunities in terms of appropriation and manipulation of research resources. Diverse spaces of resource production of digital technologies have led to the creation of many platforms dedicated to SSH. They constitute centres for bringing together interdisciplinary and technological competences, which offer many services to support, augment and sustain the work of researchers - people who use digital technology; for example the SSH domain delivers criticality, a human-centred approach to data with “human agency and oversight” (EU, AI HLEG)[10], foregrounding fundamental rights that are primary aspects of the EU’s requirements for ethical Artificial Intelligence.

Infrastructures are vital routes to help the EU address the waste due to the lack of FAIR research data. RIs encourage education and infrastructurally cohesive approaches to data stewardship and on making research accessible, particularly the fundamentals of the FAIR approach. Researcher education is critical across all domains, in particular promoting standards-led optimisation of research for open knowledge creation.

Data storage and digital interactivity have opened up new opportunities in terms of appropriation and handling of research resourc-

10. High-level expert group on artificial intelligence, European Commission *https://ec.europa.eu/digital-single-market/en/high-level-expert-group-artificial-intelligence*

es. Consequently, we have seen a diversification in the locations of digital resource production which have resulted in the creation of many tools and services accessible in dedicated platforms. They form clusters for bringing together disciplinary and technological skills that offer many services to support researchers in the Humanities who use ICT either directly because the research data is digital or as an environment allowing for access to new processing tools.

Exponential growth in the amount of data, their increasing use by SSH scholars, as well as the rapid evolution of technology, opens up new opportunities for SSH research. The use of *Big Data* and *Machine Learning* also bears new methodological challenges with implications for empirical research: the implementation of surveys on emerging social trends in longitudinal perspectives can lead to important advances in epistemological and methodological fields. In particular, Big Data raises some important issues for the SCI domain.

In light of the changes outlined in the preceding section, new forms of Research Infrastructures combining storage and state of-the-art information extraction methods and services are required if the research community is to utilise all potential research opportunities. This section identifies a number of areas in which the changing research landscape needs to foster new research opportunities in SSH and at the disciplinary boundaries with other scientific communities.

INCREASING THE GLOBAL REACH

Given that RIs in the Social Sciences and Humanities will be stably anchored in Europe in the future, further actions have to be undertaken to make them well-known, attractive and compatible on a global scale. This can progress in two steps. Even though cooperation on Research Infrastructures is increasing in the European Union and with Associated countries, this cooperation needs to be further deepened in terms of financial sustainability and the use of FAIR principles, in a context where government support will be constrained for financial and budgetary reasons in a post COVID-19 scenario, and there needs to be close cooperation to make the existing infrastructures sustainable. Secondly, Europe's expertise in all the areas discussed here is also a sphere of global scientific leadership for Europe, which can be strengthened through a cooperation strategy across countries. The current and further experience how to collaborate across countries in Social Sciences and Humanities through its distributed Research Infrastructures can serve as a model how to collaborate worldwide and would allow for European leadership in scaling-up European to worldwide infrastructure in many domains.

The accessibility of digital research data – e.g. survey data in the Social Sciences, digitized and annotated documents and cultural heritage in the Humanities – the development of standards and tools allowing for inter-operability is obviously the key driver for increasing global research not only in the Social Sciences and Humanities but in the whole scientific system. It can be stated that not only there is still a possible gap between different standards for certain kinds of data – depending on the source from which they were derived – between European Research Infrastructures and non-European Research Infrastructures, there are also rather difficult challenges to meet that are inherently connected to the content types of data and research traditions between different parts of the world. In particular, it needs to be mentioned that countries that have been ravaged by war and conflict in recent times need cooperation on appropriate Research Infrastructures to preserve their cultural heritage, and cooperation in areas such as trafficking of cultural heritage assets have made encouraging progress in enabling such cooperation during the H2020 programme which is being continued in the Horizon Europe programme.

Digital tools and functions may have to be updated when applied to sources in languages, scripts or symbols more recently encountered by the technology. The underlying understanding of text types, art classification systems and semantics would potentially have to be adjusted, complete methodologies would have to be (re-)negotiated. The same is true for political and sociological research terms and classification systems. In order to integrate and interconnect heritage and knowledge from and about societies and cultures from all over the world, their history and self-conception, a lot of work has to be done to enable global infrastructures to offer a certain degree of consistency between these data and concepts.

SUSTAINABILITY AND GEOGRAPHICAL COVERAGE

There is an increased sustainability of the research data due to the fact that all RIs provide archives for storing data and state-of-the-art methods to analyse and interpret them. This is an important difference with respect even the recent past where data could disappear when a researcher retired. Currently not only data are stored in sustainable, long-lasting and secure archives, but many of the current RIs – e.g. the **ESFRI Landmarks CLARIN ERIC** and **CESSDA ERIC** – also use methods such as Persistent Identifiers for resources and data collections, so that the same version can always be retrieved and so that research based on their data can be replicated or extended.

We also need to consider the sustainability of the RIs themselves. Research Infrastructures need to be sustainable: i) financially and organisationally; ii) technically; and iii) in terms of human resources. These three dimensions of sustainability are heavily interlinked and therefore require adequate financial resources. The organisational sustainability is supported through the use of the ERIC and other legal structures. The financial sustainability of the central and national operations may still be an issue worth considering. For all of the SSH Infrastructures, geographical coverage is crucial for the quality of the research they support and hence for their sustainability. Data from one country is not only of interest for the researchers of this country itself, but also for everyone else in Europe for comparison. To compare attitudes to different aspects of society, it is not enough to have information from one part of Europe if other parts are missing. For those Research Infrastructures where language plays an important role, it is obvious that a very good geographical coverage is needed, so that all types of languages, and preferably all languages, are described and will be the basis for the research developments. European data collecting Research Infrastructures have a higher European Added Value, if they are able to provide data from all over Europe. Technical sustainability has to do with upgrading to new versions, following and updating standards, including new tools and possibilities, following international developments. All current SSH Research Infrastructures are heavily involved in and committed to continuous technical development.

Sustainability in terms of human resources is at the heart of our Research Infrastructures. There are three classes of activities where human resources are crucial:

- building and operating the infrastructure and keeping it up-to-date in the light of technological and methodological developments and evolving user needs (this is treated above under technological sustainability);
- instrumentation and population of the infrastructure with community specific data and services;
- education, training and research support for existing and future users.

There are various instruments to make these things happen in a sustainable way, and they are all implemented to some extent by the current ESFRI SCI Landmarks. For example, building knowledge about the availability of RIs within standard university curricula is a good, sustainable long-term investment. In the shorter term the obligation for Research Infrastructures to build and maintain what could be called a Knowledge Infrastructure is important. Knowledge Infrastructure is a formalized way of recognizing and sharing knowledge among members. It is an acknowledgement that not all useful knowledge can be concentrated at the central level, and that the knowledge present at the national level is crucial for sustainability and has to be made visible and shared. This is particularly true for distributed Research Infrastructures like the SCI RIs.

PART2

LANDSCAPE ANALYSIS

SECTION2

INTERCONNECTIONS

The Section 2 of the Landscape Analysis is dedicated to represent how complexity and diversity of each research domain bring naturally the Research Infrastructures to adopt a transdisciplinary approach. The RIs, besides their research services, often drive large scientific developments, whose scientific results and innovation potential can be exploited by other RIs within their own and also other domains.

The interdisciplinary and complementary approach of RIs is fundamental to stimulate researchers and technology developers to drive their progresses and solve emerging and complex challenges by answering new scientific questions. Obviously, the cross-cutting character is valid for the domain of Data, Computing & Digital Research Infrastructures as data and computing aspects have permeated almost all fields of research. Equally, the importance and cross-cutting nature of collaboration with the Social & Cultural Innovation domain has been recognised for other ESFRI domains. In the following, we provide examples for each domain of collaboration among ESFRI and non-ESFRI RIs, often established through bilateral or institutional agreements. Ideas for future collaboration are also mentioned. A schematic overview of the analysis of interconnections among ESFRI RIs in Operation Phase or in advanced Preparation Phase and thematic areas is also provided.

The Landscape Analysis of Interconnections has been realized by the Strategy Working Groups in the respective domain

121 DATA, COMPUTING & DIGITAL RESEARCH INFRASTRUCTURES
122 ENERGY
124 ENVIRONMENT
129 HEALTH & FOOD
136 PHYSICAL SCIENCES & ENGINEERING
142 SOCIAL & CULTURAL INNOVATION

INTERCONNECTION ●
NO INTERCONNECTION ○

Domain	RI	DIGIT	ENE	ENV	H&F	PSE	SCI
DIGIT	PRACE	●	●	●	●	●	●
ENERGY	ECCSEL ERIC	○	●	●	●	○	●
ENERGY	EU-SOLARIS	○	●	●	●	●	●
ENERGY	IFMIF-DONES	○	●	○	○	●	●
ENERGY	JHR	○	●	○	●	●	●
ENVIRONMENT	ACTRIS	●	●	●	●	●	●
ENVIRONMENT	DANUBIUS-RI	●	○	●	●	○	●
ENVIRONMENT	DiSSCo	●	○	●	●	○	○
ENVIRONMENT	EISCAT_3D	●	○	●	○	●	○
ENVIRONMENT	eLTER RI	●	○	●	●	○	●
ENVIRONMENT	EMSO ERIC	●	○	●	●	●	●
ENVIRONMENT	EPOS ERIC	●	●	●	●	●	●
ENVIRONMENT	EURO-ARGO ERIC	●	○	●	●	●	●
ENVIRONMENT	IAGOS	●	●	●	●	●	●
ENVIRONMENT	ICOS ERIC	●	●	●	●	●	●
ENVIRONMENT	LifeWatch ERIC	●	○	●	●	●	●
HEALTH & FOOD	AnaEE	●	●	●	●	●	●
HEALTH & FOOD	BBMRI ERIC	●	○	○	●	●	●
HEALTH & FOOD	EATRIS ERIC	●	○	○	●	●	●
HEALTH & FOOD	ECRIN ERIC	●	○	○	●	●	●
HEALTH & FOOD	ELIXIR	●	○	●	●	○	●
HEALTH & FOOD	EMBRC ERIC	●	●	●	●	●	●
HEALTH & FOOD	EMPHASIS	○	●	●	●	●	●
HEALTH & FOOD	ERINHA	○	○	●	●	○	●
HEALTH & FOOD	EU-IBISBA	○	●	●	●	○	○
HEALTH & FOOD	EU-OPENSCREEN ERIC	●	○	●	●	●	○
HEALTH & FOOD	Euro-BioImaging ERIC	●	○	●	●	●	●
HEALTH & FOOD	INFRAFRONTIER	●	○	●	●	●	●
HEALTH & FOOD	INSTRUCT ERIC	●	○	●	●	●	○
HEALTH & FOOD	METROFOOD-RI	●	●	●	●	●	●
HEALTH & FOOD	MIRRI	●	●	●	●	○	●
PHYSICAL SCIENCES & ENGINEERING	CTA	●	○	●	○	●	●
PHYSICAL SCIENCES & ENGINEERING	ELI ERIC	●	●	●	●	●	●
PHYSICAL SCIENCES & ENGINEERING	ELT	●	○	○	●	●	●
PHYSICAL SCIENCES & ENGINEERING	EMFL	○	●	●	●	●	○
PHYSICAL SCIENCES & ENGINEERING	ESRF EBS	●	●	●	●	●	●
PHYSICAL SCIENCES & ENGINEERING	ESS ERIC	●	●	●	●	●	●
PHYSICAL SCIENCES & ENGINEERING	EST	●	●	●	○	●	○
PHYSICAL SCIENCES & ENGINEERING	European XFEL	●	●	●	●	●	○
PHYSICAL SCIENCES & ENGINEERING	FAIR	●	●	●	●	●	○
PHYSICAL SCIENCES & ENGINEERING	HL-LHC	●	●	○	●	●	●
PHYSICAL SCIENCES & ENGINEERING	ILL	●	●	●	●	●	●
PHYSICAL SCIENCES & ENGINEERING	KM3NeT 2.0	●	○	●	○	●	○
PHYSICAL SCIENCES & ENGINEERING	SKAO	●	○	●	●	●	●
PHYSICAL SCIENCES & ENGINEERING	SPIRAL2	●	●	○	●	●	○
SOCIAL & CULTURAL INNOVATION	CESSDA ERIC	●	●	●	○	○	●
SOCIAL & CULTURAL INNOVATION	CLARIN ERIC	●	●	○	●	○	●
SOCIAL & CULTURAL INNOVATION	DARIAH ERIC	●	●	●	●	○	●
SOCIAL & CULTURAL INNOVATION	E-RIHS	●	○	●	○	●	●
SOCIAL & CULTURAL INNOVATION	EHRI	●	○	○	●	○	●
SOCIAL & CULTURAL INNOVATION	ESS ERIC	●	●	●	●	○	●
SOCIAL & CULTURAL INNOVATION	SHARE ERIC	●	○	●	●	○	●

DATA, COMPUTING & DIGITAL RESEARCH INFRASTRUCTURES

The **DIGIT** domain includes Data, Computing, Cloud, Digital and Networking Infrastructures. Current Research Infrastructures in all domains depend on availability of information sources, data transfer, and computational resources. This dependence makes the interaction with all other domains inherent. The **DIGIT**-**ENE** interaction is strong in modeling of energy systems in real-time and with a high-resolution, modeling of energy materials and components, and modeling the interactions between domains, for instance between **ENE** and **ENV**. The **DIGIT**-**ENV** interaction results in applications of various High-Performance Computing (HPC) techniques for climate models, large volume and complex data analytics (Big Data analytics), in implementing e-tools to ensure data interoperability, data access, data-curation. The **PSE** domain continues to develop new methods of handling extreme amounts of data to be processed by **DIGIT** RIs thus influencing the **DIGIT**-**PSE** interaction. The last decade is marked by the process of unification of the existing databases on materials for **ENE**, **H&F** and **PSE** which is governed by the rapid development of the **DIGIT** domain. The **DIGIT**-**ENE**, **DIGIT**-**H&F**, **DIGIT**-**PSE** interaction boosted research, growth, and innovation within the physical and life sciences and engineering. The **DIGIT** RIs has also played an essential role in the digital turn that is transforming part of the Social Sciences and Humanities, with Big Data being the core of the **DIGIT**-**SCI** interaction. Most of the **SCI** RIs use data storage facilities provided by the **DIGIT** infrastructures and implement modern techniques like artificial intelligence (deep machine learning, deep neural networks) for their research, that rely on massive computing resources.

The contribution to the EOSC development – as a fundamental enabler of the digital transformation of science – is a general characteristic of the interactions between the **DIGIT** domain and all thematic RIs in the **ENE**, **ENV**, **H&F**, **PSE**, and **SCI** domains. The latter are data-generators, but also developers of tools, methods and standards. Progress in building the EOSC, most notably the legal status of the EOSC Association and the partnering agreements with Member States and national initiatives, has been a major step forward and this roadmap witnesses the fruitful interaction between RIs and EOSC, mediated and supported by Digital Infrastructures. EOSC will be supported by high-speed connectivity to transport data and powerful high-performance computers to process data. New data produced by laboratories, observatories, analytical, computational and scholarly work will become progressively FAIR (Findable, Accessible, Interoperable, Reusable) by design feeding the EOSC with quality-verified datasets ready for exploitation and reuse.

See the **DIGIT Table** for an extended overview of the interconnections across domains established by those **DIGIT RIs** in Operation Phase or in advanced Preparation Phase.

PRACE
Partnership for Advanced Computing in Europe

ENE
High Performance Computing for energy
Modelling of Energy Systems (high-resolution, real time).
Modelling of Energy Materials and Components.
Modelling of the interaction between Energy and Environment.

ENV
High performance computing for environmental sciences
Modelling of complex dynamical systems (oceans, atmosphere, climate, weather forecast).
Modelling of earth and ocean dynamics.

H&F
High performance computing for health and food
Modelling and simulation of biological processes.

PSE
High performance computing for physical sciences and engineering
Modelling and simulation of condensed matter behaviour.
Modelling and simulation of out of equilibrium phenomena.
Computing theoretical models in HEP, hydrodynamics, etc.

SCI
Social and cultural aspects of advanced computing
High-impact scientific discovery and engineering research and development across all disciplines to enhance European competitiveness for the benefit of society.

ENERGY

From the primary energy harvest to its transformation into secondary energy, its use and the disposal of waste, the energy cycle is a complex one, which involves all domains represented in the ESFRI Roadmap. The energy harvest, transformation and disposal of its waste is intimately linked with the **ENV** domain. In some cases, RIs themselves produce components that are of direct impact for the **H&F** domain. Efficient energy harvest and transformation are naturally the direct consequence of scientific discovery based on up to date **PSE**. The R&D and the diffusion of the results, as in any other domain, relies on IT under the responsibility of **DIGIT**. Last but not least, both the passage from primary energy to secondary energy and its use have impact on the environment and require that society embraces and supports the transition process: the understanding of the society appraisal and reactions to change is the expertise of the **SCI** domain.

Five RIs represent the portfolio of the **ENE** domain: ECCSEL ERIC (Carbon Capture and Storage), EU-SOLARIS (Concentrated Solar Power), MARINERG-i (Marine Renewable Energy), JHR (R&D in the field of fission) and IFMIF-DONES (R&D in the field of fusion). JHR Reactor and IFMIF-DONES have not yet enter into Operation Phase. Three RIs – EU-SOLARIS, JHR Reactor and IFMIF-DONES – have been selected for a detailed questionnaire.

The issues addressed by the five RIs have profound links with **ENV** and **SCI** challenges, e.g. the possibility of CO_2 removing (ECCSEL), R&D in support to Nuclear Power Plants (JHR) or alternative use of solar power (EU-SOLARIS). IFMIF-DONES is part of a longer-term challenge, nuclear fusion, which is expected to be part of a sustainable energy mix in the second part of this century. In particular, often the acceptance of advanced technologies needs that the society becomes an involved partner in their development, hence the methodology of social science is a key element to understand the expectations of the population. All RIs have links with **DIGIT**, not only because they all have e-needs to fulfil with respect to their users, but also to meet the challenge of EOSC.

As in many high technology fields, the link with the domain of **PSE** is natural and strong, as illustrated by a few examples. EU-SOLARIS is focussed on CSP, and high-temperature materials for heat transfer and energy storage are in the spotlight, leading to foreseeable collaborations in this domain. The JHR has objectives in the fields of nuclear technology in support to the industry and fundamental science (by providing a high neutron flux source), and in radioisotopes supply for medical applications. It therefore has a link with the MYRRHA (waste disposal and radioisotope production) and naturally with many European laboratories – BR2 operated by SCK.CEN (Belgium), HFR operated by NRG and JRC (The Netherlands), LVR15 operated by CVR (Czech Republic), MARIA operated by NCBJ (Poland). In the field of radioisotopes, it is also part of the PRISMAP, the European medical isotope programme: Production of high purity isotopes by mass separation, a consortium of 23 beneficiaries from 13 countries, one European Research Laboratory and an International Organisation. The isotope production by the JHR and the MYRRHA lends itself to collaboration with **H&F**. IFMIF-DONES technology is based on accelerator, leading to collaboration with MYRRHA and the European Spallation Source ERIC, ILL, and SPIRAL2 (within **PSE** domain). Both the JHR Reactor and IFMIF-DONES will have, as one of their main objectives, the study of material under neutron irradiation, and therefore are expected to have impact on the important field of material science, together with other ESFRI RIs in **PSE**.

See the **ENE Table** for an extended overview of the interconnections across domains established by those **ENE RIs** in Operation Phase or in advanced Preparation Phase.

ECCSEL ERIC European Carbon Dioxide Capture and Storage Laboratory Infrastructure	ENV	**Carbon dioxide Capture and Storage (CCS) research in environmental sciences** Carbon capture and storage verification and climate change.
	H&F	**Carbon dioxide Capture and Storage (CCS) in health and food** Study of the impact of CO_2 on benthic organisms and marine ecosystem; measurement on carbon cycle and impact on health and agriculture.
	SCI	**Social and cultural aspects of Carbon dioxide Capture and Storage (CCS) research** Carbon capture and storage verification, climate change and impact on human well-being.

EU-SOLARIS
European Solar Research Infrastructure for Concentrated Solar Power

ENV
Concentrating Solar Thermal (CST) technologies research in environmental sciences
Concentrating solar thermal solutions for energy budget.

H&F
Concentrating Solar Thermal (CST) technologies in health and food
CST impact on health and agriculture.

PSE
New technologies and approaches for Concentrating Solar Thermal (CST) technologies
Material science and engineering for energy storage.

SCI
Social and cultural aspects of Concentrating Solar Thermal (CST) technologies
CST, climate change and impact on human well-being.

IFMIF-DONES
International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Source

PSE
New technologies and approaches for nuclear fusion research
Irradiation of structural materials for nuclear fusion technology.
Accelerator technology: high current CW particle beams.

SCI
Social and cultural aspects of nuclear fusion research
Energy security and social acceptance of nuclear fusion.

JHR
Jules Horowitz Reactor

H&F
Nuclear fission research in health and food
Production of advanced radioisotopes for therapeutic and diagnostic applications.

PSE
New technologies and approaches for nuclear fission research
Development and optimization of energy materials and components;
irradiation of structural materials for nuclear fission technology.

SCI
Social and cultural aspects of nuclear fission research
Energy security and social acceptance of nuclear fission.

ENVIRONMENT

The Environment domain covers the study of the physical, chemical and biological world we live in, and how it affects us. Environmental RIs have multiple roles in tackling global challenges by producing accurate data and scientific and technical knowledge that underpin tools supporting decisions. The RIs' observation of environmental phenomena in their different spatial and temporal scales benefits from the rapid technological advances which they help fostering.

The RIs in the **ENV** domain provide many possible linkages with other domains. Whether the focus is on use of life sciences in **H&F**, the environment's role in energy systems in **ENE**, the underlying processes of matter and energy in **PSE**, or the environment in interaction with human society in **SCI**, there is multiple scope for cross-fertilization. Methodological and technological advances in one domain can affect RIs in another domain.

Three RIs – LifeWatch ERIC (e-infrastructure ecosystems and biodiversity), ACTRIS (short-lived atmospheric components) and eLTER RI (long-term ecosystem research) – were identified to represent Infrastructures in different project phases with significant potential or existing linkages to other scientific domains.

DIGIT. The cross-fertilization is most evident with the **ENV**-**DIGIT** domain as rapid advances in ICT are harnessed with specific or generic applications in all RIs, and data-driven research options start to be vigorously explored in the **ENV** domain.

- Advances in ICT have opened up new possibilities for developing cross-domain approaches and involve multiple scientific communities that can make use of cross-cutting services in order to address issues of common interest. For example, the LifeWatch ERIC, which includes e-infrastructures, has created a so-called 'horizontal composability layer', which allows the combination of different data treatment units into complex workflows, including a tool providing mapping between ontologies and vocabularies, the LifeWatchEcoPortal. Such a tool is applicable in different domains. The possibilities for scaling-up their application are examined in ongoing projects in the context of EOSC.

- Cross-over activities between **ENV** and **DIGIT** are for the ACTRIS mostly addressed as a participation to the ENVRI cluster where consideration on data policies, high-performing computing, and data licensing are jointly addressed.

- eLTER RI uses cloud-based platforms such as EOSC. As many other environmental RIs, it is working closely with stakeholders – e.g. the Group on Earth Observations (GEO) – to find out how *in situ* data obtained from ESFRI RIs can improve GEO data products. AI and machine learning methods, applied in more powerful ICT platforms, are expanding the range of methods for evaluating ecosystem signals across different data streams.

- Digital RIs create new capabilities that allow analysis of high-throughput data, whether from genomics, Earth observation or *in situ* sensors, and these also facilitate interaction between eLTER RI and other RIs. In addition, it responds to the Digital Twin challenge in Europe.

Blockchain technology, such as LifeWatch ERIC enabled its application in the **ENV** domain, is another tool that can assist in scientific data workflow management. The opportunities created by these forms of technology development, together with generic architectures, are a significant driver for collaboration across ESFRI domains, with common solutions to common problems. This results in transversal e-services that can be employed by communities from different scientific domains.

HEALTH & FOOD. There is an intimate relation between purpose-driven life sciences for food or health, and the study of biological phenomena generally.

- eLTER RI is connected to the **H&F** domain with common interests in ecosystem issues which can make its research relevant for agriculture, food, biotechnology and bioenergy production. Solutions to these questions impact the environmental RIs as well as the AnaEE, MIRRI and EMPHASIS, and MIRRI. Beyond **H&F**, eLTER RI embraces multi-disciplinary research in a broader societal context (see below in **SCI** section).

- The key activities of ACTRIS focus on understanding the processes and quantifying the impacts of aerosols, clouds and trace gases on Earth's climate and radiation budget, air quality, human health, crop yields and ecosystems. There is thus a clear link of ACTRIS with the **H&F** domain, aiming to assess a range of issues from the premature mortality due to the exposure to atmospheric pollutants to the aerial transport of micro-plastics to understand how they enter the food chain after deposition to the ecosystems. ACTRIS expertise was also of fundamental importance to support industries and authorities during the COVID-19 crisis for evaluating the efficacy of cloth facemasks in reducing particulate matter exposure.

- An example of implementation by the LifeWatch ERIC infrastructure with a direct impact in the **H&F** domain is a Virtual Research Environment allowing the early detection of invasive alien species based on environmental DNA. This facilitates the identification of potential diseases, pathogens or pests for crops, aquaculture and other food production systems on land and in the sea.

ENERGY. Environmental knowledge and resources are key to the transition to carbon-neutral, renewable energy. ACTRIS provides the clearest examples.

- It-supports studies on radiation reaching the ground to estimate solar energy power potential.

- ACTRIS atmospheric simulation chambers allow investigating the effect of different engine running conditions on exhaust emissions.

PHYSICAL SCIENCES & ENGINEERING. RIs in the environmental domain stand to gain detailed insights on energy and matter from facilities in the **PSE** domain (see below in **PSE** section).

SOCIAL & CULTURAL INNOVATION. Ultimately, understanding economic and societal considerations is key to understanding how our societies can become more sustainable.

- A distinctive feature of eLTER RI is the extension of natural science research to the study of society-nature interaction, allowing integrated focus on ecological and socio-ecological interactions. This approach enables linking with other domains and disciplines for which the use of ecosystem services is relevant. One specificity of eLTER is that it integrates about 250 eLTER sites and eLTER Platforms for socio-ecological research, representing major European natural and socio-ecological gradients. The eLTER platforms have embedded tools to analyse features associated with societally relevant attributes, such as the study of competing land uses, the protection of recreational values or the conservation of drinking water. The eLTER information system is designed to address transdisciplinary challenges.

- ACTRIS is an infrastructure supporting study of climate change and air quality as fundamentally societal issues; ACTRIS long-term datasets are used to evaluate the effectiveness of policies for reducing emissions of pollutants and to connect intervention policies and public acceptance from a local to a national context.

The complexity of grand global challenges – climate and land-use change, biodiversity loss, eutrophication and environmental sustainability – requires RIs to enable and support synergistic and integrative approaches. The **ENV** RIs address these challenges with co-creation and co-design of services in collaboration with RIs from the different domains. Finally, when novel technologies emerge, long-term data from **ENV** RIS are a key fundamental prerequisite to address their viability, impacts and added-value for environmental sustainability.

See the **ENV Table** for an extended overview of the interconnections across domains established by those **ENV RIs** in Operation Phase or in advanced Preparation Phase.

ACTRIS Aerosol, Clouds and Trace Gases Research Infrastructure	DIGIT	**Open data resources and management for aerosol, clouds, and trace gases observations** Data access and curation, standardisation of data ad metadata, data and services interoperability.
	DIGIT	**ICT tools for atmospheric research** Virtual Research Environments (VRE) for data processing, trend analysis, and satellite cal/val. HPC for atmospheric global and regional models, data assimilation and processing of large volume of data.
	ENE	**Aerosol, clouds, and trace gases observations for energy supply and consumption** Key atmospheric parameters and environmental assessments related to different energy production forms.
	ENE	**Aerosol, clouds, and trace gases observations for energy supply** Diagnostics development for wind and solar radiation energy applications.
	H&F	**Aerosol, clouds, and trace gases observations for health and food** Measurements of air quality parameters and impact on health. Measurements of air quality parameters and extreme weather events and impact on agriculture.
	PSE	**New technologies and approaches for aerosol, clouds, and trace gases observations** Development of laser optics and detectors. New techniques for atmospheric corrections and aerosol physics.
	SCI	**Social and cultural aspects about aerosol, clouds, and trace gases observations** Key atmospheric parameters, climate change and impact on human well-being.

DANUBIUS-RI International Centre for Advanced Studies on River-Sea Systems	DIGIT	**Open data resources and management for interdisciplinary research on river-sea systems** Development of DANUBIUS Commons – common set of standards, rules, methodologies supporting interdisciplinary research in freshwater, transitional and coastal marine environments.
	H&F	**Advanced studies on river-sea systems for health and food** Surface waters analysis in global biogeochemical cycles, food and energy production, food security, aquaculture, environmental medicine.
	SCI	**Sustainability scenario development for human societies in river-sea systems** Integration of data from interdisciplinary earth and life sciences with social, economic ad behaviour information on communities living in river-sea systems, aiming to support sustainable management plans at entire basin scale.
DiSSCo Distributed System of Scientific Collections	DIGIT	**Open data resources and management for scientific collections** Multimodal access to collections for a linked open data approach.
	H&F	**System of scientific collections for health and food** Natural science collections for bio- and geo-diversity information, climate change, food security, health and bioeconomy.
EISCAT_3D Next generation European Incoherent Scatter radar system	DIGIT	**Open data resources and management for monitoring of the atmosphere and ionosphere** Collection and archive of basic data; data processing to describe the ionosphere and neutral atmosphere; selection of well-designed radar pulse schemes.
	PSE	**New technologies and approaches for monitoring of the atmosphere and ionosphere** Development of new methods of radar coding, signal processing and data analysis. Sun-earth interactions, radio astronomy, space security, plasma physics, magnetic field studies.
eLTER RI Integrated European Long-Term Ecosystem, critical zone and socio-ecological system Research Infrastructure	DIGIT	**Open data resources and management for long-term ecosystem research** Access to data across multi-repositories.
	H&F	**Long-term ecosystem research for health and food** Identification of drivers of ecosystem changes for climate, food security, health and bioeconomy.
	SCI	**Social and cultural aspects of long-term ecosystem research** Understand the effects of global, regional and local changes on socio-ecological systems and their feedbacks to environment and society.
EMSO ERIC European Multidisciplinary Seafloor and water-column Observatory	DIGIT	**Open data resources and management for monitoring of the seafloor and water column** Provision of data and metadata.
	H&F	**Seafloor and water column observations for health and food** Biogeochemical and physical parameters measurements to address natural hazards, climate change and marine species/ecosystems under anthropogenic change; biodiversity and ecosystem stability.
	PSE	**New technologies and approaches for seafloor and water column observations** Development of instrument and technologies.
	SCI	**Social and cultural aspects of seafloor and water column observations** Key hydrosphere observations, climate change and impact on human well-being.
EPOS ERIC European Plate Observing System	DIGIT	**High performance computing for solid earth science** Integration of data and services – including data products, models and facilities HTC resources for data, metadata and services integration.
	DIGIT	**Open data resources and management for solid earth science** Access to quality controlled data from diverse earth science disciplines, tools for analysis and modelling data fairness in solid earth science.

	ENE	**Solid earth science for energy supply and consumption** Carbon capture and storage verification.
	ENE	**Solid earth science for energy supply** Geo-resources; geothermal heating; anthropogenic hazards.
	H&F	**Health impact of natural gas emissions and volcanic ashes** Environmental impact of tsunamis, landslides, volcanic eruptions, lahar and gas emissions for food security.
	PSE	**New technologies and approaches for solid earth science** Development of instrument and new technologies.
	SCI	**Social and cultural aspects of solid earth science** Solid earth observations for environmental changes and hazards and impact on human well-being. Hazard assessment, risk communication and emergency management. Increasing resilience of society to natural and anthropogenic hazards.
EURO-ARGO ERIC European contribution to the international Argo Programme	DIGIT	**Open data resources and management for oceans observing systems** Access to quality controlled data and data products for climate and oceanography.
	H&F	**Global array of oceans observing systems for health and food** Measurements of physical and biogeochemical parameters of the oceans and influence on climate change and impact on health.
	PSE	**New technologies and approaches for oceans observing systems** Development of instrument and technologies, e.g. new sensors to be mounted on autonomous platforms.
	SCI	**Social and cultural aspects of oceans observing systems** Key ocean observations, climate change and impact on human well-being.
IAGOS In-service Aircraft for a Global Observing System	DIGIT	**Open data resources and management for atmospheric composition observations** Near real time data on atmospheric chemical species to weather and research services.
	ENE	**Global observations of atmospheric composition for energy supply and consumption** Key atmospheric parameters and environmental assessments related to different energy production forms.
	H&F	**Global observations of atmospheric composition for health and food** Measurements of air quality parameters and impact on health.
	PSE	**New technologies and approaches for atmospheric composition observations** Development of instrument and technologies.
	SCI	**Social and cultural aspects of atmospheric composition observations** Key atmospheric observations, climate change and impact on human well-being.
ICOS ERIC Integrated Carbon Observation System	DIGIT	**Open data resources and management for integrated carbon observation system** Highly standardised quality control data archived for the long term, services for GHG model integration, comparison and visualisation.
	ENE	**Integrated carbon observation system for energy supply and consumption** Large scale monitoring of atmospheric CO_2 around CCS.
	H&F	**Integrated carbon observation system in health and food** High precision measurement on carbon cycle in agricultural systems, support for climate-smart agriculture, evaluation of bioenergy, common analyses of plant and microbial adaptation to change in relation to carbon cycle.

	PSE	**New technologies and approaches for integrated global carbon and GHG observations** Development of instruments, new arrays for local (city) and regional emission verification, and technologies for satellite ground verification.
	SCI	**Social and cultural aspects of integrated carbon observation system** Key observations on carbon cycle and greenhouse gas budget and perturbations, climate change and impact on human well-being, common studies on behaviour related to climate change.
LifeWatch ERIC e-Infrastructure for Biodiversity and Ecosystem Research	DIGIT	**High performance computing for biodiversity and ecosystems** Integration of biodiversity and ecosystem data and services – including data products, models and facilities.
	DIGIT	**Open data resources and management for biodiversity and ecosystems** Provide Virtual Research Environments (VRE) to run scientific experiments in cooperative environments.
	H&F	**Biodiversity and ecosystems in health and food** Advancement of scientific and technological research on human microbiota, vectors for diseases and parasites and impacts on human health and well-being.
	H&F	**Biodiversity and ecosystems in health and food** Advancement of scientific and technological research on conservation of biodiversity in species of agricultural interests, ecosystem impacts on/from agriculture, fisheries and aquaculture.
	PSE	**New technologies and approaches for monitoring biodiversity and ecosystem** Development of ICT instruments and technologies for the control of atmospheric and hydrosphere composition.
	SCI	**Social and cultural aspects of biodiversity and ecosystems** Development of ICT instruments and technologies on socio-ecological systems, past and future ecosystem services and human well-being.

HEALTH & FOOD

The Health & Food domain has undergone very dynamic development in the last decade, beginning with RIs covering biological and biomedical sciences (*Health*) and expanding into *Food*, to fill the gap, which is essential to human well-being and health. **H&F** exhibited enormous ability and agility to respond to demands of research communities, societal challenges, and gaps on the roadmap and became a central for establishing connections to RIs from all the other domains. Besides the vibrant development and capability to bundle capacities and cluster expertise and a complementary service, the **H&F** RIs diversified over the last decade and exist in two basic subdomains, the *Health* and *Food*. The established interactions to other ESFRI domains could be exemplified by ELIXIR (biological and biomedical data resources), Euro-BioImaging ERIC (biological and biomedical imaging), EMPHASIS (Multi-scale Plant Phenomics and Simulation) and AnaEE (Analysis and Experimentation on Ecosystems).

Broadening the *Health* for logically interlinked *Food* brought further intensification of interactions with environmental and social domains, creating new opportunities for inter-sectorial solutions and innovations.

Thus, *Food* has become a significant second pillar of the **H&F** as the *Agri-food* tackles major challenges including sustainable food production and distribution systems, and hunger versus agri-food markets and their functioning. The increasing attention to agri-food system sustainability represents a global issue strictly connected to the food security dimensions – i.e. food physical availability, utilization, and stability. Here the **H&F** RIs have established a pivotal cross-sectoral interaction platform interconnecting the environmental domains, sustainability of food production in the context of climate change, and human health.

SOCIAL & CULTURAL INNOVATION. The **SCI** domain has been currently linked to the **H&F** activities via EOSC, a part of the European Cloud Initiative, which builds a competitive data and knowledge economy in Europe. Partnerships outside the biomedical field are being further strengthened in particular with the IT infrastructure community (tangible with EGI) and randomised interventional studies (including with cluster randomisation) showing a very powerful tool to generate evidence on the efficacy of social, economic or educational policies.

ENVIRONMENT. The area of Environment is naturally very close to the *Food* subdomain, though also biomedical RIs have setup expanding interactions to the **ENV** domain at the cross-section of both areas where environment affects the human health. In the *Food*, RIs including EMPHASIS, AnaEE, EMBRC ERIC, and METROFOOD-RI closely collaborate with the **ENV** domain.

The EMPHASIS and AnaEE collaborate, bringing innovative solutions for a sustainable intensification of agriculture by integrating plant phenomics and agricultural ecology to foster the development of novel scientific concepts, sensors and, integrated models. Both, EMPHASIS and AnaEE intensively interact with ICOS ERIC, ACTRIS and eLTER RI. For instance, about half of the AnaEE platforms are collocated with ICOS ERIC and/or ACTRIS sites. There are strong synergies between EMPHASIS and the ecosystem-oriented eLTER RI (about 25% collocations) or between the marine biology EMBRC ERIC and ecosystem infrastructures AnaEE or LifeWatch ERIC. METROFOOD-RI, a RI at the cross-section of health, food, and environment has built close links to **ENV** domain, dealing with sustainability of agri-food systems, limitation environmental burden and negative effects on biodiversity, reduction of wastes and resource consumption, soil health protection and biodiversity restoration, improving agriculture, and supporting agroecological transition.

Regarding the environment impact on human health, new cross-disciplinary activities and initiatives have been currently developing, bridging the existing gaps between environment, food, health and social sciences. Here, **ENV** and biomedical RIs have begun to describe environmental determinants of health (human exposome) to improve understanding of the impact of environmental exposures on population health and characterizing the risk factors behind development of chronic conditions. This effort centrally bridges the **ENV** RIs with **H&F** enabling assessment of environmental risks, development of innovative tools for modelling gene modifications, chronic diseases and ageing as well as discovery of novel tools for the risk mitigation and prevention in close collaboration with existing landmarks BBMRI ERIC, INFRAFRONTIER, and ELIXIR.

PHYSICAL SCIENCES & ENGINEERING. The development of new technological and digital approaches in biology has revolutionized methods to understand life and has largely contributed to the development of new knowledge on its functioning, from the atomic scale to the scale of the organism without discontinuity and in their native state. The interaction with **PSE** could nicely exemplified by for instance EMPHASIS, AnaEE, Euro-BioImaging ERIC, INSTRUCT ERIC and all others as such interaction creates natural bridges between physicists, chemists, digital specialists, agri-researches, etc. to develop new concepts and future technologies, all facilitating the innovation.

EXTENSIVE MULTIDOMAIN INTERACTIONS. **H&F** Life Science RIs have shown to be transversal in all thematic research areas and have developed also an effort to interact with partners and users outside Europe. **H&F** RIs have built new strategic relationships also outside the EU via the RI-VIS Communication Project[1]. The European Monitoring and Evaluation Programme (EMEP)[2] makes extensively use of a wide variety of large cross-national Research Infrastructures, and that encompasses each of the ESFRI domains. EMEP is a network developed over the past 35 years in order to support effect-based cost-effective air pollution policies.

Many RIs in the **H&F** domain are well-positioned to develop interactions with most ESFRI domains as they are archetypal of multi-domain interconnections. Thus, EU-IBISBA project (Industrial Biotechnology, IB) with connections to other domains became part of its conceptual basis. Industrial Biotechnology is the application of biological systems for industrial purposes. While powered by enzymes and microorganisms, it relies on synergy between biology and chemical engineering and covers a wide range of market sectors, from bio-based fuels and plastics to bulk and fine chemicals, food and feed ingredients, waste treatment, pollution prevention and resource conservation. IBISBA thus complement generic or specialized approaches and meets needs from **ENE**, **ENV**, **PSE** domains.

Moreover, complementarities and the central position regarding the human health and well-being allow joining forces to tackle also such global situations, which represent the COVID-19 pandemics as well as non-communicable diseases that originate from diet patterns within the European food systems context. The clustered resources and expertise available from the biomedical RIs demonstrated how the ESFRI RI's principles help to provide solution to such a pan-European challenge.

Finally, connecting with cohorts initiatives (general population or more specialized cohorts), European registries (Rare disease), genomic information initiatives (B1MG) or health data repositories outside the specific RIs field, will be instrumental in developing integrated approaches to solve Health issues that are naturally interlinked with the **SCI** domain.

See the **H&F Table** for an extended overview of the interconnections across domains established by those **H&F RIs** in Operation Phase or in advanced Preparation Phase.

1. RI-VIS Communication Project
https://ri-vis.eu/network/rivis/Home

2. European Monitoring and Evaluation Programme (EMEP)
www.emep.int

RI	Domain	Interconnection
AnaEE Analysis and Experimentation on Ecosystems	DIGIT	**Open data and modelling resources for managed and natural ecosystems** Modelling platforms by providing the necessary hardware and software, as well as the access to expertise, datasets and modelling libraries.
	ENE	**Managed and natural ecosystems for energy supply and consumption** Bioenergy and bio-renewables – trade-offs between food supply, energy supply, biodiversity and ecosystem services, carbon sequestration in ecosystems.
	ENV	**Managed and natural ecosystems in environmental sciences** Land use and exploitation by agriculture change, food security and environmental sustainability.
	ENV	**Managed and natural ecosystems in environmental sciences** Bioenergy and bio-renewables – trade-offs between food supply, energy supply, biodiversity and ecosystem services, carbon sequestration in managed and unmanaged ecosystems.
	ENV	**Managed and natural ecosystems in environmental sciences** Health, environment and air/water/food pollution.
	ENV	**Managed and natural ecosystems in environmental sciences** Climate change, weather extremes, and epidemiology of pathogenic agents, in humans, animals and plants.
	PSE	**New technologies and approaches for managed and natural ecosystems** Internet of things, new technologies – sensors, drones to satellites – to better predict and model agricultural systems, crop/livestock yield, and interactions with the environment.
	SCI	**Social and cultural aspects of managed and natural ecosystems** Land use and exploitation by agriculture change, food and non-food systems, ecosystem services.
BBMRI ERIC Biobanking and BioMolecular resources Research Infrastructure	DIGIT	**Open data resources and management for biobanks and biomolecular resources** Catalogue on sample/data collections with aggregated results. User-search on sample-level and patient-/donor-level data, including clinical data, and in some cases deep phenotype and omics data.

	PSE	**New technologies and approaches for biobanks and biomolecular resources** Biomedical engineering and precision medicine: facilitate access to samples/data for health research (i.e. imaging, digital pathology).
	SCI	**Social and cultural aspects of biobanks and biomolecular resources** Facilitate access to longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing. Facilitate access to longitudinal studies and cohorts in complex disease studies, e.g. obesity and food demand and consumption.
	SCI	**Social and cultural aspects of biobanks and biomolecular resources** Providing guidance on the ethical, legal and societal aspects in data/sample management for the life sciences.
EATRIS ERIC European Advanced Translational Research Infrastructure in Medicine	DIGIT	**Open data resources and management for translational medicine and drug development** Open access to anonymised clinical data.
	PSE	**New technologies and approaches for translational medicine and drug development** High-end technologies to advance new products from target validation to early clinical trials.
	SCI	**Social and cultural aspects of translational medicine and drug development** Use of longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing. Use of longitudinal studies and cohorts in complex disease studies, e.g. obesity and food demand and consumption.
	SCI	**Social and cultural aspects of translational medicine and drug development** Anthropological studies using resources in biomedical engineering, clinical data and precision medicine: ethical implication.
ECRIN ERIC European Clinical Research Infrastructure Network	DIGIT	**Open data resources and management for multinational clinical research and trials** Clinical research medata repository and clinical research data repository(ies) for storage, integration and sharing of data from clinical trials.
	PSE	**New technologies and approaches for multinational clinical research and trials** New approaches and design in particular in precision medicine and machine learning stratification, small populations, platform trials.
	SCI	**Social and cultural aspects of multinational clinical research and trials** Use of longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing. Use of longitudinal studies and cohorts in complex disease studies, e.g. obesity and food demand and consumption.
	SCI	**Social and cultural aspects of multinational clinical research and trials** Trial management: ethical, data protection and cross border legal implication.
	SCI	**Social and cultural aspects of interventional studies** Randomised studies in social science, in particular cluster-randomised assessment of public policies.
ELIXIR A distributed infrastructure for life-science data	DIGIT	**High performance computing for integrated bioinformatics resources and services** Data resources for the life sciences and the long-term preservation of biological data; repositories for publishing open data in the life sciences.
	ENV	**Integrated bioinformatics resources and services in environmental sciences** Sequencing of the DNA and RNA of crop and forest plants, as well as their pathogens and pests; marine metagenomics.
	SCI	**Social and cultural aspects of integrated bioinformatics resources and services** DNA and RNA in medical and translational research, and rare diseases: ethical implication.
	SCI	**Social and cultural aspects of integrated bioinformatics resources and services** Use of longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing. Use of longitudinal studies and cohorts in complex disease studies, e.g. obesity and food demand and consumption.

EMBRC ERIC European Marine Biological Resource Centre	DIGIT	**Open data resources and management for marine biological resources** Interoperability and standardisation of data generated by marine research, marine biological observation, and bioinformatics; processing, curation and storage of large datasets of sequences, metadata, historical time series and literature resources.
	ENE	**Marine biological resources for energy supply and consumption** Bioenergy and bio-renewables – bioenergy microbes, plants, crops, aquaculture.
	ENE	**Marine biological resources for energy supply and consumption** Bioenergy and bio-renewables – trade-offs between food supply, energy supply, biodiversity and ecosystem services.
	ENV	**Marine biological resources in environmental sciences** Volcanic cold seeps, proxies for the future high CO_2/low pH oceans; polluted low-oxygen sites, and artificial habitats such as renewable energy test sites for research on bio-fouling.
	ENV	**Marine biological resources in environmental sciences** Health, environment and air/water/food pollution on human health.
	PSE	**New technologies and approaches for marine biological resources** Satellite tag and sensor design for specialised services for tracking large marine organisms, such as mammals and turtles in their natural habitat.
	SCI	**Social and cultural aspects of marine biological resources** Anthropological studies using resources in biobanks and omics.
	SCI	**Social and cultural aspects of marine biological resources** Marine and maritime education (ocean literacy). Attitudes to new types of sea food.
EMPHASIS European Infrastructure for Multi-scale Plant Phenomics and Simulation	ENE	**Multi-scale plant phenotyping and simulation for energy supply and consumption** Agriculture and land-use change, food and non-food systems.
	ENE	**Multi-scale plant phenotyping and simulation for energy supply and consumption** Development and optimization of specific energy plants; competition of food supply and biomass for bioenergy.
	ENE	**Multi-scale plant phenotyping and simulation for energy supply and consumption** Bioenergy and bio-renewables – bioenergy microbes, plants, crops, biofuels.
	ENV	**Multi-scale plant phenotyping and simulation in environmental science** Precision agriculture and internet of things, new technologies – sensors, drones to satellites - to better predict and model agricultural systems, crop/livestock yield, and interactions with the environment.
	ENV	**Multi-scale plant phenotyping and simulation in environmental science** Land use and exploitation by agriculture change, food and non-food systems.
	ENV	**Multi-scale plant phenotyping and simulation in environmental science** Bioenergy and biorenewables – bioenergy microbes, plants, crops, biofuels – and the environment.
	ENV	**Multi-scale plant phenotyping and simulation in environmental science** Bioenergy and biorenewables – trade-offs between food supply, energy supply, biodiversity and ecosystem services.
	ENV	**Multi-scale plant phenotyping and simulation in environmental science** Health, environment and air/water/food pollution on human health.
	ENV	**Multi-scale plant phenotyping and simulation in environmental science** Climate change, weather extremes, and epidemiology of pathogenic agents, in humans, animals and plants.

	PSE	**New technologies and approaches for multi-scale plant phenotyping and simulation** Internet of things, new technologies – sensors, drones to satellites - to better predict and model agricultural systems, crop/livestock yield, and interactions with the environment.
	SCI	**Social and cultural aspects for multi-scale plant phenotyping and simulation** Land use and exploitation by agriculture change.
ERINHA European Research Infrastructure on Highly Pathogenic Agents	ENV	**Surveillance of highly pathogenic micro-organisms in environmental sciences** Climate change, weather extremes, and epidemiology of pathogenic agents, in humans, animals and plants.
	SCI	**Social and cultural aspects for surveillance of highly pathogenic micro-organisms** Use of longitudinal studies and cohorts in infectious disease studies, with high risks for public health, society and the economy.
	SCI	**Social and cultural aspects for surveillance of highly pathogenic micro-organisms** Outbreak preparedness, surveillance and response.
EU-IBISBA European Industrial Biotechnology Innovation and Synthetic Biology Accelerator	ENE	**Industrial biotechnology innovation for energy supply and consumption** Bioenergy and bio-renewables – bioenergy microbes, plants, crops, biofuels.
	ENV	**Industrial biotechnology innovation in environmental sciences** Identification of genes, enzymes and regulation of the metabolic pathways to degrade the environmental contaminants and to synthesize chemical compounds by biotransformation / biorefinery processes – e.g. pharmaceuticals, biofuels, biomaterials, enzymes.
EU-OPENSCREEN ERIC European Infrastructure of Open Screening Platforms for Chemical Biology	DIGIT	**Open data resources and management of high-throughput screening data of chemical compounds** Large-scale open-access data for computational data integration and prediction of drug-target interactions and networks, adverse effects and drug combinations; well-annotated, standardised and controlled datasets with good coverage of chemical space.
	ENV	**High-capacity screening and chemical optimization platforms for compounds in environmental sciences** Development of new and safer products – e.g. Drugs to treat diseases, selective herbicides to protect crops, food additives for livestock.
	PSE	**New technologies and approaches for high-capacity compound screening and chemical optimization platforms** High-end technologies to advance new products from target validation to preclinical studies. Imaging, diagnostics and novel therapeutic approaches.
Euro-BioImaging ERIC European Research Infrastructure for Imaging Technologies in Biological and Biomedical Sciences	DIGIT	**Open data resources and management for biological and biomedical imaging** Public data repository (bioimage archive) to store, integrate and serve image datasets from published scientific studies. Cloud-based image data services, to run image analysis algorithms on large openly available image datasets to address new biological questions; pre-clinical image data archiving and processing.
	ENV	**Biological and biomedical imaging in environmental sciences** Studies on the bacterial response to environmental stimuli. Study of the molecular and cellular mechanisms underlying plant resilience under stress conditions, including warming, drought, and others associated with a changing climate.
	ENV	**Biological and biomedical imaging in environmental sciences** Microscale studies of the microbial communities and their cellular interactions and physiology in matrixes such as soil, seas and underground waters to study the determinants of biodiversity and determine organisms' characteristics and behaviour under changing conditions.
	ENV	**Biological and biomedical imaging in environmental sciences** Study of causal climate change effects and threats, e.g. characterization of emergent disease vectors and pathogens including their molecular/cell biological pathways, and their pathogenic effects in whole organisms and humans.
	PSE	**New technologies and approaches for biological and biomedical imaging** Novel detection modalities to reveal new processes and linking them to data from other infrastructures. Access to a range of cutting-edge technologies in biological and biomedical imaging for life scientists and beyond; image data analysis and exploring imaging data in combination with non-imaging big datasets, data analysis support and training.

SCI
Social and cultural aspects for biological and biomedical imaging
Use of longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing.
Biomedical engineering and precision medicine: ethical implications.

INFRAFRONTIER
European Research Infrastructure for the generation, phenotyping, archiving and distribution of mouse disease models

DIGIT
Open data resources and management for mouse functional genomics
Data resources of EMMA, the non-profit repository for the collection, archiving (via cryopreservation) and distribution of relevant mutant mouse strains essential for basic biomedical research.

DIGIT
Open data resources and management for mouse functional genomics
Novel approaches for large-scale data analysis and visualisation using AI and deep learning approaches.

ENV
Mouse functional genomics in environmental sciences
Study of the genetic, environment and pharmacological components of human disease.

PSE
New technologies and approaches for characterising and analysing genetic models of human diseases
Access for life scientists to cutting-edge technologies for large-scale functional characterisation of rodent models of human diseases.

SCI
Social and cultural aspects for genetic disease modeling
Longitudinal studies of age effects on health and disease in rodent models.
Ethical implications of genetic disease modelling, 3RS.

INSTRUCT ERIC
Integrated Structural Biology Infrastructure

DIGIT
Open data resources and management for integral structural biology
Data analysis: bioinformatics, computational software, image processing.

ENV
Integrated structural biology in environmental sciences
Suddenly shapes, sizes and assemblies of molecules assigned to various compartments in cells and put into context with their surrounding environment.

PSE
New technologies and approaches for integrated structural biology
Analytical facilities at molecular scale – i.e protein production, cryo-electron microscopy, NMR, nanobody drug discovery, protein crystallisation, X-ray approaches.

METROFOOD-RI
Infrastructure for promoting metrology in food and nutrition

DIGIT
Open data resources and management for food and nutrition
Collection, dissemination and sharing of information about principles, terminology, tools.
Harmonization and integration of food composition databases and tools.
Development of new standardized tools for food quality, safety & authenticity and for traceability.

ENE
Metrology in food and nutrition for energy supply and consumption
Agriculture and land-use change, food and non-food systems.

ENE
Metrology in food and nutrition for energy supply and consumption
Bioenergy and bio-renewables – trade-offs between food supply, energy supply, biodiversity and ecosystem services.

ENV
Food and nutrition in environmental sciences
Agriculture and land-use change, agroecology, food and non-food systems.

ENV
Food and nutrition in environmental sciences
Health, environment and air/water/food pollution, environmental quality, food defense.

PSE
New technologies and approaches for metrology in food and nutrition
New devices and technologies to exploit alternative sources of food and circular economy solutions; advanced digital solutions for food production, resource efficiency and waste management.

SCI
Social and cultural aspects for food and nutrition
Better use of longitudinal studies and cohorts in complex disease studies, e.g obesity and food demand and consumption; consumer sciences, food behaviours and attitudes.

	SCI	**Social and cultural aspects for metrology in food and nutrition** Agriculture and land-use change, food and non-food systems, including local food systems and food transparency.
MIRRI Microbial Resource Research Infrastructure	DIGIT	**Open data resources and management for microbial resources and/or their application** Interoperability of data, facilitated data mining, availability of trusted data.
	ENE	**Microbial resources for energy supply and consumption** Bioenergy and bio-renewables – bioenergy microbes, plants, crops, biofuels.
	ENV	**Microbial resources for environmental sciences** Microbial resources for the production of renewable biobased chemicals/materials.
	ENV	**Rescuing and preserving microbial biodiversity** Investigation and preservation of microbial biodiversity, preservation of biodiversity of endangered environments, linking biodiversity to bioprospection.
	ENV	**Research on pathogenic microorganisms and human / human-animal infectious diseases** One health, human / human-animal infectious diseases, antimicrobial resistance and responsible use of antibiotics.
	ENV	**Resources and methods for biological management of soils and crops** Soil health, microbial resources as/for biofertilizers or biopesticides, antimicrobial resistance and responsible use of antibiotics, one health.
	ENV	**Microbial resources and methods for biomonitoring and/or bioremediation** Microbial pathogens, persistent organic pollutants and plastics in soils and waters.
	SCI	**Social and cultural aspects on the role of microbes on health and well-being** Health and food literacy, prevention of infectious diseases, antimicrobial resistance and responsible use of antibiotics, food safety and food spoilage, consumption of new microbial-based food products.

PHYSICAL SCIENCES & ENGINEERING

Examples of specific linkages of Research Infrastructures in the **PSE** domain can be found with all other five domains **ENE**, **ENV**, **H&F**, **SCI**, **DIGIT**. All **PSE** projects are linked with DIGIT due to their character and the large amount of data that need to be processed, analysed and distributed. **PSE** RIs are aiming to achieve full compliance with the FAIR data principle – archived data access, interoperability and long-term sustainability. Most of the **PSE** RIs are active drivers of the European Open Science Cloud, an environment for hosting and processing research data. The CERN World LHC Computing Grid (WLCG) connects up to 200 computing clusters and offers near real-time access to LHC data. Also, the expected future demand will outgrow the foreseeable technology development and call for further innovative digital solutions. This experience and know-how can serve as a guide for other domains. In the following we will try to illustrate some aspects of the specific linkage.

Analytical infrastructures. ELI, EMFL, European Spallation Source ERIC, European XFEL, ESRF EBS, ILL – play an important role in answering the societal challenges of today within Horizon Europe, especially in the areas of **ENE**, **ENV** and **H&F**. The cooperation between RIs allows to fully harness the power of analytical RIs. Bridging information from X-ray, neutron and electron-beam facilities, is vital to understand and predict the behavior of materials and to guide the design of new materials. In **ENE** and **ENV**, the development of new functional materials is essential for a climate neutral and circular economy in Europe. Here, analytical RIs reveal material properties and transformations that lead to the development of improved sources of renewable energy; carbon-negative insulation, carbon capture and conversion, and energy storages – hydrogen and batteries. They enable the knowledge creation that is fundamental for the success of alliances and partnerships such as the European Battery[3] and European Clean Hydrogen Alliances[4] and the European Clean Hydrogen Partnership[5]. Batteries and fuel cells are layered systems in which the components determine the overall performance. At ESRF, hard X-ray phase-contrast tomography enabled a statistical analysis of the chemo-mechanical transformation of composite electrodes under fast charging conditions. The results of the study help to improve batteries in terms of lifespan, energy density and usability, thus tackling three of the main obstacles to a broad deployment of electro-mobility. Photocatalysts are being developed for sustainable processes, such as cleaning of water, energy generation in solar cells, hydrogen production and the conversion CO2 into useful chemicals and fuels[6]. The techniques available in analytical facilities reveal material properties at the atomic scale and thereby allow them to be tailored according to end-user needs. Photon (ESRF, XFEL) and electron microscopy identify the different organic compounds in aerosols – an important factor for the climate and subject of ACTRIS. Neutron scattering facilities (ILL, ESS) study the formation of ice clouds. The high repetition rate of X-ray pulses allows the study of nano-particles important for catalysis of soot particles in pollution. Applications of analytical RIs in **H&F** include deep understanding of underlying molecular mechanisms of a large variety of microbial diseases, viruses (such as COVID 19) and cancer. Innovative technologies at analytical RIs facilitate the development of integrated, multi-parametric and multiscale analytical imaging at sub-nanometer to mm scales. Multidisciplinary groups have used the laser-like X-rays of XFEL to explore the atomic structure and dynamics of proteins relevant to the SARS-CoV-2 virus and antibiotic resistant bacteria. European XFEL is able to solve structures of bio molecules within few minutes and analyze membrane proteins for the development of drugs targeted at cell membranes.

Astronomy & Astroparticle Physics. ELT, SKAO, CTA, and EST and KM3NeT 2.0 – are connected with **ENV** domain, e.g. through the applications of LOFAR (SKA pathfinder) to monitor the Earth's subsurface with seismic-vibration sensors. KM3NeT 2.0 will provide a unique opportunity for environmental scientists to access data on sea currents, temperature, acoustic activity, etc. collected from sensors in deep sea. CTA on cosmic astroparticle detection is using the data on atmosphere quality (transmission) from the LIDAR techniques coming from ACTRIS. The EMSO ERIC in **ENV** domain is linked to KM3NeT 2.0 as the EMSO regional Facility in Sicily is also a test site for KM3NeT 2.0. EST will study solar magnetic activity causing terrestrial changes. This can develop into a dedicated research studying the links between the solar output and the Earth's climate, relevant for the long-term ecosystem research eLTER RI. EST will closely monitor the properties of the atmosphere which affect its capability for observing the Sun, e.g. precipitation per year, density

3. European Battery Alliance
https://www.eba250.com/

4. European Clean Hydrogen Alliances
https://www.ech2a.eu/

5. European Clean Hydrogen Partnership
https://www.fch.europa.eu/news/eu-proposal-set-clean-hydrogen-partnership-europe-1

6. Examples are taken from the publication "Analytical Research Infrastructures – A key Resource for the five Horizon Europe Missions, 2020 and input from XFEL
https://www.lens-initiative.org/wp-content/uploads/2020/09/ARIE-MISSIONS-PosPaper-FINAL-RELEASE_09.2020.pdf

of aerosols at different months, or the impact of societal activities on the quality of the sky. If the atmosphere is affected by human activity and loses its capability to protect the society from harmful UV radiation, EST will monitor that degradation. Dedicated studies of geomagnetic storms by EST could be used in risk management relevant to **ENE** domain. Imaging technologies used, for example, by ELT on the forefront of research for image processing can be used in medicine and biology (**H&F**). SKA pathfinder LOFAR_Argo is pioneering measurements of the micro-climate in potato crops using LOFAR antennas and mote sensors. Development of global network of ground based gravitational wave (GW) observatories VIRGO, LIGO, KAGRA and the future INDIGO connects the RIs (ELT, SKAO, CTA, KM3NeT 2.0) within **PSE** domain in the multi-messenger approach. With the proposed next generation GW observatory, the Einstein Telescope, Europe will take the leading role in GW astrophysics.

Nuclear & Particle Physics. HL-LHC, FAIR, SPIRAL2 and KM3NeT 2.0 have outstanding applications in **H&F** domain. FAIR/GSI, GANIL/SPIRAL2 and CERN participate in research programs in biophysics, radio-biology and medicine dedicated to optimization of hadron-therapy protocols and new, less invasive cancer treatments. Today almost 30 proton and carbon therapy centres are operated in Europe. GSI together with CERN have pioneered heavy-ion cancer therapy in Europe with the first hundreds of patients treated at GSI, leading to knowledge transfer for the construction of the first clinical facility in Europe of this kind, the HIT in Heidelberg and later to CNAO in Pavia, MIT in Marburg and MedAustron in Wiener Neustadt. FAIR, which is being constructed in Darmstadt, aims to explore the frontiers and propel biophysical and medical research on cancer treatment and to participate in developing a new generation of less-costly medical accelerators, making hadron therapy more accessible to the European population. Highlights of diversified biophysical research at FAIR are the novel combined use of particle therapy with immunotherapy and radio-genomics for patient selection and personalized medicine, which are an essential tool to support new therapeutic solutions. Ultra-fast dose delivery methods will extend ion therapy to moving organs (such as the lungs) and ultra-high dose rate (FLASH) irradiation. The latter as well as mini-beam radiotherapy (MBRT) need extensive pre-clinical testing. A further reinforcement of European collaboration in hadron therapy through the ENLIGHT network and other EU-funded projects will be highly beneficial. Radiobiological risk assessments for manned space mission is needed in order to assure good health conditions in deep space. Recently and as a reaction to the COVID-19 outbreak the computing facilities for large data processing and storage in high energy physics have successfully been used in the domain of **H&F** (e.g. vaccine development). Activities at CERN (HL-LHC) include not only CPU & Data Storage for particle physics but also open science/open source type platforms such as Zenodo. Synergies and closer collaboration with **H&F** RIs ECRIN ERIC and Euro-BioImaging should be developed in the future. In **ENE** domain, nuclear and particle beams are used in material research in studies of special membranes, nanotubes and radiation-hard electronics. There are strong synergies and interactions of **PSE** RIs FAIR and SPIRAL2 with **ENE** infrastructures MYRRHA and IFMIF-DONES. IFMIF-DONES and SPIRAL2 are planning to use high neutron flux in the energy range (1–20 MeV) for study of materials for fusion reactors and element-sensitive radiography with fast neutrons. CERN ISOLDE and MEDICIS, ILL, SPIRAL2 and the first phase of MYRRHA facilities study innovative isotopes for cancer diagnostics and therapy, such as alpha therapy and theragnostic.

See the **PSE Table** for an extended overview of the interconnections across domains established by those **PSE RIs** in Operation Phase or in advanced Preparation Phase.

CTA Cherenkov Telescope Array	DIGIT	**Open data resources and management for ground-based observatory for gamma-ray astronomy and opportunities for remote operation** Metadata and gamma-ray data openly available, after proprietary period. On-line data analysis tools for multi-messenger approach. Investigation of opportunities for remote operation.
	ENV	**Cherenkov Telescope Array for environmental studies** Environmental characterization of several CTA candidate sites. Opportunity for detailed aerosol measurements in Chile and La Palma.
	SCI	**Cherenkov Telescope Array in social and cultural sciences** Global collaboration: example of World Observatory. Social and cultural aspects of stimulating young people to choose career paths in science and technology in compliance with innovative society challenge.
ELI ERIC Extreme Light Infrastructure	DIGIT	**Open data resources and management for investigation of light-matter interactions** Metadata and data on extremely powerful laser sources, atto-second pulses, nuclear spectroscopy and particle acceleration by the intense optical field.
	ENE	**High-intensity and short-time light pulses impact on the research of fusion technologies** Development of alternatives of fusion technologies by inertial confinement, characterization of the plasma.
	ENE	**High-intensity and-short-time light pulses impact on the research of photovoltaic process** Ultrafast laser facilities with very fine time resolution to unravel obstacles in the photo-generation cycle.
	ENV	**High-intensity and-short time light pulses impact on the future materials for low power electronics** Ultrafast laser and attosecond laser to study new materials for low power electronics.

	ENV	**High-intensity and short-time light pulses impact on the study of plastic degradation and household waste** Determination of plastic degradation products by laser spectroscopy. Laser-based spectroscopic techniques for multimodal analysis of household waste for better recycling.
	H&F	**Opportunity for better understanding and treatment of diseases** High-resolution imaging of biological structures occurring in cancer at a macroscopic level to be addressed by novel laser sources.
	H&F	**Opportunity for better understanding and treatment of diseases** Enhanced tumour control and reduced side effects, in particular optimised proton and heavy-ion therapy plants and innovative laser-driven particle sources.
	SCI	**Intense and coherent light sources with different time structure for social and cultural sciences** Spectroscopy, imaging: analysis of samples of the cultural and natural heritage.
ELT Extremely Large Telescope	DIGIT	**Open data resources and management for ground-based astronomy and opportunities for remote operation** Metadata and astronomy data openly available, after proprietary period. On-line data analysis tools for multi-messenger approach. Investigation of opportunities for remote operation
	H&F	**Opportunity for application of imaging technologies in health and food** Extremely Large Telescope at the forefront of research for image processing with application potential in medicine and biology.
	SCI	**Estremely Large Telescope in social and cultural sciences** Global collaboration: example of World Laboratory. Social and cultural aspects of stimulating young people to choose career paths in science and technology in compliance with innovative society challenge.
EMFL European Magnetic Field Laboratory	ENE	**High magnetic field facilities in energy materials** Development and optimization of energy materials and components; experiments on materials behaviour in extreme magnetic fields.
	ENE	**High magnetic field facilities in energy materials** High magnetic fields as key to understand and tailor the quantum nature of the photovoltaic process. Probes of the fundamental properties of next-generation materials for low power electronics.
	ENV	**High magnetic field facilities with impact to environmental sciences** Studies of morphological, structural, optical and photocatalytic properties, e.g. in nanocomposite thin films in photocatalysts for new materials for sustainable processes.
	ENV	**High magnetic field facilities with impact to environmental sciences** Developing techniques such as magnetic-density separation with potential for effective solutions for optimized recycling.
	H&F	**High magnetic field facilities in new and high precision imaging techniques for health and food** Development and optimization of new technologies for magnetic resonance under extreme magnetic fields for medical imaging and diagnostic.
	H&F	**High magnetic field facilities in new and high precision imaging techniques for health and food** NMR high field-high frequency for protein crystallography and structural biology. Basic research on high-energy magnetic fields to indicate potential of the use of magnetic fields as external stimuli to be promising new venue for targeted *in vivo* drug delivery.
ESRF EBS European Synchrotron Radiation Facility Extremely Brilliant Source	DIGIT	**Open data resources and management for synchrotron radiation facility** Large sets of metadata and data on physics, chemistry, material science, life sciences, heritage science, palaeontology, nanotechnology, engineering; data analysis tools.
	ENE	**Synchrotron radiation facility in energy materials** Development and optimization of energy materials and components: analysis of materials in extreme conditions and *in operando* conditions.
	ENE	**Synchrotron radiation facility in energy materials** Advanced material characterization for battery cells with X-rays. Help understanding the underlying physical processes of low power electronics and to design working devices.

	ENV	**Synchrotron radiation facility in spectroscopy and analysis of contaminant components** Reflectometry on the interactions on contaminants in the atmosphere and liquid systems. Detailed determination of degradation of plastic products rays including studies for optimization of recycling.
	H&F	**Synchrotron radiation facility in heath and food** Protein crystallography and spectroscopy; high resolution structural biology, X-ray imaging, mammography, drug development, detailed imaging of biological tissues, high dose FLASH therapy.
	SCI	**Synchrotron radiation facility in social and cultural sciences** Materials structure, spectroscopy, imaging: analysis of samples of the cultural and natural heritage.
European Spallation Source ERIC European Spallation Source	DIGIT	**Open data resources and management for neutron science and technology** Large sets of metadata of physics, chemistry, material science, life sciences, heritage science, palaeontology, nanotechnology, engineering; data analysis tools.
	ENE	**Spallation neutron source for energy materials** Development and optimization of energy materials and components: analysis of materials in extreme conditions and *in operando* conditions such e.g. probing advanced materials characterisation for future batteries and low power electronics.
	ENV	**High flux neutron beams facility in spectroscopy and analysis of contaminant components** Reflectometry on the interactions on contaminants in the atmosphere and liquid systems. Neutron scattering as information on the early stages of ice cloud formation.
	ENV	**High flux neutron beams facility in spectroscopy and analysis of contaminant components** Investigation of properties of photocatalysts for cleaning at the atomic scale. The neutron tomography with potential to bring new information in the field of agronomy – water migration in soils, monitoring of root development, etc.
	H&F	**Spallation neutron source in heath and food** Protein crystallography and spectroscopy: high resolution structural biology, microscopy, spectroscopy. Fundamental role in the development of nanoparticles for drugs.
	H&F	**Spallation neutron source in heath and food** Analytical imaging approaches of cancer tissues with high spatial resolutions. Studies of foods to understand their behaviour and evolution (egg white, meat under cooking, champagne bubbles, etc.).
	SCI	**Spallation neutron source in social and cultural sciences** Materials structure, spectroscopy, imaging: analysis of samples of the cultural and natural heritage.
EST European Solar Telescope	DIGIT	**Open data resources and management for large-aperture solar telescope observations and opportunities for remote operation** Metadata and astronomy data openly available, after proprietary period. Investigation of opportunities for remote operation.
	ENE	**Large-aperture solar telescope observations in energy** Sun observations for the understanding of auroras and other reflections of magnetic phenomena on Earth.
	ENE	**Large-aperture solar telescope observations in energy** Dedicated studies of geomagnetic storms for risk management concerning overloading of energy lines. Energetic particles and radiation released from the Sun and their relation to risk of satellite damage and excessive radiation exposure of space crews.
	ENE	**Large-aperture solar telescope observations in energy** Energetic and magneto-hydrodynamic processes in the solar atmosphere as complementary, natural space laboratory for nuclear fusion research.
	ENV	**Large-aperture solar telescope observations on environmental sciences** Opportunity for dedicated research activity aiming to understand the links between the solar output and the Earth's climate. Study of solar influence on the Earth's climate in long term (e.g. Maunder minimum and global cooling); possible link with studies on long-term ecosystem research.

European XFEL
European X-Ray Free Electron Laser Facility

DIGIT

Open data resources and management for X-ray Free Electron Laser radiation facility
Large sets of metadata and data on physics, chemistry, material science, life sciences, heritage science, palaeontology, nanotechnology, engineering; data analysis tools.

ENE

X-ray Free Electron Laser facility in energy processes and materials
Development and Optimization of Energy Materials and Components: analysis of materials in extreme conditions and *in operando* conditions, time resolved methods.

ENV

X-ray Free Electron Laser facility in environmental sciences
XFEL to study molecular mechanisms of catalysts reactions. Improving the development of better and more environment-friendly catalysts.

H&F

X-ray Free Electron Laser facility in heath and food
Protein crystallography and spectroscopy: single-protein X-ray diffraction, time resolved spectroscopy

FAIR
Facility for Antiproton and Ion Research

DIGIT

Big data management and high through computing analysis for exotic nuclear reactions
Large sets of metadata and data on nuclear physics, instable isotopes, nuclear spectroscopy and particle acceleration; data analysis tools.

DIGIT

Big data management and high-through computing analysis for exotic nuclear reactions
Development of digital technologies for competitiveness and fit for the Green Deal in an innovative energy-efficient and sustainable Data Centre. Uptake of Artificial Intelligence, High Performance Computing (HPC), Cybersecurity as well as Advanced Digital Skills.

ENE

Nuclear physics in energy materials
Development and Optimization of Energy Materials and Components. Development of battery components by ion-track technology (e.g. separators electrodes). Development of nanostructured catalysts (by ion-track technology). Development of thermoelectric materials and of membranes.

ENV

Nuclear physics in environmental sciences
Detection of radiation for the environmental survey. Earthquake precursor detection with nuclear techniques. Innovative energy-efficient and sustainable Data Centre for the benefit of environment.

H&F

Nuclear physics in health and food
Participation in research programs for radiobiology and medicine dedicated to hadron therapy. Development of a new method for the use of radioactive ion beams (beta+ emitters) in charged particle therapy for simulations, treatment and visualization of solid tumours, including online imaging.

H&F

Nuclear physics in health and food
Artificial Intelligence methods for treatment planning (4D).
Space research and radio-biological risk assessments for manned space missions, to assure health in deep space.

HL-LHC
High-Luminosity Large Hadron Collider

DIGIT

Big data management and high through computing analysis for large hadron collider
GRID and cloud management of data analysis and storage.
Open science/open source type platforms such as Zenodo as recently used for sharing of data regarding urgent research (COVID19).

ENE

Large hadron collider in energy projects
Sharing of technologies between HL-LHC and projects in energy.

H&F

Large hadron collider in health and food
Developing accelerators and radio-isotope for medical treatments.
Involvement in hadron therapy projects trough developing relevant technologies.

SCI

Large hadron collider in social and cultural sciences
Global collaboration: example of World Laboratory.
Social and cultural aspects of stimulating young people to choose career paths in science and technology in compliance with innovative society challenge.

ILL Institut Max von Laue - Paul Langevin	DIGIT	**Open data resources and management for neutron science and technology** Large sets of metadata of physics, chemistry, material science, life sciences, heritage science, palaeontology, nanotechnology, engineering; data analysis tools.
	ENE	**Neutron science and technology in energy materials** Development and optimization of energy materials and components: analysis of materials in extreme conditions and *in operando* conditions such e.g. probing advanced materials characterisation for future batteries and low power electronics.
	ENV	**High flux neutron beams facility in spectroscopy and analysis of contaminant components** Reflectometry on the interactions on contaminants in the atmosphere and liquid systems. Neutron scattering as information on the early stages of ice cloud formation.
	ENV	**High flux neutron beams facility in spectroscopy and analysis of contaminant components** Investigation of properties of photocatalysts for cleaning at the atomic scale. The neutron tomography with potential to bring new information in the field of agronomy – water migration in soils, monitoring of root development, etc.
	H&F	**Neutron science and technology in health and food** Protein crystallography and spectroscopy: high resolution structural biology, microscopy, spectroscopy. Contribution to research of innovative isotopes for cancer diagnostics and therapy. Fundamental role in the development of nanoparticles for drugs.
	H&F	**Neutron science and technology in health and food** Analytical imaging approaches of cancer tissues with high spatial resolutions. Studies of foods to understand their behaviour and evolution (egg white, meat under cooking, champagne bubbles, etc.).
	SCI	**Neutron science and technology in social and cultural sciences** Materials structure, spectroscopy, imaging: analysis of samples of the cultural and natural heritage.
KM3NeT 2.0 KM3 Neutrino Telescope 2.0	DIGIT	**Open data resources and management for under water observatory for neutrino and high energy particle detection and opportunities for remote operation** Metadata and neutrino detection data openly available, after proprietary period. On-line data analysis tools for multi-messenger approach. Investigation of opportunities for remote operation.
	ENV	**Neutrino telescope in environmental sciences** Deep-sea technology and science: measurement of water optical and oceanographic properties, behaviour of bioluminescent organisms; measurement of sea currents, and identification of acoustic noise sources.
SKAO Square Kilometre Array Observatory	DIGIT	**Big data management and high through computing analysis for radio-astronomy telescope and opportunities for remote operation** Very large datasets, curation, storage and access. On-line data analysis tools for multi-messenger approach. Investigation of opportunities for remote operation.
	ENV	**Square Kilometre Array Observatory for environmental sciences** Development of seismic application of LOFAR (SKA pathfinder), to continuously monitor the Earth's subsurface with seismic-vibration sensors. Geodesic research and Space Weather applications.
	H&F	**Square Kilometre Array Observatory for health and food** Development of LOFAR_Argo pioneering measurements of the micro-climate in potato crops using LOFAR antennas and mote sensors.
	SCI	**Square Kilometre Array Observatory in social and cultural sciences** Social and cultural aspects of stimulating young people to choose career paths in science and technology in compliance with innovative society challenge.
SPIRAL2 Système de Production d'Ions Radioactifs en Ligne de 2e génération	DIGIT	**Big data management and high through computing analysis for exotic nuclear reactions** Large sets of metadata and data on nuclear physics, instable isotopes, nuclear spectroscopy and particle acceleration; data analysis tools.
	ENE	**Nuclear physics in energy materials Development and Optimization of Energy Materials and Components** Complementarity to approaches to projects in energy studying nuclei far from stability and research of fundamental interactions and symmetries with nuclear probes.
	H&F	**SPIRAL for health and food** Participation in the research programs in radio-biology and medicine dedicated for optimization of hadron-therapy protocols. Contribution to research of innovative isotopes for cancer diagnostics and therapy.

SOCIAL & CULTURAL INNOVATION

Over the past years, it has become evident that for addressing climate change, environmental sustainability, energy transition, migration management, health promotion and disease prevention, data about social behaviour and cultural practices (past and present) is indispensable alongside with the recognition of the importance of ethical, legal, and societal issues. Consequently, the cross-cutting essence of **SCI** data is recognized more and more in order to ensure the essential active support from society to successfully introduce and deploy new technologies that are being developed to provide solutions for some of the main challenges of our time.

The importance of social and cultural data as reflection, illustration and contextualisation of global societal and cultural dynamics has become obvious. However, whilst some data, e.g. from astronomy and physics, but also certain medical data can be collected by large tools and machines, social and cultural data – and for that matter also health and ecological data – can typically only be collected via more labour-intensive processes and require expert knowledge from social sciences and humanities to analyse, link and enrich them.

The value of linking data from different domains to social and cultural data has been permeating in many domains of research. This has resulted in intensifying interconnections and collaborations between the **SCI** RIs and the RIs in the **ENE**, **ENV**, **H&F** and **DIGIT** and has led to active participation of SSH in such (joint) infrastructure projects as EOSC, ENRESSH, SSHOC, EURISE, as well as the RIs CERIC ERIC, ICOS ERIC, EATRIS ERIC, ELIXIR, eLTER RI and LifeWatch ERIC. Furthermore, it has intensified the importance of the promotion of metadata interoperability and management and linking of open data resources, data archives and digital preservation, of catalogues for software tools and services to provide trustworthy, sustainable, and efficient preservation of data and metadata harvesting from Service Providers and other sources. To that direction and including all the above is the cooperation of CESSDA ERIC, CLARIN ERIC and DARIAH ERIC with other domains.

In addition, **SCI** RIs produce new methods of intelligent information mining and text and multimedia analyses that are useful for all sciences and beyond, in industry and society. CESSDA ERIC, CLARIN ERIC and DARIAH ERIC have established the EURISE[7] network on software quality in which INSTRUCT ERIC might also join.

7. EURISE Network
https://eurise-network.github.io/

Furthermore, CLARIN tools may be used by any discipline in all six domains – **DIGIT**, **ENE**, **ENE**, **H&F**, **PSE** and **SCI** – and also beyond to analyse language text, e.g. identify keywords, classify the communication style, detect misinformation, discover patterns of authorship and allow innovative ways of analyzing massive amounts of research results as available in text and speech to inspire new solutions and new research questions.

The emergence of Big Data in social and cultural domains is expected to generate new means for observing political or cultural reality and producing societal knowledge essential for making the "project" Europe a success and to cope with ever increasing globalisation and digitalization. ESS ERIC Round 10 includes a module on Digital Social Contacts, looking at the impact the major changes in communication digitalization is having both in work and family life. CLARIN ERIC has produced tools to help analyse such data and e.g. provided harmonized collections of open access to parliamentary data in multiple languages to enable comparative studies of public debate on certain topics. There is further epistemological potential in merging survey data on political attitudes and big social data that could provide new insights into the functioning of the democratic system that has found itself under the surge of populism.

Health, economic and social status are vital for the societal sustainability and they emerge from complex interactions over the entire life course. Taken this under consideration, SHARE ERIC links socio-economic data to bio-medical data (**H&F**). It includes data such as grip strength, walking speed, peak flow, and blood-samples, as well as self-reported weight and height of the respondents, and links these with data from genomics, blood analyses, biomarkers and other administrative records. SHARE also collects data on cognitive abilities e.g. on the proficiency in, and the use of, digital resources, from actual IT use at the workplace and at home to eHealth and eCare. There is significant potential at the pan-European level to link a range of biomedical, health and socio-economic data resources between SHARE and ELIXIR.

Some other example of successful collaboration can be found between DARIAH ERIC and CERIC ERIC (**PSE**) with E-RIHS on providing game changer in heritage science.

Smart solutions and artificial intelligence in particular are in the cross-section of the **SCI** domain and **ENE**, **ENV**, **DIGIT** and **PSE**. This includes technologies behind carbon neutral cities, smart (digital) buildings, smart cities, smart factories, sustainable transport and traffic, sustainable construction, etc. All these areas generate large amounts of new types of social data such as spatial data, traffic data, sensors data (photonics), and also consumerism and financial data. Interactions between **SCI** and these domains (**PSE**, **DIGIT**, **ENV**) and linkage of their data could focus on examining the effects of these technological solutions on human behaviour, attitudes towards them, exploring and predicting social consequences and ethical issues.

As mentioned earlier, Natural Language Processing and (Deep) Machine Learning are continually evolving fields, and humanities research that employs tools from these disciplines, including what is also called Artificial Intelligence, presents new and interesting challenges. However, it is important that humanities and social sciences also feed back into the **DIGIT** field, so that Artificial Intelligence is developed in a balanced way taking human aspects into account.

See the **SCI Table** for an extended overview of the interconnections across domains established by those **SCI RIs** in Operation Phase or in advanced Preparation Phase.

CESSDA ERIC Consortium of European Social Science Data Archives	DIGIT	**Open data tools and services for European social science data archives** Data catalogue for software tools and services to provide trustworthy, sustainable, and efficient preservation of data; metadata harvesting from Service Providers and other sources.
	ENE	**European social science data archives for energy** Datasets providing detailed evidence about human behaviour with respect to energy issues and policies.
	ENV	**European social science data archives for environment** Datasets providing detailed evidence about a wide variety of environmental topics: attitude surveys towards environmental questions to energy and fuel, environment conservation, land use, pollution, behaviour, ocean and climates. Geographical coverage.
CLARIN ERIC Common Language Resources and Technology Infrastructure	DIGIT	**Open data tools and services for common language resources** Tools and services for the depositing, discovery, access and processing of open multiple language resources from the humanities, social sciences and beyond – e.g. corpora, lexica, audio and video recordings, annotations, grammars, etc. Language tools for development of Artificial Intelligence.
	ENE	**Common language resources and technology for energy** Datasets providing detailed evidence about human behaviour with respect to energy issues and policies.
	H&F	**Common language resources and technology for health and food** Datasets providing detailed evidence about human behaviour with respect to health and food issues and policies. Language tools for investigation of H&F texts. Datasets reflecting language acquisition and attrition process and language and speech problems.
DARIAH ERIC Digital Research Infrastructure for the Arts and Humanities	DIGIT	**Open data tools and services for digital arts and humanities** Integration of national digital arts and humanities initiatives. Platforms for data sharing and digital publishing alongside technical systems for persistent identification, authentication and long-term preservation.
	ENE	**Digital arts and humanities for energy transition** Data sets providing detailed evidence about cultural practices with respect to energy issues and policies.
	ENV	**Digital arts and humanities for climate change** Historical data on cultural practices in e.g. building and expanding cities, agricultural practices etc affecting climate change.
	H&F	**Digital arts and humanities for health and food** Datasets providing detailed evidence about and contextualisation of human cultural practices with respect to health and food issues and policies.
E-RIHS European Research Infrastructure for Heritage Science	DIGIT	**Open data tools and services for cultural heritage** Virtual access to data and tools for heritage research; searchable registries of multidimensional images, analytical data and documentation from large academic as well as research and heritage institutions.
	ENV	**Environmental sciences for cultural heritage** Measurement of key atmospheric parameters, air pollution impact on cultural heritage.
	PSE	**New technologies and approaches for cultural heritage** Analytical tools used directly in cultural heritage, better understanding of artefacts and insights into preservation. Further development of analytical tools for materials structure, spectroscopy and imaging.

EHRI European Holocaust Research Infrastructures	DIGIT	**Open data, tools and services for Holocaust research** Tools and services for the integration, enhancement, discovery, access, analysis and publication of dispersed archival data relating to the Holocaust. Virtual and physical access to archival data and provision of open platforms for data sharing and publishing.
	H&F	**Historical data on health and food** Datasets providing detailed evidence about health and food related issues and practices in conflict societies, particularly during World War II.
ESS ERIC European Social Survey	DIGIT	**Open data tools and services for cross national survey data** Modern digital technologies for efficient extraction and measurement of media context to perform event coding in a (semi-) automatic manner; software solutions to retrieve information from the web. Big data analysis from social media is also another major development.
	ENE	**Cross national survey data for energy** Datasets providing detailed evidence about human behaviour with respect to energy issues and policies.
	ENV	**Cross national survey data for environmental sciences** Common studies on behaviour related to climate change and how it impacts on human well-being. Citizens' perception of environment and air/water/food pollution.
	H&F	**Cross national survey data for health and food** Use of surveys in the healthy population in biomedical life course studies and ageing, and in complex disease studies, e.g. obesity and food demand and consumption, or examining causes and effects of infection with SARS-CoV-2.
SHARE ERIC Survey of Health, Ageing and Retirement in Europe	DIGIT	**Open data tools and services for social survey data** Innovative software for electronic survey operations, including designing and translating questionnaires, administering them to respondents, monitoring fieldwork and creating databases.
	DIGIT	**Collecting data on cognition** Examining the interactions of bio-medical and socio-economic conditions over the life course, affecting cognitive abilities that are closely linked to proficiency in, and the use of, digital resources.
	ENV	**Social survey data for environmental sciences** Survey studies on how climate change, pollution and extreme events impact on human life.
	H&F	**Social survey data for health and food** Connecting surveys to health and food data. Use of surveys in the healthy population in biomedical life course studies and ageing, and in complex disease studies, e.g. obesity and food demand and consumption.

CONCLUDING REMARKS

This section clearly shows the importance that the RIs attach to the interconnections between all ESFRI domains. In spite of the diversity of the six domains and the variety of RIs in the ESFRI portfolio, the research approach within the RIs is definitely interdisciplinary and complementary. All RIs have to a different extent interconnection with other RIs in different scientific fields which is shown either through their research methodology, technological approach, data linkage, or through the impact of their R&D within other domains. This positive achievement should be encouraged and evaluated. A continuous evaluation is indeed necessary since the different RIs are in different phases of preparation, construction or exploitation and possibility of collaboration between RIs in the same domains, between RIs of different domains or ESFRI RIs and international, European and national RIs will have different nature and framework.

We also would like to notice the ENRIITC Consortium, which brings together presently 11 actors among which EMSO ERIC (**ENV**), EATRIS ERIC (**H&F**), ESRF and ESS ERIC (**PSE**), and CLARIN ERIC (**SCI**). This consortium brings together actors from industry and RIs and can have important socio-economic impacts. It is also a forum for RIs to exchange experience and good practices.

Finally, it is worth stressing that concerning possible new collaboration between domains, Artificial Intelligence is identified as an important domain that is shared between the domain of **DIGIT** and most other domains, and for which stronger collaboration should be developed in the future.

PART2

LANDSCAPE ANALYSIS

SECTION3

RELEVANCE & IMPACT

The Section 3 of the Landscape Analysis focuses on the Research Infrastructure services and their broader impacts, describing not what the landscape is, but what it can do. As it is not feasible to demonstrate comprehensively in such a document the broad range of impact areas where Research Infrastructures make a relevant contribution, this section has been developed in the form of selected examples.

The following impact areas are addressed:

150 ESFRI ESFRI RIs FOR SUSTAINABLE DEVELOPMENT GOALS
155 ESFRI RIs IN RESPONSE TO EMERGENCIES
158 ESFRI RIs FOR DIGITAL TRANSFORMATION

ESFRI RIs FOR SUSTAINABLE DEVELOPMENT GOALS

ESFRI reflects in its White Paper that the European landscape of Research Infrastructures addresses the overall objectives of the new European Research Area (ERA) and is being constantly optimised producing new science to tackle new societal challenges and to contribute to the global Sustainable Development Goals (SDGs). The SDGs have become the world's shared framework for sustainable development and call for actions by all the actors of the society, including science and research. A holistic framework for action that reduces the complexity and encompasses the 17 SDGs and their 169 Targets was suggested by the UN Sustainable Development Solutions Network in the paper Six transformations to achieve the Sustainable Development Goals published in the journal Nature Sustainability in August 2019[1].

These six SDG Transformations are suggested as modular building-blocks of SDG achievement: (1) education, gender and inequality; (2) health, well-being and demography; (3) energy decarbonisation and sustainable industry; (4) sustainable food, land, water and oceans; (5) sustainable cities and communities; and (6) digital revolution for sustainable development.

The impact of the ESFRI Research Infrastructures reaches all these six transformations. ESFRI Research Infrastructures cover most scientific fields, from Social Sciences & Humanities via Health & Food and Environment to Energy and Physical Sciences & Engineering, and thanks to synergies and interdisciplinary research, they generate knowledge and impact in all these fields including the interface between different disciplines. This is why, by using synergistically their capacities from all scientific fields, ESFRI Research Infrastructures have high potential to address complex phenomena like grand societal and scientific challenges – e.g. climate change, population increase and differential ageing, food and energy sustainability. Of the identified 17 SDGs, all of them are addressed by the European Research Infrastructures, and are linked directly or indirectly to the research conducted within them. Therefore, following the Transformations approach described earlier, which identifies synergies in the sustainable development pathways, this chapter focuses on inter-relationships and multiple benefits which ESFRI Research Infrastructures provide in achievement of strongly interdependent SDGs. Keeping in mind that the SDGs can be addressed in parallel in several transformations, only the most relevant SDGs and contributions of Research Infrastructures will be highlighted in this Chapter. It is also important to mention that the transversal SDGs (16) Peace, Justice, and Strong Institutions and (17) Partnerships for the Goals, and the Research Infrastructures' input for their achievements are considered in articulation with all the transformations and are applicable to all the Research Infrastructures in all scientific fields. Therefore, in order to make the overview of the contributions of the Research Infrastructures to the achievements of the SDGs systematised and structured, the relevant SDGs will be presented in this Chapter in the following way:

Transformation 1: education, gender and inequality
SDG (1) No Poverty, (4) Quality Education, (5) Gender Equality, (8) Decent Work and Economic Growth, (10) Reducing Inequalities

Transformation 2: health, well-being and demography
SDGs (2) Zero Hunger, (3) Good Health and Well-being

Transformation 3: energy decarbonization and sustainable industry
SDGs (7) Affordable and Clean Energy

Transformation 4: sustainable food, land, water and oceans
SDGs (6) Clean Water and Sanitation, (13) Climate Action, (14) Life Below Water, (15) Life On Land

Transformation 5: sustainable cities and communities
SDGs (11) Sustainable Cities and Communities, (12) Responsible Consumption and Production

Transformation 6: digital revolution for sustainable development
SDGs (9) Industry, Innovation and Infrastructure

Transversal SDGs
(16) Peace, Justice, and Strong Institutions, (17) Partnerships for the Goals

1. Six Transformations to achieve the Sustainable Development Goals. Sachs, J.D., Schmidt-Traub, G., Mazzucato, M. et al. Nat Sustain 2, 805–814 (2019) https://www.nature.com/articles/s41893-019-0352-9?proof=t

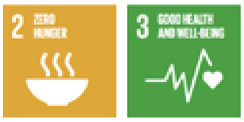
TRANSFORMATION 1
EDUCATION, GENDER AND INEQUALITY

ESFRI Research Infrastructures from all the research fields are strongly supporting the implementation of these SDGs and promote through their organization education, gender equality, and lower inequalities thus contributing to economic growth and elimination of extreme poverty. All ESFRI Research Infrastructures, along with running programs for training students and professional researchers, propose multiple education programmes, very often focused on school-age children, as well as teacher training programs at regional, national, and international levels. ESFRI Research Infrastructures put in their recruitment strategies the objective of gender balance and support all the initiatives which aim at reducing inequalities (e.g. working with refugees and people with disabilities). The Social Science domain has been selected here to illustrate remarkable contributions to this group of SDGs within *Transformation 1*.

CLARIN ERIC contributes directly to SDGs (4), (5) and (8) with its language resources which provide an easy-to-use infrastructure with digital artefacts and contribute to increasing the number of adults with relevant skills for decent jobs and digital literacy; online availability of these artefacts contributes to equal access, including people with disabilities. CLARIN datasets can be used to develop and evaluate Machine Translation or Automatic Text Simplification technologies, which can contribute to the promotion of secure working environments for migrant workers, and to the promotion of tourism, local culture and products.

The **European Social Survey ERIC** addresses all of these SDGs (1), (4), (5), (8), (10) not only tapping them individually but allowing cross domain and often across time analysis. ESS includes detailed measurement of highest level of education assessed in relation to a wide variety of other outcomes from health, well-being or economic inequality. ESS allows gender analysis of all of its data and in 2023 will include its first dedicated module on the topic 'Gender in Contemporary Europe: Rethinking Equality and the Backlash'. The module will measure five dimensions: identity, sexism, experiences, salience and policy instruments.

TRANSFORMATION 2
HEALTH, WELL-BEING AND DEMOGRAPHY



These SDGs can be achieved within *Transformation 2* and key investments in health and well-being. The Research Infrastructures in the field of biology and health are the most natural supporters of this group of SDGs.

MIRRI can contribute to deliver the impacts of the SDG (3), mostly on tackling epidemics of major communicable diseases by performing research on pathogenic microorganisms and human infectious diseases. It also develops new (bio)pharmaceuticals/therapeutic solutions, including antimicrobials, vaccines, phage therapies and microbiome therapeutics. By collaborating on the research and development of new, safe and healthy food products, or on delivering resources and methods for biological management of soils and crops, MIRRI can contribute to promoting sustainable food production systems and access to safe, nutritious and sufficient food.

EATRIS ERIC, which mission is to accelerate the translation of scientific discoveries into patient benefit, contributes directly to the SDG (3). EATRIS supports early stages of health and medicines research where the risk of failure to reach the patient is particularly high and where there is a crucial need for cross-sectoral and multi-disciplinary collaboration.

Euro-BioImaging ERIC is particularly well aligned with SDG (3), as its users are especially engaged in research that aims to elucidate mechanisms for cell regulation and survival, disease development and aging mechanisms, as well as diagnostics, and therapeutic intervention. Equally relevant is Euro-BioImaging's contribution to achieving SDG (2), as imaging of, for example, plant cells can provide important insight on nutritional composition, adaptation to extreme conditions, or phenotypic changes driven by genetic engineering.

ELIXIR contributes to SDG (2). Successful applications of bioinformatics to food production are used in farming and agriculture – e.g. crop and breeds development, pest and pathogen control – and are key to ensuring security of food supplies globally, including facing climate and environmental change. Bioinformatics applications are well recognised in the area of health, and range from disease diagnostic and prevention to epidemics preparedness and response, personalised medicine, and the development of new drugs and treatments.

INFRAFRONTIER contributes to Goal (3) particularly to the targets related to fighting pandemics and epidemics and non-communicable diseases, securing access to affordable medicines and vaccines and reduce the effects of hazardous environmental agents on health.

ESFRI Research Infrastructures from the domain of Environmental Sciences and Physics are also significant contributors to this group of SDGs.

ACTRIS brings elements that contribute to Goal (2). Capacity to forecast weather and weather extremes assist farmers to their operational decisions. In addition, tracking the deposition of specific compounds present in the particulate phase or gas phase, which have serious impacts on ecosystems' health, the quality of soils and waters and, directly or indirectly, on agricultural production. For ACTRIS better climate forecasting will be key to anticipate the key risks that climate poses to public health in particular countries and regions.

The technologies, know-how and scientific advances behind accelerator-based high-energy physics have historically produced numerous applications in medicine. The ultrafast and extremely brilliant X-ray pulses generated in fast succession by the **European XFEL** enable insight into the atomic structure of pathogenic viruses, bacteria, and their proteins in unprecedented detail. Structural data of pathogens relevant for infectious diseases and noncommunicable diseases such as cancer can inform the development of effective vaccines and medication. Scientists can also use the European XFEL to explore the dynamics of biological reactions, gaining information into, for example, how drug molecules interact with pathogens in order to develop strategies to circumvent antimicrobial resistance.

The development of new-generation superconducting magnets and other technologies in the framework of the **HL-LHC** project of CERN brings the potential of very relevant applications to imaging and facility for cancer therapy.

Examples can also be given for the domain of Social Sciences & Humanities.

DARIAH ERIC contributes to SDGs (2) and (3) providing an unprecedented data and methodological resource base for pursuing these questions, significantly supplementing existing resources for incorporating cultural and historical perspectives into research.

SHARE ERIC is the largest pan-European social science panel study providing internationally comparable longitudinal micro data which allows insights in the fields of public health and socio-economic living conditions of European individuals, both for scientists and policy makers.

The **European Social Survey ERIC** also contributes to SDG (3) providing a comprehensive comparative pan-European dataset on the social determinants of health and health inequalities including both physical and mental health, combining rich data on living conditions, with a variety of lifestyle factors and health outcomes.

TRANSFORMATION 3
ENERGY DECARBONISATION AND SUSTAINABLE INDUSTRY

This SDG can be achieved via *Transformation 3* ensuring universal access to modern energy sources, decarbonizing the energy system and reducing industrial pollution. The most relevant contributors to the implementation of this SDG are the Research Infrastructures from energy research field. The Research Infrastructures from the field of Social Sciences are important actors as well monitoring the societal attitude towards this issue.

MYRRHA will contribute in several manners to the international nuclear landscape and beyond and to SDG (7) by offering a solution for the elimination of nuclear waste by performing the transmutation of its very long-lived nuclear isotopes into short-lived ones and by providing a method for better utilisation of nuclear fuels.

EU-SOLARIS is focused on Concentrated Solar Power / Solar Thermal Electricity (CSP/STE). CSP/STE is a possible key future technology for the decarbonisation of the energy sector and the mitigation of the climate change through the reduction of greenhouse gas emissions from fossil fuels currently used to generate electricity. Each square metre of CSP mirror surface, for example, may be enough to avoid 200 to 300 kilograms of CO2/year.

The **European Social Survey ERIC** module on climate change and energy was designed to inform policy makers on the public component of the transition to a low-carbon Europe by making a systematic and detailed comparison of attitudes to climate change, energy security and energy preferences and to examine the relative importance of individual-motivational versus national-contextual variables in public energy preferences.

TRANSFORMATION 4
SUSTAINABLE FOOD, LAND, WATER AND OCEANS

These SDGs are aimed by *Transformation 4*. They focus on integrated strategies on sustainable environment, land-use and oceans healthy for people. The most relevant contributors to the implementation of these SDGs are the Research Infrastructures from the research fields of environment.

IAGOS has provided continuous measurements of greenhouse gases and short-lived climate forcers on the global scale over more than 25 years. Being relevant to SDG (15), with respect to their reference to Air Quality issues, IAGOS provides essential information on the composition of the atmosphere over different regions. IAGOS data contribute to the improvement of air quality models allowing monitoring and forecast, and assessment of mitigation scenarios. IAGOS participates in projects on the impact of aviation on climate, it can play an important role in helping aviation industry to develop along a more environmentally sustainable path.

ACTRIS and **ICOS ERIC** are also a good example of a pan-European Infrastructures particularly relevant to the SDG (13), where the community's challenge is to provide decision makers with the scientific analyses they need to adapt to climate change impacts and build climate resilience.

EURO-ARGO ERIC as part of Argo international network creates a full-depth, fully global, multi-disciplinary ocean/climate observing system to document the physical and biogeochemical ocean state and its evolution, including global ocean warming, sea level rise, acidification, deoxygenation, and the changing carbon cycle, significantly contributing to SDG (13).

EMBRC ERIC aims to answer fundamental questions regarding the health of oceanic ecosystems in a changing environment, support life-science breakthrough discoveries with the use of marine biological models, and continue long-term marine monitoring efforts. EMBRC ERIC is a driver in the development of blue biotechnologies, supporting both fundamental and applied research activities for sustainable solutions in the food, health, and environmental sectors.

TRANSFORMATION 5
SUSTAINABLE CITIES AND COMMUNITIES

These SDGs are in particular in focus of *Transformation 5* which strives for economically productive, socially inclusive and environmentally sustainable urban areas.

Helping planners to make cities more resilient to respond to heatwaves and associated impact on air quality, ACTRIS supports policies for air quality improvements.

EPOS ERIC, the European Plate Observing System, addresses SDG (11), contributing specifically to the indicator 11.b "By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030, holistic disaster risk management at all levels".

DARIAH ERIC Working Group on Digital Practices for the Study of Urban Heritage focuses on the study of digital methods and good practices of heritage and urban change, impact of urban development on cultural heritage as well as the identity of the city and the role of civil society. It reflects on the resilience of smart systems promoted today for user-personalization when interacting with city infrastructures.

TRANSFORMATION 6
DIGITAL REVOLUTION FOR SUSTAINABLE DEVELOPMENT

This SDG is aimed by *Transformation 6*, which focuses mainly on digital technologies and innovation. All the Research Infrastructures provide inputs to the digital transformation and the innovation-driven economy's growth, aligned with the European research and innovation strategy. A few examples from the domains of physics and medical research are given below to illustrate it, whereas a separate chapter which follows in this section treats particularly contribution of Research Infrastructures to digital transformation.

The research carried out at the **ILL** covers the full innovation cycle from fundamental research to technological application. The topic of materials for innovative and sustainable industry is relevant also for ESRF. The **ESRF EBS** is uniquely poised to support European industrial leadership on the circular economy and carbon-free life styles. Its unprecedented sensitivity and precision in advanced characterisation provides the researchers and industry with multiscale insight from the atomic to the macro scale into materials and products, as they are processed, as they age and are reused, fuelling the virtuous innovation cycle of materials making, characterising and modelling.

The **European Spallation Source ERIC** is working with more than 40 European partner institutions and more than 130 collaborating institutions worldwide under the in-kind model. With the in-kind model, partners supply equipment, design documentation, personnel or other services to support the construction of ESS. The model ensures that key technologies are cultivated and enhanced in member states supporting national institutes and industry thus fostering the European industry.

EATRIS ERIC has been leading the establishment of a global repurposing hub, whose aim it is to bring together global resources to collaborate and support high potential projects with high unmet medical need. EATRIS initiates and facilitates academia-industry collaborations between SME, large pharma and EATRIS member institutes. It supports the operations of Innovation Hubs, such as the EATRIS-GSK Imaging Hub, an international multi-site collaboration hub for the development of advanced imaging tools.

TRANSVERSAL SDGs

Number (16) and (17) are the SDGs relevant to all Research Infrastructures in all scientific fields. These SDGs seek to promote peaceful and inclusive societies. These goals are in the heart of all the Research Infrastructures which by nature are remarkable examples of pan-European cooperation, as highlighted in some of the contributions below.

ELT at ESO, as one of the first intergovernmental scientific organisations, created by a treaty between Member States, represents a model for peaceful scientific cooperation between nations. CERN is another international organisation which promotes scientific collaboration and the values of science across governments and other stakeholders. In particular, the **HL-LHC** is being carried out as an international project with participants from all over the world. Besides, a project like HL-LHC requires strong partnership with industry, with significant knowledge transfer from research to the private sector.

EMSO ERIC is another excellent example of partnerships for the goals. It strongly supports the participative and transformative principle that underpins the UN Decade of Ocean Science for Sustainable Development.

A significant part of data integrated into **CLARIN ERIC** comes from parliaments and other public institutions. By providing sustainable access to such data in structured, annotated and unaltered form, adapted for automatic processing (easily searchable and retrievable), CLARIN contributes to targets related to SDG (16).

This short insight into the inputs of the Research Infrastructures to the agenda of the sustainable development reflects the crucial issue that all the Sustainable Development Goals are relevant and that most of the Research Infrastructures contribute to the development of several SDGs at the same time and with a very high impact. The ESFRI Research Infrastructures have demonstrated to be important tools to achieve the transformations required to realize the United Nations' Sustainable Development Goals for a better and more sustainable future for all by 2030.

ESFRI RIs IN RESPONSE TO EMERGENCIES

EXAMPLES FROM THE COVID-19 CRISIS

ESFRI RIs demonstrated an enormous capacity to respond to the emergency represented by COVID-19 pandemics, by rapidly revising/adapting their access programmes operations and delivering their services, including *ad hoc* new services to support research related to COVID-19.

RIs in the health domain were at the forefront and immediately acted, being able to offer all the necessary services in the whole pipeline of vaccine and therapeutics development, for the research on diagnostic tools and the analysis of the direct and indirect impact of the crisis. To facilitate COVID-19 related research, fast-track access calls were issued and publicized through the RIs websites, which were continuously updated. The information was also promptly collected on the Life Sciences Research Infrastructures (LS RIs) website[2] providing the users community with a comprehensive set of available services and resources. ESFRI also gathered information on COVID-19 related activities on its website[3].

Open Science data were at the base of success stories since the current pandemic started – the genome of the SARS-CoV-2 virus was sequenced much quicker than for previous similar pathogens (such as MERS-CoV and Ebola) and deposited in the public domain. This allowed other scientists to start studying the virus and tracking its spread. Likewise, research data on the COVID-19 disease has been readily made available in the public domain, thereby helping our clinical understanding of its effects, and informing the development of treatments and tracking new variants of the virus through genomic sequencing and coordinated data-sharing efforts. **ELIXIR** has played a key role in mobilizing public data infrastructure to enable research data-sharing via the COVID-19 Data Portal[4], a single entry point that provides free and open access to viral sequence data and other relevant data including proteins, imaging, expression data and literature relating to COVID-19 and SARS-CoV-2. The establishment of the effort and connections across Europe to national-level initiatives has been supported through uplifts to the Horizon 2020 ELIXIR-CONVERGE and EOSC-Life projects resulting in the development of a set of services that include databases, analysis tools and workflows, resources to make COVID-19 data 'FAIR' and significant computing resources. At the European policy level, both the ERA Versus Corona Action Plan[5], and the HERA Incubator[6] programme have placed the European COVID-19 Data Platform at the centre of research data sharing efforts. The new HERA Incubator programme will indeed support the expansion of the COVID-19 Data Platform enabling Europe and scientists globally to respond better to other future pandemics and outbreaks of infectious disease as and when they occur.

Imaging technologies provided by **Euro-BioImaging ERIC** are powerful tools to study any infectious disease agent that might cause emergencies such as COVID-19 did. They are of key importance for studies on the structure and function of pathogens at the cellular level, to understand virus infection, binding, intracellular trafficking, replication, assembly, etc. They are also crucial in revealing how viruses affect the host cell physiology and how the virus-mediated disease condition may be targeted by drugs or other interventions. Imaging-related services are also needed in the discovery and development of new vaccines and virus-targeted drugs, e.g. imaging of immune cells to reveal binding of antibody components to viruses or viral replication inside the host cell. In the clinical field, PET-CT technologies allow imaging of the biodistribution of vaccines after administration. Image data services built on artificial intelligence and machine learning applications address the complexity of virus-mediated disease analysis, especially when combining advanced imaging data with cohort data and other large biomolecular datasets.

Structural biology technologies provided by **INSTRUCT ERIC** are central to the pharmaceutical field, in particular to determine the 3D structures of druggable proteins – and thus determine sites where small molecules might bind – or to characterize viral protein antigens or specific parts of them to unravel their interactions with human antibodies. Indeed, these technologies properly integrated produced the structural characterization of key proteins only weeks after the SARS-CoV-2 sequence was released. INSTRUCT ERIC X-ray, Cryo-EM and NMR centres have brought these technologies centre-stage in drug discovery and since then there is a strong commitment to prioritizing COVID-19 researches. INSTRUCT ERIC established also a Resource Centre with tools and information to assist research relating to SARS-CoV-2 and COVID-19.

2. Life Sciences Research Infrastructures (LS RIs)
https://lifescience-ri.eu/ls-ri-response-to-Covid-19.html

3. RIs against COVID-19 pandemic
www.esfri.eu/Covid-19

4. COVID-19 Data Portal
https://www.Covid19dataportal.org/

5. ERA Versus Corona Action Plan
https://ec.europa.eu/info/sites/default/files/covid-firsteravscorona_actions.pdf

6. HERA Incubator
https://ec.europa.eu/info/news/eu-invest-eu150-million-research-counter-coronavirus-variants-2021-feb-17_en

INFRAFRONTIER rapidly evolved a broad portfolio of services to evaluate the potential of new anti-COVID-19 compounds and therapeutics on suitable humanized models as well as BSL3 laboratories for *in vivo* testing, through which the compounds can proceed to clinical testing. INFRAFRONTIER has also launched a new service call to provide researchers access to test their innovative and novel COVID-19 therapeutics in a standardized infection pipeline that uses preclinical models developed to study COVID-19 infection and its pathophysiological consequences, including the complete characterization of genes critically involved in the infection and the effect of the new anti-viral compounds.

Drug repurposing activities and high-throughput screening assays services made available by **EU-OPENSCREEN ERIC** are key to identify candidate molecules for COVID-19 therapeutics and, to this end, a collection of about 2,500 bioactive molecules from EU-OPENSCREEN was tested. All chemical and biological data are made available in EU-OPENSCREEN open access *European Chemical Biology Database*[7] and the European COVID-19 Data Platform[4]. The EU-OPENSCREEN ERIC collection of about 1,000 fragments was used to identify novel binders to Nsp3, an essential component of the replication complex of the virus. Data for 24 compounds from the collection provided alternative starting points for the development of anti-COVID-19 therapeutics.

EATRIS ERIC provided to COVID-19 vaccine developers the *EATRIS COVID-19* Research Forum, quickly made publicly available and updated weekly, developed a self-test, which reached wide media coverage[8] and is working to develop and introduce to the market a nasal spray vaccine against COVID-19[9].

ECRIN ERIC rapidly provided informatics services to harvest information on any COVID-19 actions in the biomedical fields. Within the EOSC-Life project, ECRIN developed a secure and GDPR-compliant patient-level data pilot repository linked to the EU COVID-19 data portal, enabling COVID-19 trial data sharing, while participating in the VACCELERATE project[10] is contributing to the activities for future pandemic preparedness (HERA Incubator).

Specific role in the infection threads plays **ERINHA**, a pan-European Research Infrastructure dedicated to the study of high-consequence emerging and re-emerging pathogens. ERINHA offers access to a large range of high containment *in vitro* and *in vivo* capacities to facilitate a wide variety of studies on SARS-CoV-2/COVID-19 and coordinates joint RI European activities regarding the service to vanquish COVID-19 pandemics.

Besides RIs in Life Sciences, also other RIs provided specific services during the COVID-19 crisis.

According to UNESCO[11], the ocean can be an ally against COVID-19. Bacteria found in the deep sea are used to carry out rapid testing to detect the presence of COVID-19. Species found in the ocean offer an excellent promising future for pharmaceuticals. Years ago, research from the Woods Hole Oceanographic Institute identified microbes living in deep-sea hydrothermal vents harbour whose enzymes can be used in diagnostic tests, like those to detect the pandemics of AIDS and SARS. Their role has been revisited for COVID-19; they have been used to carry out rapid tests to detect the virus's presence. **EMSO ERIC** ecology and biodiversity services include developing samplers with other ERICs – **EMBRC ERIC**, **LifeWatch ERIC** – for DNA monitoring.

ACTRIS supported the authorities by securing the full documentation of atmospheric composition changes due to lockdowns in the various parts of Europe. The main goals were: i) to provide reliable estimates of effects of reduced emissions; ii) to open some atmospheric simulation chambers for testing protection gears such as face masks; iii) to support authorities by providing science-based analysis of current knowledge and finally; iv) to illustrate the complex interplay between emission restrictions and human behaviour, and the necessity for structural changes to reach the WHO air quality standards in Europe.

FAIR at GSI efforts have been providing new insights and new technologies that may help to fight the SARS-CoV-2 virus: i) ion radiation for vaccine development; ii) therapeutic effect of low-dose radiation in SARS-CoV-2 induced pneumonia; iii) Improved and fast virus detection with single nanopore membranes.

The biology laboratories of **European XFEL** joined DESY and its partners in the screening effort to find novel binding partners to inhibit two important SARS-CoV-2 proteins (main protease and papain-like protease) using drugs that are either already on the market for other diseases or in late clinical trials. In parallel, EuXFEL contributed to the international effort on COVID-19 research by preparing and supporting a variety of Covid-related experiments, utilizing liquid jet serial femtosecond X-ray crystallography (SFX) to investigate new structures and time-resolved SFX of COVID-19 proteins.

The particular contrast provided by neutron techniques by ILL helps scientists to determine how protein complexes function, as well as the specificity of protein interactions with membranes. Finally, neutron spectroscopy provides insight into the dynamics of the biological components, which may constitute the ultimate key to understanding their functionality.

SKAO played an active role in the COVID-19 pandemic response, with contributions spanning from managing the design and production of respiratory ventilators and 3D printing of Personal Protective Equipment to the development of educational online tools

7.
European Chemical Biology Database
https://ecbd.eu

8.
Gargling test: Czech Republic trials faster & cheaper way to check for coronavirus
https://www.youtube.com/watch?v=oOn3sQP9zlg

9.
University of Eastern Finland researchers introduce a nasal COVID-19 vaccine – Science Business, March 2021
https://sciencebusiness.net/network-updates/university-eastern-finland-researchers-introduce-nasal-Covid-19-vaccine

10.
VACCELERATE project
https://www.vaccelerate.eu

11.
COVID-19: the ocean, an ally against the virus
https://en.unesco.org/news/covid-19-ocean-ally-against-virus

to support home-schooling or contributing to a public information campaign to combat misinformation, just to mention a few.

Feasibility studies in the **ESRF Extremely Brilliant Source**, the world's first high-energy fourth-generation synchrotron, have already demonstrated it can resolve unprecedented detail revealing the damage caused by COVID-19 on human lungs, linking from the major airways all the way down to the finest micro-vasculature in an intact lung. promises to develop a transformational X-ray tomography technology that will enable the scanning of a whole human body with resolution of 25 microns, thinner than a human hair – tens of times the resolution of a CT scanner. Further, it can then zoom into local areas with cellular-level imaging, or one micron – over 100x better resolution than a CT scanner.

PRACE has made computing time available at short notice throughout Europe for projects in connection with COVID-19[12]. Thirty different projects ranging from molecular biology to epidemiology were computed.

Also, RIs in the Social Sciences domain acted promptly to assess the impact of the pandemic on the society at large. A special Corona questionnaire included in the **SHARE ERIC** targeted telephone interviews (Computer-Assisted-Telephone-Interview, CATI) from June to August 2020, brought to release the Wave 8 COVID-19 data in December 2020, available for researchers all over the world to examine the health, social, economic and environmental situation of European citizens and beyond against the background of the pandemic. A further wave of telephone interviews of the SHARE Corona survey has been conducted in 2021. This study is the ideal database to study the non-intended socio-economic and health consequences of the epidemiological containment decisions and the long-term effects of the COVID-19 pandemic.

In its 2020-2021 round, the **European Social Survey ERIC** added a dedicated COVID-19 module to its longitudinal questionnaire including a number of health indicators. Combined with its core questionnaire, the dataset will enable ample opportunities for pre-post analyses of the wider social, economic and political consequences of the SARS-CoV-2 pandemic, for examining the medium and long term effects of the pandemic across countries and social groups, and for comparing policy responses and their outcomes in terms of social inequalities and social cohesion. At the same time the pandemic highlighted the fragility of relying on face to face fieldwork for RIs like the ESS. An alternative method has been developed to ensure data collection in 2021 can proceed. The need for a permanent panel infrastructure, reaching respondents by web and other non in-person methods, was underlined.

In June 2020 **DARIAH ERIC** launched a call under its bi-annual DARIAH Theme funding scheme entitled 'Arts, Humanities and COVID-19'. Projects being submitted to this call are being asked to explore how DARIAH ERIC will collect, curate, preserve and interpret the heterogeneous record of the experience of life and work in early 2020. DARIAH will also look for innovative projects exploring humanities contributions to understanding the virus and its impacts, and what the study of culture, the arts, values, practices and language can contribute to our response to this global challenge.

Through extending the collection of parliamentary datasets with curated collections of recent parliamentary debates about the corona dynamics, the European Research Infrastructure for language resources **CLARIN ERIC** set the basis for comparative research into how public bodies have responded to the crisis across countries.

The COVID-19 pandemic has demonstrated the capacity of the ESFRI RIs to respond to emergencies providing specific services to support the science-led response to the COVID-19 outbreak and also the capacity in many cases to rapidly react and return to operate even during the lockdown period. The Covid crisis has massively accelerated some pre-existing trends, in particular digitalization. It has shaken the world, setting in motion a wide range of possible trajectories.

Perhaps the most important lesson learnt is that the ESFRI RIs ensure that research across all topics and areas can continue even during a big crisis. Not knowing where the next crisis may hit, the ESFRI RIs are preparing their research programme along all fronts including fundamental research trying to be ready to provide the necessary services to society.

12. PRACE Versus COVID-19: Actions & Activities
https://prace-ri.eu/hpc-access/hpcvsvirus/

ESFRI RIs FOR DIGITAL TRANSFORMATION

The digital transformation of Europe's economies and societies is accelerating. It is entering a next phase, where the technologies are gradually blurring the limits between the physical, digital and biological spheres and push the frontier of what computers are capable to do. These new technologies, progressively coming to maturity and impacting all sectors of our lives and of the economy, build on the use of data, and often require the critical mass of data, users and connected nodes to be viable.

ESFRI is an active actor of this European dynamics. As it was stated already in the ESFRI Roadmap 2018 (page 117), the pan-European e-Infrastructures for Networking, High-Performance Computing and High-Throughput Computing are already well-established and provide production services used by international research and Research Infrastructures projects.

The fundamental principles of Open Science form the basis of the European Open Science Cloud (EOSC) initiative which will offer researchers a virtual environment with open and seamless services for storage, management, analysis and re-use of research data, across borders and scientific disciplines by federating existing data infrastructures. EOSC will deploy a European Research Data Commons where data are findable, accessible, interoperable and reusable (FAIR), and also as open as possible.

CONTRIBUTION TO EOSC

All the ESFRI RIs are at the forefront of data science. As providers of thematic quality data and services, which are FAIR compliant or are working to reach this objective, they have been making significant contributions to the cultural change towards open/FAIR data, open science and innovation, which is a main underlying concept for EOSC. On the other hand, RIs and their communities as key consumers/users of EOSC data and services within and across scientific domains, they are central for EOSC development, quality and sustainability. The broader the federation of thematic RIs in EOSC and the uptake of EOSC generic (horizontal) services, the better the chances for EOSC to be sustained in the longer term. Research Infrastructures are thus central in the research lifecycle and in all the aspects of Open Science and FAIR data/services inside the European Research and Innovation Area.

These activities are supported at EU level within the EOSC cluster projects which support also their participation and inputs to the development of the European Open Science Cloud. There are five thematic cluster projects – ENVRI-FAIR, EOSC-Life, ESCAPE, PaNOSC, SSHOC – who coordinate their actions towards EOSC and who are core partners in the EOSC Future project. It will integrate the services developed in the cluster projects to EOSC, making them fully compatible and accessible to the entire EOSC eco-system. The five science clusters bring together 72 world-class Research Infrastructures from the ESFRI Roadmap and beyond. The coordinators of the science cluster projects meet regularly to discuss joint activities, exchange views on technology choices and debate how the outputs from the projects can be best sustained once the projects end. The current dynamic between the science clusters may lead to a long-term collaboration for cross-disciplinary open science.

It is therefore a great opportunity and in the benefit of all stakeholders, including ESFRI RIs, thematic clusters and EOSC to make the most out of this venture. The experience gathered by ESFRI, ESFRI RIs and the ESFRI Clusters should be utilized to the maximum extent in the EOSC implementation, especially in this current second phase, fully reflecting the engagement and responsibility of RIs in and for Open Science. EOSC highlights the potential of the RIs with their data, software and services and their broader potential impacts. The RIs participation in the development of the EOSC are therefore a particularly vivid example to the digital transformation in the research and innovation field.

OPEN SCIENCE

Most of the RIs on the ESFRI Roadmap are at the forefront of Open Science movement and make important contributions to the digital transformation by transforming the whole research process according to the Open Science paradigm. The Research Infrastructures guarantee the quality of data and enable the exploration and use of data and codes produced by their users which can be the source of a new approach to the research questions, or at least lead to a reduction in research times and costs. There exist although differences in the concrete implementation of Open Science by Research Infrastructures. These differences are specific to each scientific field. The methods of producing research data are very different depending on the field of research and may have developed before the concept of Open Science was adopted.

Astronomy has a long history of open sharing of data and scientific findings, allowing a cumulative development of knowledge about our Cosmos and supporting the achievement of the conditions for transparency and international cooperation in science. In the modern era, astronomy is at the forefront of digitalisation for Open Science. ESO was early leader in this regard, establishing an open-access ESO Science Archive and setting up cooperative partnerships with other Research Infrastructures to ensure interoperability.

CTA is working to build an EOSC for astronomy, Astroparticle & Particle Physics and its application for science projects, including also a science analysis platform where the science community can access and combine data and analysis software from multiple ESFRIs and stage it for innovate analysis workflows, e.g. to perform multi-messenger analysis and push the digital transformation. Open science, and specifically the ability to find, access, inter-operate, re-use both **SKAO** data and software, is at the heart of SKAO's software development culture and practices. The scientific return of a project at the scale of SKAO will only be maximised if the data products can be accessed by future users, to answer as yet unforeseen questions.

All the RIs from the environmental research field have a long tradition in providing open access to data. In particular, **ACTRIS**, **IAGOS**, **ICOS ERIC** and **EURO-ARGO ERIC** contribute with their data products to Copernicus, the European Union's Earth observation programme, which provides open data and services to benefit all European citizens.

EPOS ERIC provides: (a) a portal (Integrated Core Services-Central hub, ICS-C) integrating FAIRly digital assets from ~250 asset suppliers; (b) an appropriate governance, legal and financial framework tackling long-term sustainability to secure the assets and the ICS-C; (c) a suitable approach for sharing best practices among data providers, domain-specific geoscience organizations and EPOS ERIC. In EPOS assets represent data, scientific products, services and software for solid Earth science. The EPOS federated approach is aimed at engaging national and international Research Infrastructures to share data, making them accessible and usable.

In the health domain **ECRIN ERIC** has developed tools and services to optimise data management in clinical research. ECRIN developed a data centre certification programme based on about 100 criteria and 3-days site audits to ensure compliance with GCP, FDA and EU regulations. About 15 centres are currently certified in Europe, and the certification programme is now going global, with certified centres in Asia (two in Japan, one in Korea).

In the Social Sciences the principle of open science especially in relation to data access has been strong for many decades. The **European Social Survey ERIC** for example makes all of its data freely available without privileged access for non-commercial use around the world and has over 160,000 registered data users.

BIG DATA VOLUME

Research Infrastructures constitute a central actor for the production or processing of research data because the majority of them produce, manipulate, process and/or exchange data. The massive growth in demand for computing resources in recent years calls for a coherent and ambitious strategy at the levels of infrastructure capacity (networks, computing and processing, storage and archiving capacities), associated services, and more generally a rethinking of the place of research data.

User experiments at the **European XFEL** generate vast amounts of data in a very short period of time. The maximum burst data rate per scientific instrument that must be captured is currently 8 TB/s and translates, when operating scientific instruments in parallel, to a sustained data rate of over 40 GB/s. For a typical user experiment running over 6 days, this can lead to user datasets in excess of 1 PB. Together with the scientific user community, European XFEL is developing computational methods to efficiently analyse the data, both in real time and on the subsequently recorded data to derive meaningful scientific results.

The **HL-LHC** project presents unprecedented challenges in terms of data processing and storage. CERN operates a number of FAIR data related services that represent major contributions to EOSC, including access to petabytes of LHC experiments' data together with associated training material and software via the CERN Open Data Portal[13] according to a published open data policy[14].

An important activity is currently being kicked off in **ESRF** for developing data compression algorithms. This is of high interest to all photon sources because all of them are confronted with a steady increase of the data produced by fast high-resolution detectors.

In the health scientific domain, over the last

13. CERN Open Data Portal
http://opendata.cern.ch/

14. CERN Open Data Policy for the LHC Experiments
http://opendata.cern.ch/docs/cern-open-data-policy-for-lhc-experiments

decades, advances in technologies such as genome sequencing and mass spectrometry have resulted in ever larger volumes of valuable research data being generated. The computational biology enabled through this has transformed our understanding of life at all levels and forms. **ELIXIR** is a distributed, virtual infrastructure where users access online the many hundreds of digital services that are run by ELIXIR Nodes. These include databases, software tools, computing services, interoperability resources and standards, and training in how to use those.

Moreover, new methods in bioimage informatics, including machine-learning approaches and artificial intelligence, are developing at breath-taking speed, opening new and exciting possibilities to fully exploit FAIR image data for life scientists and beyond. Currently, biomedical and life science researchers produce large-scale image data and, therefore, have acute needs for advanced image data analysis and imaging bioinformatics. However, these researchers are often equipped with limited computational resources and basic informatics skills. Consequently, they are not yet enabled to implement and use complex analysis workflows or to make their image data FAIR.

Euro-BioImaging ERIC is working to change this. Through Euro-BioImaging, users already can archive their image data and have access to community-accessible tools for image analysis and processing that can be used via the cloud (as part of EOSC-Life). Euro-BioImaging aims to fuel the new discipline of imaging bioinformatics and to integrate data research across different scientific domains to address larger questions and key societal challenges, e.g. health and ageing, climate change, and food security.

RIs in the Environmental domain produce vast amounts of data with on average a good level of Fairness. However, to study complex phenomena as the Earth System or the Climate System there is a need to increase High-Performance computing resources.

In data-intensive industries access to very large volumes of high-quality data is of primary importance. The most important tech companies are not based in Europe, consequently their activities aimed at acquiring huge amounts of data do not always meet European standards, especially when it comes to privacy and data protection. **CLARIN ERIC** offers a more sustainable alternative, emphasising the quality of data (which are accompanied with metadata and annotations) over the quantity. CLARIN data and tools can be used to develop, train and evaluate many language-related data-intensive technologies, such as Machine Translation, Automatic Text Simplification or Automatic Text Summarisation, Automatic Text Generation, Knowledge Extraction or Machine Learning. The multilingual and multimodal character of the data and resources available through CLARIN promotes a culture of global citizenship and appreciation of cultural diversity, which is also another contribution to shaping digital transformation in alignment with Europe's values.

DIGITAL INNOVATION

The European Strategy of shaping Europe's digital future can strongly be supported by large-scale RIs that have already proven to be an excellent environment for creating digital innovations. The associated cutting-edge research is always driven by novel technological opportunities, including digital technologies. Big Data, Data Processing and Analysis, Data access, High Data Rates, Modern Computing technologies are nowadays extremely important to face many global challenges (climate, environment, health, including the COVID-19). These are indeed common RI tools which are constantly evolving towards innovations on the grounds of RIs. A great example of very recent innovations in the field of digital technologies for competitiveness and fit for the Green Deal is a direct spin-off of the FAIR project, an innovative energy-efficient and sustainable data center called Green IT Cube which is currently one of the most efficient scientific computing centers in the world, using an innovative patented water cooling system of the racks and making it thus a great example of the digital sector's policy to minimize carbon emission.

As a major analytical research facility, the **ILL** relies heavily on IT infrastructure to convert its experimental output into scientific knowledge. In this context, digital transformation holds the promise of major disruptive innovation. Machine learning can be applied to the recognition of patterns within the experimental data, making it possible to optimise the measurement strategy and fine-tune instrument parameters during operation and development. The **ESRF** has started an ambitious programme to work on machine learning methods. Machine learning is of importance for reducing noise in the data, automatically detect patterns which otherwise would go unnoticed, and for optimizing experimental conditions allowing to shorten the time required for the data acquisition process.

ACTRIS provides access to users to Virtual Research Environment to conduct specific experiments, simulations, and online data processing. **LifeWatch ERIC** seeks to understand the complex interactions between species and the environment, taking advantage of High-Performance, Grid and

Big Data computing systems, and the development of advanced modelling tools to implement management measures aimed at preserving life on Earth.

ELIXIR activities are at the heart of the digital transformation of life science research. ELIXIR connects, coordinates and integrates bioinformatics resources across Europe, building a coherent life science infrastructure for the digital age and supporting everything from expert bioinformaticians to life science generalists and users from academia to industry.

Digital transformation is also a cornerstone of personalised medicine. In this context **EATRIS ERIC** and **ECRIN ERIC** are developing methodological standards which include the generation, through stratification cohorts, of multi-omic data with subsequent machine-learning stratification to identify homogeneous patient clusters, then clinical trials will test treatment options driven by this complex profiling.

DARIAH ERIC mission is to empower research communities with digital methods to create, connect and share knowledge about culture and society. Its distributed structure is optimally constructed to support digital transformation across its network.

In its 2021 round, the **European Social Survey ERIC** is including a special module on 'digital social contacts at work and in family life'. The module will include items on opportunities for access to digital communication (e.g. Internet access at home), the need for them (e.g. lower co-residence) and trust in digital social contact (e.g. privacy concerns), as complements to questions on workplace culture and available country information (e.g. on work related state policies). These are likely to shape individual agency to establish digital social contact in a way that it facilitates work-life balance and encourages relationship quality or well-being. The ESS is also building infrastructure for an on-line panel of the future with the hope to link a representative sample in a digitally designed Research Infrastructure of the future.