Strategy Report on Research Infrastructures

ROADMAP **2018**

PART2

# LANDSCAPE ANALYSIS

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. The unique contribution played by the ESFRI RIs in all scientific domains is analysed along with the interconnections and cross-cutting aspects of the whole European RIs ecosystem.

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

The Landscape Analysis is composed of three sections.

## SECTION 1

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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, and the interfaces of the RIs belonging to the same disciplinary area are captured by plots with the relevant dimensions. The gaps, challenges and future needs are analysed for each group of thematic RIs and summarised. Research develops both within disciplinary domains and across disciplinary borders so that the needs for competitive research imply to enable a smooth access to multiple and diverse RIs.

In addition, the Section1 indicates *high strategic potential areas of research in the field of Social & Cultural Innovation,* that resulted form the Roadmap preparation work.

## SECTION2

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is an all-new analysis effort to render explicit the relevant connections that already exist among different thematic areas by means of the ESFRI RIs, and to identify the critical needs and opportunities for new links and new research practices.

The interconnections mediated by ESFRI RIs are displayed in the graph – **Interconnections between ESFRI RIs and scientific domains** – and in the extended caption – **Description of the interconnections.** The ensemble of the information represents the baseline formed by ESFRI RIs and its high potential for interdisciplinary and multidisciplinary research. It is clear that the high need of new knowledge across the disciplinary boundaries cannot be addressed by the RIs alone, even less by the sole set of ESFRI RIs; it does involve the organization of research at large. The contribution of well interconnected RIs can play a major role in favouring the establishment of standards and good practices on two fronts: the data interchange/interoperability among RIs – a prototype implementation of the EOSC – and the multifaceted research process that – in case of *Grand Challen*ges of non-disciplinary nature – requires effective work-plans across the full system of Research Infrastructures.

## SECTION3

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describes the state of play of the Research Infrastructures in addressing *transversal issues* like education and training, needs for digital infrastructure, contribution to innovation along with the *horizontal analyses* like socio-economic impact, territorial impact, pan-European and global dimensions that are carried out by all RIs.

The impact of RIs on European research, innovation, culture and society is reflected in training to research and higher education, transfer of disruptive knowledge and refinement of technical understanding to the economy sector of production and services. The prime role of RIs in generating high-quality data for enabling a knowledge-based economy is transversal to all disciplines and research practices. The analysis of the impact is conducted for all areas with consistent methodology and gives evidence of the contributions and challenges in generating innovation and socio-economic benefits at national, European, and global levels.

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

PART2

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# PART2

## LANDSCAPE ANALYSIS

# SECTION 1

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PART2

**LANDSCAPE ANALYSIS - SECTION1**

# ENERGY

# ENERGY

The energy sector is key to social and economic development. Especially in some non-OECD countries the energy sector sees very high growth rates due to rising GDP. However, it contributes significantly to global $CO_2$ emissions. For the EU, the reduction of $CO_2$ emissions in a sustainable framework is a major driver of its energy policy. This provides opportunities for new technologies both for application within and outside of the EU.

Thus the European Commission's Energy Union[1] strategy has formulated the objective of creating a secure, sustainable, competitive and affordable energy system. This fundamental transformation will be achieved by more flexible, more decentralized and more integrated ways of production, 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 stakeholders from industry and research as well as society. For this reason, Europe has elaborated its path towards energy innovation in the Strategic Energy Technology Plan (SET-Plan)[2]. Energy Research Infrastructures (RIs) play a major role in joining Europe's efforts to drive forward, test and demonstrate technologies and their interplay in the future energy system.

Energy RIs are to a great extent interdisciplinary undertakings, as expertise from Physics, Engineering, Computer Sciences and other academic fields converge to support energy technologies and systems development. This is reflected by strong interactions of the energy field with the other ESFRI domains. ESFRI Energy RIs are:

- the **ESFRI Landmark JHR** (Jules Horowitz Reactor), which will serve materials research for the safe operation of current and future nuclear power technologies; the **ESFRI Landmark ECCSEL ERIC** (European Carbon Dioxide Capture and Storage Laboratory Infrastructure) for the development of carbon capture and storage as well as utilization technologies.

- the **ESFRI Project MYRRHA** (Multi-purpose hYbrid Research Reactor for High-tech Applications), a multipurpose fast neutron spectrum irradiation facility for nuclear research; the **ESFRI Project EU-SOLARIS** (European Solar Research Infrastructure for Concentrated Solar Power), the thermal solar power research activities in the field of renewable energies; the **ESFRI Project WindScanner** (European WindScanner Facility), a distributed RI for renewable energies focusing on the high precision characterization of wind fields; the **ESFRI Project IFMIF-DONES** (International Fusion Materials Irradiation Facility-Demo Oriented NEutron Source) for fusion materials irradiation.

This Landscape Analysis for the energy domain is divided in five main areas, which, in themselves, comprise a number of specific 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. A representation of the interplay of the fields and energy RIs is shown in **Figure 1.**

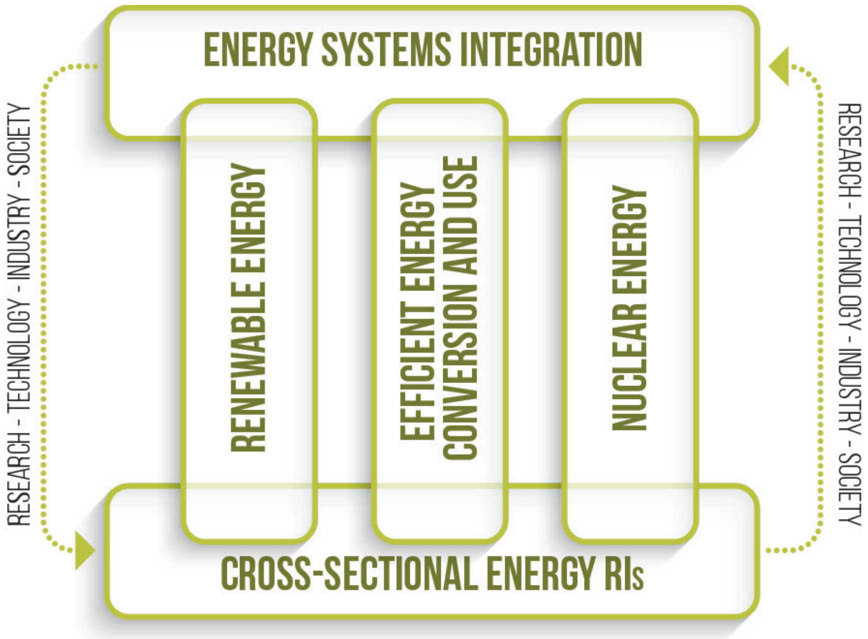



FIGURE 1.
Energy RIs Interplay.

1. COM(2015)080, A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy

2. COM(2015)6317, Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation [latest communication]

# ENERGY SYSTEMS INTEGRATION

Significant investments in infrastructure for smart energy distribution, storage and transmission systems are underway through the Thematic Objectives[3] for Cohesion Policy in 2014-2020. European Regional Development Fund (ERDF) support is available to improve energy efficiency and security of supply through the development of smart energy systems[4]. The SET-Plan and the Energy Roadmap 2050[5] also highlight the expectation that fossil fuels will continue to have a significant 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[6]. However, there is a need to research the design, operation and integration of all parts of the energy system of the future in a safe and secure manner. The main focus of this section is on the technical aspects of energy systems integration. It is also important to point out that the socio-economic and human behavioural aspects are essential for energy transformation processes.

## II CURRENT STATUS

### ENERGY NETWORKS

The future European energy system, with an envisaged high penetration of renewables, needs a strong interplay between different energy carriers such as electricity, heating and cooling – e.g. gas and other chemical fuels. Such a system demands control and integration 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 operate *Smart Grids*, from *Micro-grids* to buildings. 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.

### 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 are major constraints, as well as regulatory issues, EMSs and technology capabilities. Advanced EMSs that can coordinate distributed storage over the territory and the grid are a challenge for the development of *Smart Grids* and for the satisfaction of different kinds of demands – electrical, loads, thermal loads, etc. Infrastructures to support the design and evaluate *Smart Grid* reference architectures are highly needed. Demonstration and test of energy storage at medium and large scale, including the possibility to test completely novel components, will give practical information on the use and benefits of the energy storage technology 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 providing collaborations, hosting researchers, sharing data, exchanging lecturers, participating in common projects, delivering University masters and PhD activities. However, improved scientific exchange and collaboration should be achieved through the testing of new algorithms (EMSs) both for designing and operational management in the RIs at international level. 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, storage systems – from the development of single components up to a complete energy system. Most smart energy network projects have evolved from smart meter read-out pilots into increasingly complex systems to match electrical demand with the variable electricity production of renewable sources. However, only a few up to now are looking at the mixture of energy carriers. Focus has been limited to grid operation overlooking possible communication solutions. Therefore, energy system RIs enabling energy system tests in combination with communication technologies need to reveal their actual potential in dealing with future challenges of even more complex systems. Such test systems should combine meteorological forecasts, energy production facilities, storage devices and systems, end-us-

3. http://ec.europa.eu/regional_policy/en/policy/how/priorities

4. https://www.energyplan.eu/smartenergysystems/

5. 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

6. 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

er components, penetration of renewable, different energy carriers like electricity, heating/cooling and gas including market models. Having multiple electricity retailers and the freedom to switch from one electricity retailer to another are not taken into account and could be interesting in a future energy RI. Building integrated smart energy network/storage testing and demonstration infrastructure will give device 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. Also, the ongoing R&D activities on storage technologies based on batteries or other storage systems, on the conversion of excess energy into chemical carriers will, in the long run, make available an integration of the technology into the wider energy system. Generally, the improvements in storage capacity and economy will promote future technologies in the *Smart Grid* and compare to grid extension or curtailment approaches. The results of such RI will therefore facilitate decisions on investments connected to the transformation of the energy system for companies as well as for public operators. The US, China and Korea have large ongoing demonstrator projects with large infrastructure investments – mostly in *Smart Grid* and *Micro-grid*, establishing the capacity of testing the global competitive advantage of individual components.

### EFFICIENT CLEAN TRANSPORT

Transport accounts for approximately one quarter of the EU Greenhouse Gas emissions and the target is to reduce this to 60% by 2050. The electrification of private transport is starting to gain market traction; however, the roll-out has been hampered by costs, and by political and techno-economic uncertainties around the launch of charging infrastructures. Cleaner and more energy efficient vehicles are a significant growing part of the European Energy System and have an important role to play in achieving EU policy objectives of reducing energy consumption, $CO_2$ emissions, and pollutant emissions. The Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles[7] aims at a broad market introduction of environmentally-friendly vehicles. It addresses purchases of vehicles for public transport services. Clean Transport Systems can go a long way towards meeting the future energy demands of the transport sector; however, the availability and cost of relevant raw materials – e.g. batteries – is likely to be another major issue to overcome. Investments in transport services and infrastructure directly benefit citizens and businesses. Smart mobility, multi-modal transport, clean transport and urban mobility are particular priorities for Cohesion Policy during the 2014-2020 funding period. Cohesion policy also supports investments in infrastructure for smart energy distribution, storage and transmission systems (particularly in less developed regions). As covered by the public procurement Directives and the public service Regulation. It is also possible to receive EU support for low-carbon transport investments under the Thematic Objective aimed at supporting the shift towards a low-carbon economy in all sectors, in particular for promoting sustainable multimodal urban mobility.

In order to make sure that these investments achieve maximum impact, particular emphasis is placed during the 2014-2020 period on the need to ensure a sound strategic environment, including the adoption by Member States of a *comprehensive transport plan* that shows how projects will contribute towards the development of the Single European Transport Area and the trans-European transport network.

### SMART CITIES AND 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 transport systems and thermal energy storage systems, ICT can contribute to effective energy use and interactive balancing of real-time energy supply and demand. 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. H2020 is rolling out smart city lighthouse projects to demonstrate drastic improvements and interactions in urban energy (including large-scale building renovation), transport and 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)[8] aims to promote integrated solutions leading to sustainability and a higher quality of life. The EERA Joint Programme on Smart Cities[9] 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[10] 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 EUROCITIES[11] or the European Network of Living Labs (ENoLL)[12]. Smart cities can be identified and ranked along a variety of axes or dimensions of city structures, including smart energy, smart mobility, smart people, smart governance, smart economy, smart buildings, smart health and smart education. Shared access to data, with a specific challenge focused approach could be attractive to researchers and assist urban decision makers.

7. https://ec.europa.eu/transport/themes/urban/vehicles/directive_en

8. http://ec.europa.eu/eip/smartcities/index_en.htm

9. https://www.eera-sc.eu/

10. http://www.europarl.europa.eu/RegData/etudes/etudes/join/2014/507480/IPOL-ITRE_ET(2014)507480_EN.pdf

11. http://www.eurocities.eu/

12. https://enoll.org/

## GAPS, CHALLENGES AND FUTURE NEEDS

**ENERGY SYSTEMS INTEGRATION – OVERVIEW.** 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 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 *Smart Grid* control systems that involve different kinds of energy and relation to the local scale (multi-generation Low Voltage grids) that are able to deal with the combination of all use cases, including incentives to grid operator and electricity retailer 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 systems such as blockchain and crypto currencies to enable 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 energy storage via heat, chemical and physical storage solutions. In terms of energy storage RIs on materials, production technologies and testing of battery cells and systems would be required to align with a European strategy supporting battery cell production in Europe.

**SMART CITIES AND COMMUNITIES.** There are 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 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 and especially when promoting the networking of smart cities to leverage experience and shared learning. Data protocols for sharing high volumes of information are needed, as well as particular attention to data privacy matters. Even more important will be how ICT will enable the future designs in urban form, services and infrastructures; moving beyond simply checking which data are available and how to best use these.

**CLEAN AND EFFICIENT TRANSPORT.** The focus on the need for low emission vehicles and the standardisation of testing 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 elements, not just of the *Smart Micro-grid*, but also of the broader energy systems. As the pace of development of electric vehicles is picking up and with the evolution of autonomous vehicles, it will be important to have RIs to enable researchers to study the effects of the legal frameworks as well as the physical infrastructure within which these will operate.

## 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 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. With increasing deployment, cost reduction can be achieved through industry driven incremental innovation. However, specifically the development of new concepts requires long term research and state-of-the-art Research Infrastructure. Costs of development of these new concepts are high, knowledge is scattered and markets are often global. Therefore, substantial synergies can be obtained in sharing advanced Research Infrastructures.

Several EU initiatives are currently coordinating research activities in Europe like the Solar European Industrial Initiative (SEII), the EERA Joint Programme on Photovoltaics, the EERA Joint Programme on Bioenergy (EERA JP-Bioenergy), the European Industrial Bioenergy Initiative (EIBI)[13] and BRIDGE-PPP, the EERA Joint program in deep Geothermal energy, the EERA Ocean Energy Joint program and European Ocean Energy Association (EU-OEA), the European Technology and Innovation Platform on Wind Energy (ETIPWind)[14] and the EERA Joint Programme on Wind Energy[15]. In respect to Concentrated Solar Power (CSP), the EERA Joint Programme on CSP and the European Solar Thermal Electricity Association (ESTELA)[16] include the main stakeholders of this sector. Finally, the mix of different hybrid renewable systems helps in defining economically appealing and environmentally sustainable strategies, including supporting grid stability and deliver balancing power.

13. *http://www.etipbioenergy.eu/?option=com_content&view=article&id=191*

14. *https://etipwind.eu/*

15. *https://www.eera-set.eu/eera-joint-programmes-jps/wind-energy/*

16. *http://www.estelasolar.org/*

## CURRENT STATUS

### PHOTOVOLTAICS

The Joint Research Programmes such as the EERA Joint Programme on Photovoltaic (EERA JP-PV) (37 partners from 19 EU Countries) or SOPHIA (17 partners) and its follow-up CHEETAH (34 partners) contribute to improving EU research and to optimize the use of RIs. According to the SOPHIA project and CHEETAH, the most relevant EU RIs are from Germany (3), Spain and Italy (2), and France, The Netherlands, Belgium, Denmark, Great Britain, Finland, Norway and Austria with one each.

The last strategic research agenda of the EU PV Technology Platform considers that the main challenges are related to the overall costs of the best technologies. A recent study[17] shows data expected in 2020 and 2030, respectively, are: typical turnkey price for a 50 kW system [€/W, excl. VAT] (0.9 and 0.6); typical electricity generation costs in Southern Europe [€/kWh] (0.04 and 0.03 including 4% WACC), typical system energy payback in Southern Europe [years] (0.5-1.0 year in 2050 for smaller systems and depending on PV technology and energy mix[18]. For utility scale plants typical generation costs (LCoE) below 0.02 €/kWh are expected in Southern Europe in 2030 (including 4% WACC) and approaching 0.01 €/kWh in 2050. To reach these low LCOE values, or even lower, reliability of PV systems will be key (lifetimes beyond 30 years).

There is a state-of-the-art European basic research on materials and design of large plants, addressing quality and sustainability aspects. RIs strategy tends to be aligned with industrial needs. Financial efforts are focused on testing, pre-industrial facilities. Following the new IP Pillars, three main drivers for the development of new/existing infrastructures are: pilot/demo scale lines, manufacturing technologies/fabrication processes and modelling facilities for simulation and better forecasting the energy output of PV systems applied in different environments (from built environment to large power plants). Furthermore, social aspects for general public support to broadly install PV are becoming more important. 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.

17. http://www.etip-pv.eu/publications/etip-pv-reports.html

18. http://www.iea-pvps.org/index.php?id=314

### RENEWABLE FUELS

The EU scientific effort is well articulated between associations aimed both at developing R&D and promoting flagship plants. In addition to the EERA Joint Programme on Bioenergy (36 partners from 19 EU countries) and the Bio-Based Industries Joint Undertaking (BBI JU)[19], two other initiatives in the landscape are the European Technology and Innovation Platform (ETIP Bioenergy)[20] - created by merging the European Industrial Bioenergy Initiative (EIBI)[21] and the European Biofuels Technology Platform (EBTP) - and the Joint Task Force on Bioenergy and Biofuels production with Carbon Capture and Storage (Bio-CCS JTF), involving members of ZEP (Zero Emissions Platform) and the EBTP. Research Infrastructures were grouped within H2020 Infrastructures – e.g. the Biofuels Research Infrastructure for Sharing Knowledge II (BRISK2)[22], according to SET-Plan objectives and whose activity is to fund researchers from any EU Country to carry out research at any of the 28 EU partners' facilities. The RI was also a part of several Networks of Excellence, related to various aspects of bioenergy production and utilization, like SUSTDEV NOE-BIOENERGY, DER-LAB and ECO-ENGINES. Demo pre-commercial facilities exist, such as the UPM Stracel BTL (FR), Forest BtL Oy (FI), Beta Renewable (IT) or Abengoa 2G Ethanol Demo Plant (ES), among others. The main strategic research challenges are into feedstock and conversion processes of biomass into biofuel. Existing initiatives already connect high-level stakeholders and experts from relevant industries and research centres. The main challenges cover the efficiency, economic competitiveness and system integration of biomass conversion into biofuels and energy.

19. https://bbi-europe.eu/

20. http://www.etipbioenergy.eu/

21. http://www.etipbioenergy.eu/?option=com_content&view=article&id=191

22. http://briskeu.com/

The Standing Committee on Agricultural Research (SCAR) set up the Strategic Working Group *Sustainable Bio-Resources for a Growing Bioeconomy* (SWG SBGB) gathering the representatives of 15 countries and the Collaborative Working Group of 12 countries on *Integrated Biorefineries* (CWG IB). SWG SBGB discusses the issues related to more efficient production of biological resources, logistical questions, the biomass potential available across Europe, and fostering new connections between well-established sectors. The main technical barriers to the successful implementation of the bioeconomy identified by SWG SBGB include utilization of different bio-based feedstocks within a single biorefinery, and standardization of bio-based products. The CWG IB focuses on aspects related to the investment in research, innovation and skills.

EU-US cooperation on advanced biofuels is based on joint initiatives, such as the EC-US Task Force on Biotechnology Research: Bio-Based Products and Bioenergy Working Group. There is also research cooperation between EU and Central/South America through initiatives such as BECOOL in the framework of a joint EU-Brazil call on Advanced Biofuels.

### CONCENTRATED SOLAR POWER

The European R&D community related to Concentrated Solar Power (CSP) is well established. The main EU RIs are managed by: DLR in Germany (facilities located in Cologne, Jülich and Stuttgart), ENEA in Italy (with facilities in Casaccia and Portici), CNRS in France (Odeillo) and CIEMAT in Spain (through Plataforma Solar de Almería-PSA). The Cyprus Institute (CyI), the IMDEA-Energy in Spain and the University of Évora in Portugal have recently expanded the landscape of large-scale facilities, contributing with the Pentakomo (CyI), Móstoles (IMDEA) and Mitra test sites. Most of these RIs are collaborating, offering international access to their facilities through the FP7 European project SFERA-II (2013-2017). These RIs are also members of the EERA Joint Programme on Concentrating Solar Power (EERA JP-CSP), participating in its FP7 IRPSTAGE-STE (2014-2018) and partly in the **ESFRI Project EU-SOLARIS**.

Two complementary strategic research agendas are in place. ESTELA's (European Solar Thermal Electricity Association)

Strategic Research Agenda (SRA) was published in 2013. This SRA aims to directly meet the industrial 2020 targets through: a) increase efficiency/cost reduction – mirrors, heat transfer fluid and others as selective coatings and prediction/operation tools; b) dispatch ability – integration systems, storage systems and forecasting models to regulate and manage electricity production; c) environmental profile – reduce current impact of heat transfer fluid, water desalination and reduce water consumption without jeopardizing the plant efficiency. Another more recent research agenda is the *Initiative for Global Leadership in Concentrated Solar Power,* which has been submitted to the SET-Plan Steering Group for final endorsement beginning of 2017. It has been developed within the EERA JP-CSP (29 participants) and STAGE-STE project. The **ESFRI Project EU-SOLARIS** is expected to be the first of its kind, where industrial needs and private funding will play a significant role.

From the commercial deployment point of view, it is worth mentioning that CSP plants with a cumulative capacity of about 2.3 GW were in commercial operation in Spain in December 2016, representing about half (48%) of the worldwide capacity. Outside Europe, about 1.74 GW of CSP are currently in operation in the US, while China is championing new developments with 1.34 GW under construction or development. Globally, more than 100 projects are in planning phase, mainly in India, Morocco, South Africa, Middle East countries and Chile. However, the need for additional RIs in Europe has been identified according to the needs of the commercial CSP plants, where the cost competitiveness is a key barrier along with the operational flexibility and energy dispatchability. In this area, the US *SunShot* Initiative programme aims to reduce the levelised cost of electricity (LCOE) generated from CSP systems to 6 cents/kWh, without any subsidies, by 2020.

### WIND

Many initiatives coordinate the research activities in Europe: the European Wind Industrial Initiative (EWII) and EERA joint program on Wind energy (49 partners from 14 EU countries), European Technology and Innovation Platform on Wind Energy (ETIP-Wind), driven by the European wind energy industry and coordinated by the European Wind Energy Association, and the European Academy of Wind Energy (43 entities from 14 EU countries). In this sector, the RIs in the EU are: a) Wind Turbines Test Fields with RIs in Germany (3), Spain (2), Greece, Denmark (2), Netherlands and Norway (1); b) Components Test Facilities with RIs in Denmark and Germany (3), Spain, United Kingdom, Netherlands and Finland with 1; c) Wind Tunnels with RIs in Greece and Netherlands, Norway, Denmark, Finland and Germany (1); d) Wind Energy Integration Testing Facilities distributed in Spain (4), Norway, Netherlands, Germany and Denmark (1). A specific reference goes to the **ESFRI Project WindScanner**, in the ESFRI Roadmap since 2010, which finalised its first Preparatory Phase at the end of 2015. The **ESFRI Project WindScanner** uses remote sensing-based wind measurement systems to provide detailed wind field maps of the wind and turbulence conditions around either a single wind turbine or across a farm covering several square kilometres. There are 4 RIs related to material testing and hydraulic located in Greece, Germany, Denmark and Norway.

The challenges are the following: a) resource assessment and spatial planning, including the publication of an EU Wind Atlas in the next five years and the better understanding of wind characteristics that are relevant for the safe operation of larger and larger wind turbines; b) wind power systems that include the development of new wind turbines and components up to 15-20 MW in the year 2020; c) wind energy integration into the grid, including the long distance connection of large wind farms to the grid; d) offshore deployment and operations that include the development and testing of new structures for deep water. Industry needs test facilities to innovate the design.

The ETIP Wind's Strategic Research and Innovation Agenda (SRIA) has three objectives: i) cost reduction, ii) System integration, iii) First class human resources. WindEurope expect the EU Wind Energy sector to grow to 205 GW, including 24 GW of offshore wind by 2020, to cover 16.5% of EU's electricity demand. By 2030, wind should be able to cover 30% of the EU's electricity demand. The EU wind fleet would consist of 323 GW of wind, including 70 GW of offshore wind. Offshore wind would need to ramp up to a pace of more than 4 GW per year. At the end of 2016, the EU had a fleet of 153 GW of wind power, China had 169 GW, and the US 82 GW. There were 487 GW installed worldwide.

Regarding the existing test facilities abroad, US shows a very competitive scientific community with high level test facilities – e.g. NREL-NWTC blade test facilities, drive train test facilities and field test and Clemson's University, 15 MW drive train testing facility, and the WTTC with a 90m blade test facility.

### GEOTHERMAL

Geothermal energy in the Earth's upper few kilometres is vast and the potential in this renewable energy source is of significant importance for the energy shift from fossil to environmental friendly energy. Geothermal energy appears to have the potential to become a very important, potentially even dominant, supply of heat energy and dispatchable electricity production in the near future. The potential for utilization needs to be measured, production technology, and enhanced or new innovative solutions developed to access this energy.

All major research institutions are involved in the EERA Joint Programme on Geothermal Energy – 37 participants from 12 EU countries, including Iceland, Turkey and Switzerland. Other major research centres – which cover wide areas of geothermal research – and technology platforms are located in Iceland, France, Italy, Germany or Spain. There are 5 sites in construction or planned and 2 existing sites focused on research and demonstration: Soultz-sous-Forêts (FR) and Groß Schönebeck (DE). Other large existing industry-owned sites are in Iceland.

Geothermal energy for heat and cold extraction and storage is an increasingly important component in the energy balance of buildings and for neighbourhood heating/cooling systems. For traditional, high, intermediate and low-temperature areas, improvements in production methods, drilling and well completion, mapping and managing the underground reservoirs, are essential. Recent results from deep drilling to access superheated or even supercritical fluids are encouraging, indicating the possibility of dramatic improvements in production as well as addressing unexplored geothermal potential. Possible major production from offshore areas is becoming more relevant, as offshore technology improves and the production cost decreases. A number of major projects investigating enhanced geothermal systems (EGS) are ongoing, including in Europe. In EGS, the permeability of the deep subsurface is increased using hydro-fracturing and other methods. If cost-effective technology for achieving this can be developed, major large-scale geothermal energy production in many non-traditional areas will rapidly follow. Key issues here include costs and limiting induced seismicity caused by the operations.

The main strategic research agendas are from the Technology Platform (TP) on Renewable Heating and Cooling and the EERA Joint Programme on Geothermal Energy. The challenges in 5 years (Exploration technologies to image the subsurface to reduce the mining risk prior to drilling) are: to define the reservoir characteristics and geothermal potential in different environments, to develop experimental test of materials and treatment to prevent or mitigate corrosion and scaling. The longer term challenges are: cost-effective drilling technologies for very deep geothermal wells at extreme conditions of temperature and pressure including supercritical fluid systems; prediction of geo-mechanical behaviour of fracture zones, with particular focus on reservoir performance evaluation and induced seismicity; improvement of methods to enhance reservoir performance and to study the processes of long-term geothermal exploitation; enhancing the viability of current and potential geothermal resources by improving thermodynamic cycles and optimizing power conversion; securing natural resources and ensuring sustainable utilization of underground space. Currently, the EU RIs for hotter systems are associated with volcanic areas – e.g. Iceland, Italy, Spain, Portugal or Greece. Testing of drilling methods (e.g. PENA, EL) or of process at the subsurface (e.g. GeoLaB, DE), are in construction or planned.

**OCEAN**

The most relevant EU initiatives are: 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 OES with 21 countries. The list of EU RIs grouped by countries is: United Kingdom (5), Spain (5), Portugal (3), Norway (2), Ireland, Italy, Netherlands, Germany and France (1). In Sweden there are no sea test facilities, only 2 research sites. The European Ocean Energy Roadmap 2010-2050 published by EU-OEA identifies: i) installation of ocean energy generating facilities with a combined minimum capacity of more than 240 MWh; ii) developing or refining test sites for ocean energy conversion devices in real operating environments; iii) Grid availability; iv) resource assessment to support ocean energy deployment.

The industrial goals are to install 3.6 GW of ocean energy systems by 2020 and to reach 188 GW by 2050 (EU-OEA Roadmap 2010-2050). 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 in harsh environments. There is widespread international interest in Wave & Tidal (W&T) energy and it is particularly high in Australia, Asia, US & South America. Currently there are a small number of W&T energy systems installed on the global level. Europe has global leadership in W&T energy technologies and industrial know-how. European projects such as SI Ocean may provide a basis for more intensive cooperation in the future.

## 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, exchange and training researchers inside and outside Europe. An efficient use of infrastructures is also needed to accelerate the implementation of innovative technologies in the 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.

Lack of standardization is the biggest obstacle to rapid cost reduction and definitive deployment of the **CONCENTRATED SOLAR POWER** sector. Activities are currently underway in Europe under control of AENOR (the Spanish official standardization body), the International Electro-technical Committee (IEC) and SolarPACES (IEA Implementing Agreement). Activities in this respect are on their way within STAGE-STE and SFERA-II projects, too.

Concerning **WIND ENERGY**, better coordination of EU RIs should create the conditions for the long-term development. There is need of new multi-actor facilities – especially in the field of exploring and understanding new physics for larger turbines. In Wind Conditions an important infrastructure can be the the **ESFRI Project WindScanner**. Low-speed, high-Reynold number aerodynamics requires large and dedicated wind tunnels. The development of large turbines become such large investments that the industry requires trans-European RIs for short-term technology validation purposes.

The development of new **GEOTHERMAL** 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** (European Plate Observing System, 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 (MARINERG-i).

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.

# 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 simply because 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 often 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. However, 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

For effectiveness at a systems level and especially because of the intermittent supply from some electricity sources, it is becoming increasingly important that the energy consumption and efficiency of buildings are considered together with the energy supply mechanisms available, for example plants producing both electricity and heat for use in buildings. Optimal solutions for different types of buildings – e.g. industrial, commercial, single dwelling, high rise flats – in different climatic conditions will be different. It is especially important that rapid changes in demand for heating and cooling in buildings does not destabilize the electricity supply system, which will require some integrated steering of supply and demand. It is also important that optimization of electricity use does not lead to severe de-optimization in buildings, such as increased maintenance costs due to fluctuating internal temperatures and humidity, or (energy) costs for additional insulation which outweigh energy savings for heating/cooling. The practical situation is complex, and consumer behaviour is affected by various political decisions related to, for instance, building norms, taxation and subsidies. It is important that these decisions are based on solid empirical data. This demands investments in *real life laboratory* Research Infrastructures, including monitoring energy use in buildings and energy production. As the European energy system is becoming increasingly integrated, a pan-European perspective is necessary.

### ENERGY EFFICIENCY AND USE IN INDUSTRY

The concepts mentioned above regarding buildings and the need for a systems perspective are also relevant for industry. In addition, there are major possibilities for improved energy efficiency and/or reduced greenhouse emissions from many industrial processes. Not all waste products (waste material, heat) are effectively utilized today, seen from an energy efficiency perspective, even if promising results have already been obtained - e.g. in heavy industry. Where a major opportunity for enhanced industrial energy efficiency is assessed, research and development investments may be strongly motivated. In some cases, public investment in research and pilot and demonstration plants will be motivated. It is important that new insights and solutions developed in different European countries are effectively spread. The following areas may merit major investments over the coming years.

A state-of-the-art automation information technology and connectivity will enable the digitalization of production that goes far beyond conventional automation of industrial production. Initiatives have been started around the globe to foster digitalization, like IIoT (Industrial Internet of Things)[23] in the US, Industrie 4.0[24] in Germany, or China 2025[25]. Another aspect of energy saving represents predictive modelling and simulation, coupled with the artificial intelligence for automatic optimization of processing with respect to use of resources, energy, productivity and product quality. The intelligent combination of sensor technology combined with these digital models lead to new dimensions in the efficient use of energy in industry.

Metals, polymers and ceramics are crucial materials for energy transition and low-carbon economy. Since it will never be possible to produce them without energy, we have to change to carbon-free energy sources in order to reduce or prevent $CO_2$ emissions in the long term. Industry is working consistently on the further development of the processes towards the stepwise de-carbonization of production. Specifically, the companies plan to make a gradual shift from the use of fossil fuels via bridging technologies to the potential use of hydrogen in the production of materials. Areas which may merit major investment over the coming years include: cement and ceramic production (much $CO_2$ release), the aluminium, iron and steel industries, pulp mills for paper production, etc. Important energy

23. https://www.i-scoop.eu/internet-of-things-guide/industrial-internet-things-iiot-saving-costs-innovation/

24. https://www.gtai.de/GTAI/Navigation/EN/Invest/industrie-4-0.html

25. https://www.csis.org/analysis/made-china-2025

saving aspects are also: recycling, refinement, re-use and waste elimination.

Very important energy related research is in the metals industry advancing in the directions of: Light alloys and metal-matrix composites (for lighter vehicles), High-temperature extreme alloys and composites (for increase of thermodynamic efficiency in boilers), and development of thermoelectric alloys that will in the future be able to convert the waste heat into electricity (see project Metallurgy Europe)[26].

### POWER-TO-X (-TO-POWER)

The increasing use of intermittent sources of energy such as wind and solar demands new solutions to ensure a continuously reliable electricity supply. With the share of renewable energy rising, the electricity grid runs up against its limits due to the large dynamic fluctuations which have to be accommodated. In this context, energy storage on different time scales gains importance. Battery storage can contribute, but long time storage of high energy quantities calls for other solutions. One way which reduces the $CO_2$ footprint of the whole energy system is to convert electricity at times of surplus power into storable energy, to be released at times of low supply. Long-term storage, needed to meet seasonal variation in supply and demand and which could limit the need for grid expansion, will only be possible by converting excess energy into chemical carriers by using carbon dioxide, water and/or nitrogen, the so-called Power-to-X (P2X) scheme. This includes conversion into hydrogen or methane gas (P2G). Further chemical processing can also lead to liquid fuels or base chemicals for value added products. Apart from their general contribution to decarbonizing the energy supply, these process routes provide potential for the saving of fossil resources in industry. The topic P2X therefore responds to the EU SET Plan actions 1 (renewables), 2 (materials) and 8 (transportation).

Currently, European countries run around 50 P2G demonstration projects, with efforts accelerating and increasing over the past 3 years. The main focus is on splitting of water and/or $CO_2$ to produce hydrogen or syngas, complemented by the respective work on system integration. For example, the European STORE&GO project focuses on the synthesis step at 1 MW level in three demonstration environments in Germany, Italy and Switzerland. France recently started the 1 MW Jupiter 1000 project. Germany released a 10-year Kopernikus research project Power-to-X. With 50 partners from research, industry and society it represents the biggest EU wide concerted effort in the field so far. The focus is on low-emission electricity-based liquid fuels and chemical products. Another German flagship project, Carbon2Chem, targets the conversion of carbon dioxide from the steel industry into fuels and base chemicals. EERA JP Energy Storage covers the area of P2X in its sub-programme Chemical Storage.

### CARBON DIOXIDE CAPTURE, STORAGE AND UTILIZATION

Carbon Dioxide Capture, Transport and Storage (CCS) is one of the main objectives of the European energy policy, the low carbon policy. Most of the European countries are focusing on decarbonising the power sector and energy intensive industry and thus reducing anthropogenic $CO_2$ emissions. However, political uncertainties related to safety on land storage of the CCS force countries with big industrial activities like Germany to step out of research and development in CCS. The Global CCS Institute gives among other information, a database of facilities world wide ranging from large scale, pilot and demonstration to test centres[27]. NETL's Carbon Capture and Storage Database[28] includes active, proposed, and terminated CCS projects worldwide. The database contains several hundred CCS projects worldwide. European activities towards CCS are served by two entities: the Zero emission Platform (ZEP) and the European Energy Research Alliance Joint Programme on CCS (EERA JP-CCS). ZEP is a unique coalition of stakeholders and acts as advisor to the European Commission on the research, demonstration and deployment of CCS for combating climate change. Nineteen different countries contribute actively to ZEP's activities, while 40 different companies and organisations comprise the Advisory Council. The EERA Joint Programme on CCS (EERA JP-CCS) has a strong R&D focus and encompasses 40 public European research centres and universities working on a common programme. The EERA JP-CCS including a new $CO_2$ transport sub programme and has contributed to the SET Plan Integrated Roadmap. Member States are involved in the CCS deployment activities and plans through the European Industrial Initiative EII on CCS. Technology Centre Mongstad (TCM) is the world's largest facility for testing and improving $CO_2$ capture using two units each approximately 12 MWe in size, able to capturing 100.000 tonnes $CO_2$/year. A new legal operation agreement for TCM is established through 2020. The major open access RI on the ESFRI Roadmap is the **ESFRI Landmark ECCSEL ERIC**. a top quality European Research Infrastructure devoted to second and third generation CCS technologies. For accelerating the commercialisation and deployment of CCS methods, the **ESFRI Landmark ECCSEL ERIC** has been transferred to a European Research Infrastructure Consortium (ERIC) as a legal entity recognised by the Council Regulation of the European Commission offering access to 44 research facilities. The UKCCSRC Pilot-scale Advanced Capture Technology (PACT) facilities are national specialist R&D facilities for combustion and carbon capture technology research. The purpose of PACT is to support and catalyze industrial and academic R&D in order to accelerate the development and commercialization of novel technologies for carbon capture and clean power generation. There is a network coordination between TCM, **ESFRI Landmark ECCSEL ERIC** and PACT. Long-term monitoring and documentation of stored $CO_2$ in geological reservoirs have been achieved. The Sleipner $CO_2$ Storage facility was the first in the world to inject $CO_2$ into a dedicated offshore geological sandstone reservoir since 1996 and over 16.5 million tonnes have been injected at the end of 2016. The Snøhvit $CO_2$ Storage facilities has captured more than 4 million tonnes of $CO_2$ at an LNG facility in northern Norway and transported in a pipeline back to the Snøhvit field offshore and injected into a storage reservoir. To capture $CO_2$ from industrial processes has some advantages like lower capture cost, excess energy that can be used for $CO_2$ capture and stable $CO_2$ source. The concentration of $CO_2$ in the flue gas is often higher than in power systems, in cement plants typically from 18 to 22 vol%. They are often also located in industrial clusters/coastal locations which can possibly lower transport cost. There are three pilot plants in Captur-

26. http://metallurgy-europe.eu/

27. https://www.globalccsinstitute.com/

28. https://www.netl.doe.gov/research/coal/carbon-capture

ing Carbon in Norway; Norcem AS (cement plant), Yara Norge AS (ammonia plant) and Klemetsrudanlegget AS (waste-to-energy-recovery plant) selected for detailed studies of full-scale carbon capture at their respective plants. Total $CO_2$ injection capacity for all three plants in full scale operation is approximately 1.3 Mtpa. A combined pipeline and shipping system is being examined for $CO_2$ storage in the Smeaheia area offshore. A final investment decision is targeted for 2019 with ambitions to begin operation in 2022.

There is increasing attention towards $CO_2$ utilisation (CCU). Specifically, a number of facilities that use $CO_2$ in products, or to support operations have been constructed or announced in the last decade. It is important to note that not all $CO_2$ utilisation options will necessarily contribute to longer term climate change mitigation: the storage lifetime can be counted in days to years as opposed to centuries. There are many different ways to use $CO_2$ and key technologies can be grouped into polycarbonate plastics, chemicals and mineralization/cements. Development of new catalysts replacing chemical products usually derived from fossil fuels is of major interest. Notwithstanding the above points, the market for products derived from use of $CO_2$ is small relative to what is needed to be stored in order to limit global temperature rise to well below 2°C – a cumulative 90 Gigatonnes of $CO_2$ captured and stored in the period to 2050.

## GAPS, CHALLENGES AND FUTURE NEEDS

It can be argued that research has been focussing on single components, rathen than concentrating on the analysis of complex energy systems on different scales where the different elements interact. Research Infrastructures investigating systems in practical use could be of significant benefit. One example of this is the use of **ENERGY IN BUILDINGS**, and increasing the supply of energy from buildings. The latter may relate to production of electricity, for example, or 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 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 plasmochemical 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. The R&D tasks range from basic research over questions of up-scaling to the 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 needs to be combined and developed on European scale and size 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 EU Industry, government and non-governmental organizations.

It remains unclear if large scale **CARBON DIOXIDE CAPTURE, STORAGE AND UTILIZATION** 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.

# NUCLEAR ENERGY

## CURRENT STATUS

### NUCLEAR FISSION

The 128 Nuclear Power Plants[29] (NPPs) are supplying 815.2 TWh (about 30% of electricity) in the EU. 4 NPPs are under construction and 24 in planning. Nuclear power thus plays an important role to provide a stable, base load electricity. The main strategic objectives are the safety aspects and the long-term waste disposal. The previous landscape analysis made a detailed list of aimings towards these objectives. Since the analysis is rather recent, no major change has occurred. In the field of Accelerator Driven System which could be used for transmutation of long-lived actinides, a staged approach was adopted by the **ESFRI Project MYRRHA**, leading to the full realisation of the facility by 2030.

In many countries, the issue of prolonging the life of existing NPPs leads to the development of materials research under nuclear irradiation. This could be done through experiments and numerical simulations. The latter, with the development of high performance computers (HPC), 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 decision from some countries to step out of nuclear energy, the issue of the dismantling of NPPs is becoming an important one. Many Master Programmes have included this topic in their cursus.

Present NPPs are based on three main concepts (Heavy Water, Pressurized Water or Boiling Water). The Generation IV Initiative offers the perspective of a better use of the fuel, increase of safety and reducing the amount of long-lived waste. Another new development of interest that should be encouraged is the Small Modular Reactor, delivering about 300 MWe.

### NUCLEAR FUSION

The European fusion programme[30] has two main objectives, to prepare the successful operation of ITER and the preparation of DEMO. The construction of the ITER tokamak is now moving at full speed, with a first plasma by 2025 and the D-T operation by the end of 2035.

From a physics perspective, two concepts are being explored in the Euratom programme, the tokamak and the stellarator. The consortium EUROfusion operates all the main installations, the tokamaks ASDEX-Upgrade, JET, MAST, TCV and WEST and the superconducting stellarator W7-X. For the study of the physics of the divertor – a key element where heat and particles are exhausted from the plasma – a dedicated device, the Divertor Test Tokamak (DTT)[31], is being considered and was recently approved. In the framework of the Broader Approach (BA) Agreement[32] EU and Japan are building a new superconducting tokamak JT-60SA, which will be jointly exploited by EU and Japanese teams.

The second main objective of the EU fusion programme is the design of a DEMOnstration fusion reactor. DEMO will produce a substantial amount of electricity and be self-sufficient in Tritium[33] and is scheduled to be operational by the mid of the 21$^{st}$ century. During Horizon 2020, DEMO work will be in the pre-conceptual phase, where many design concepts are examined, and a concept selection will be performed in FP9.

The construction of a fusion reactor relies on the knowledge of suitable material under the irradiation by 14 MeV neutrons. Within the BA, R&D for the neutron irradiation source IFMIF is being developed for critical components. However, the BA does not foresee its construction. The EUROfusion programme – based on the roadmap to the realisation of fusion energy – still supports IFMIF and proposes the **ESFRI Project IFMIF-DONES** (International Fusion Materials Irradiation Facility-Demo Oriented NEutron Source) as an interim step.

The EUROfusion programme benefitted since its beginning from the HELIOS HPC in Rokkasho. After its decommissioning, since 2016, a new European HPC Marconi-Fusion is in operation with a capacity of 6 petaflops. This opens up new possibilities for fusion plasma simulation as well as for materials science.

Both fission and fusion are part of EURATOM. The impact of the Brexit on these two fields is still to be negotiated. In the case of fusion, JET is the main and largest tokamak in operation with the ability to operate with D-T mixture and plays a pivotal role in the scientific preparation of ITER. How the issue will be solved will have impact on the medium term fusion programme.

### CROSS-CUTTING ISSUES BETWEEN FISSION AND FUSION

Many topics are common to fission and fusion. Materials research is the most prominent one. For fission it is a key element for the prolongation of NPP operation. For fusion, the qualification of suitable material is crucial for the construction of a fusion reactor. As mentioned, the field of experimental investigation and numerical simulation are cross-cutting fields. Another cross-cutting issue is the development of accelerator to be used in ADS for fission and neutron source for fusion material irradiation.

## GAPS, CHALLENGES AND FUTURE NEEDS

Two main gaps have been identified: i) for fission, the interest in SMR should trigger an experimental effort in this field; ii) for fusion, the issue of the divertor and of material development require the implementation of the **ESFRI Project IFMIF-DONES** device.

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.

29. http://www.world-nuclear.org/information-library/country-profiles/others/european-union.aspx

30. https://www.euro-fusion.org/programme/

31. Italy is considering the funding of DTT as a national programme while waiting for a later funding by EUROfusion

32. The Broader Approach agreement between Japan and EURATOM covers many other activitie http://fusionforenergy.europa.eu/understandingfusion/broaderapproach.aspx

33. 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.

# CROSS-SECTIONAL ENERGY RIs

RIs for simulation and modelling, as well as advanced characterization and testing facilities, are essential tools for designing advanced materials, for exploring energy conversion processes and for designing and optimizing energy systems. Energy technology-oriented roadmaps have prioritized the need for such RIs in Europe. Progress in energy research specifically could be enhanced by comprehensively using methods or data that are already available or newly generated. The energy research community thus would strongly benefit from exploiting synergies across different technologies and could further advance the cross-cutting methodological development. Cross-cutting RIs providing these services therefore are the key to accelerating innovation in this sector.

## II CURRENT STATUS

### ENERGY MATERIALS

Energy technologies with their high and rapidly changing technical demands are particularly dependent on fast innovations in the structural and functional materials sector. The markets for materials for energy and environmental applications are expected to grow at an above average rate. The main research task in this context is to develop materials with increasing performance and reliability at lower costs. At European level the topic, for example, is addressed as part of the *SET-Plan Roadmap Materials for Low Carbon Technologies* and in various cross-sectional aspects of the 10 key actions to the SET-Plan. It finds expression in the correspondent research and industrial platforms (e.g. EERA, EIIs, EMIRI). Energy materials research currently exploits large-scale European characterization facilities, such as the synchrotrons **ESFRI Landmark ESRF EBS** (European Synchrotron Radiation Facility Extremely Brilliant Source, PSE), PSI, DESY, Diamond, ALBA, Soleil, BESSY, ANKA, Elettra, the future **ESFRI Landmark European Spallation Source ERIC** (PSE), the neutron facilities **ESFRI Landmark ILL** (Institut Max von Laue - Paul Langevin, PSE), ISIS, FRM-2 Munich, SINQ and latest generation electron microscopes. Computational materials science gains importance with regard to creating new materials or chemical agents with tailor-made properties (Computational Materials Design). For this, High Performance Computing (HPC) Infrastructures and data processing (see below) are increasingly used in the analysis of experimental data to determine materials properties and in simulating complex 3D dynamic transport, reaction, ageing and damage processes.

### DATA, SIMULATION AND MODELLING

The multi-disciplinarity of energy-related themes means that it is difficult to identify a community for this field at first sight. The task is integrating activities with the objective of developing and applying scale bridging approaches to design new materials and to study materials as well as energy related processes. 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; systems design and operational and 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 Technology Platform for High Performance Computing (ETP4HPC), and the **ESFRI Landmark PRACE** (Partnership for Advanced Computing in Europe, DIGIT) facilitate high-impact scientific discovery and engineering research and development across all disciplines. The new Energy oriented Centre of Excellence for computing applications (EoCoE), working closely with associated experimental and industrial groups, is expected to have a multiscale integrating character and contribute to filling this gap, along with databases and research platforms. Distributed RI platforms such as DERlab and ERIC-Lab and a rising number of national *living* laboratories collecting and processing data of complex real energy systems have the potential to advance the digital realtime integration of distributed and volatile energy resources into energy systems.

# GAPS, CHALLENGES AND FUTURE NEEDS

**ENERGY MATERIALS.** In spite of the availability of quite a number of methods and facilities, large cross-sectional RIs and research platforms explicitly dedicated to R&D for energy materials still often lack coherence with regard to scale-bridging and multi-method approaches. RI for materials discovery/development and for materials characterization covering length scales - from the atomic structure to macroscopic engineering components – and for different time scales – ranging from sub-picoseconds up to the lifetime of energy systems of tens of years – should also include life cycle experiments, ageing and non-equilibrium loads. The future of characterization therefore is expected not only to include individual techniques which are pushed to their limits, but also to be a situation where the community devises coherent and synergistic strategies employing a range of cutting-edge characterization methods to address complex multiscale problems in materials and systems. In addition, there is a particularly strong need to develop techniques for *in situ* and *in operando* studies of energy materials and components during operation – e.g. for electrochemical and electronic materials and devices.

**DATA, SIMULATION AND MODELLING.** At the front end of the energy-related innovation chain, the objective of computational materials science and chemistry is to create new reliable and cost-efficient materials or chemical agents for changing demands within the new energy systems. For this, dedicated HPC and integrated databases are needed for the rational design of new materials in terms of structure and properties, but also in simulating complex conversion processes on all scales and *in situ/in operando*.

On the energy system's side, a multi-scale approach is needed to properly address the interaction between local power, heat generation and energy carriers, as well as between the distributed and local energy systems and the central energy system. The corresponding system transformation, based on emerging technologies, requires tests and validation before implementation. In order to meet these requirements, while keeping legal, technical and environmental standards, there is a need for expanding the European capacity in energy systems real-time simulation. Modelling of large-scale energy storage, power grids and complete urban system structures is necessary, including information on the social and economic dimensions. RI in this field would provide a virtual environment of the energy system in which new policies, regulation, control strategies or technologies can be tested and optimized *ex ante*. Since much of the development and smart resource management happen locally, the models should be able to capture data with very detailed geographical resolution. On the other hand, merging regional, national and European views is needed when outlining the design of the future energy system and related policies. This knowledge requires adequate HPC capacities as well as concerted approaches of handling big data volumes. It is key to further political decisions and to determining the immense investments needed in the energy sector in coming years.

# CONTENTS



PART2

**LANDSCAPE ANALYSIS - SECTION1**

# ENVIRONMENT

# ENVIRONMENT

Environmental sciences are traditionally divided into four research and study domains: **ATMOSPHERE**, **HYDROSPHERE**, **BIOSPHERE** and **GEOSPHERE**. These different *spheres* are closely interlinked, and therefore environmental sciences can also be presented according to *Grand Challenges*, such as loss of biodiversity, pollution, depletion of natural resources, risks, hazards and climate change.

**Atmosphere, hydrosphere, biosphere and geosphere are closely interlinked spheres of environmental sciences responding to big human challenges from loss of biodiversity to climate change.**

Many of the most critical and urgent issues that human society faces are linked to key environmental challenges. Managing and responding to natural and anthropic environmental changes need to be understood at the Earth System level. The effect of pollution and climate change, including associated impacts on biodiversity and ecosystem integrity, need to be fully understood urgently. The sustainable and responsible use of key natural resources and ecosystem services such as food, water, energy and minerals by a more demanding and growing population is vital. Modern society is progressively vulnerable to the increased frequency of natural hazards such as extreme weather, earthquakes, space weather, epidemic disease outbreaks, which can cause loss of life and have an enormous impact on the society with large economic deficits. Tackling environmental challenges is crucial for mankind and for life on Earth and given the scale, complexity and the interlinkages of the challenges, a multidisciplinary approach is essential. Layers of complexity to carrying out environmental research are added by the multidisciplinary aspect amongst the main Earth system domains and by the considerable range of spatial and temporal scales involved.

Because of its complexity, the environmental research as a whole should be facilitated by comprehensive observations with an integrated approach including experiments and modelling which are essential for understanding and predicting the Earth's environmental system.  A federated approach to IT resources and e-science facilities – including liable data policies according the FAIR principle – is also necessary. The objective of achieving a comprehensive multidisciplinary approach to improve our scientific understanding of the Earth's system can be obtained with the realisation of the current ensemble of RIs in the Environmental domain which are highly integrated in respective global efforts. The existing Environmental RIs already adopt this approach; many include observing systems which generate key data for the European and the international scientific communities, and contribute to global data systems, among them Global Atmosphere Watch (GAW)[1] and the European component of GEO[2] in creating a Global Earth Observation System of Systems (GEOSS)[3] that will link Earth observation resources world-wide across multiple Societal Benefit Areas – agriculture, biodiversity, climate, disasters, ecosystems, energy, health, water and weather – making those resources also available for better informed decision-making. Their main objectives are:

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

Several RIs in the Environmental domain are also feeding in the European Union's flagship Copernicus[4] programme, focusing on operational monitoring of the atmosphere, oceans and land services, whose main users are policy-makers and public authorities. Copernicus is providing validated information services in six areas: land monitoring, marine monitoring, atmosphere monitoring, emergency management, security and climate change.

Other linkages with the Joint Programming Initiatives (JPI's)[5] such as JPI Climate, JPI Oceans, JPI Water, JPI-FACCE as well as with other initiatives such as EMODNET[6], the European Environment Agency (EEA)[7] and the INSPIRE Directive[8] should be strengthened.

The ESFRI environmental RIs play also a key role at global scale in the UN framework, contributing to the UN Sustainable Development Goals[9], the UN Framework

1. GAW aims to understand and control the increasing influence of human activity on the global atmosphere.
*http://www.wmo.int/pages/prog/arep/gaw/history.html*

2. GEO, established in 2005, is a voluntary partnership of governments and organizations that envisions "a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations and information".
GEO Member governments include 96 nations and the European Commission, and 87 Participating Organizations comprised of international bodies with a mandate in Earth observations
*https://www.earthobservations.org/index2.php*

3. Global Earth Observation System of Systems (GEOSS)
*http://www.earthobservations.org/geoss.php*

4. Copernicus – European Programme for the establishment of a European capacity for Earth Observation
*http://www.copernicus.eu/*

5. Joint Programming Initiative (JPI)
*http://ec.europa.eu/research/era/joint-programming-initiatives_en.html*

6. EMODNET
*http://www.emodnet.eu/*

7. European Environment Agency (EEA)
*https://europa.eu/european-union/about-eu/agencies/eea_en*

8. INSPIRE Directive
*https://inspire.ec.europa.eu/*

9. UN Sustainable Development Goals
*https://sustainabledevelopment.un.org/*

Convention on Climate Change (UNFCCC)[10] and the Convention on Biological Diversity (CBD)[11].

Environmental RIs play an important role for the scientific community and the society at large by:

- providing centres of frontier scientific research as focal points for education and training of researchers and contributing significantly to the European skills base;
- delivering essential data for more reliable communication to the general public on events such as volcanic eruptions, earthquakes, poor air quality and extreme weather as well as information on biodiversity impacts;
- generating coherent, comparable and sustained time-series of key environmental variables;
- producing accurate data and scientific and technical knowledge that underpin the construction of tools supporting decision making and development of efficient regulations and policies;
- 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;
- developing new technologies, such as laser-based sensors, high resolution wireless networks and remotely operated autonomous systems, which leads to additional co-benefits.

Environmental Research Infrastructures have multiple roles in tackling the *Societal Challenges* as listed in the EU Horizon 2020[12] program with *Climate action, environment, resource efficiency and raw materials* being closest connected to them. *Health, demographic change and wellbeing* as well as *Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the Bioeconomy* are strongly dependent on the whole environment, particularly when it comes to climate change adaptation, pollution, or overuse of ecosystem services. Environmental catastrophes can shutter societal security and cause migration with related security problems. The *Societal Challenges Secure, clean and efficient energy* and *Smart, green and integrated transport* even directly respond to environmental necessities and can receive guidance from a comprehensive understanding of the Earth System. Needless to say that societies that concern their environment are inclusive, innovative and reflective.

There is an urgent need to sustain, integrate and further develop a diverse set of Environmental RIs in a way that Europe can address both the key societal and economic challenges as well as improve our basic scientific knowledge.

10. UN Convention on Climate Change (UNFCCC) https://unfccc.int/

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

12. H2020 Societal Challenges https://ec.europa.eu/programmes/horizon2020/en/h2020-section/societal-challenges

# 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 the 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 on different thematic areas like climate change, air quality, environmental hazards, environmental risks, food security and the water cycle.**

The research on the atmosphere is multidisciplinary, embracing atmospheric chemistry, physics, dynamics and radiation; and it combines observations and modelling. It also has to cover 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. The atmospheric domain interacts with marine, terrestrial, freshwater, solid earth systems and the near space.

The atmosphere contains a wide range of trace species. The identification and quantification of their properties, atmospheric transport and transformation processes and life cycles 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 Research Infrastructures has to play an important role.

Atmospheric Research Infrastructures do not only provide monitoring, but exploratory infrastructures are also needed to study the processes. Atmospheric processes are multiscale in time and space, from the sub-second, sub-micron scale of microscopic processes 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.

## CURRENT STATUS

The European atmospheric landscape covers a wide range of actions ranging from the establishment of ESFRI long-term atmospheric Research Infrastructures to EU-funded projects such as Integrating Activities (IA), Design Studies, and other projects.

- Long-term atmospheric observation platforms: the **ESFRI Project ACTRIS** (Aerosols, Clouds and Trace gases Research Infrastructure); the **ESFRI Landmark IAGOS** (In-service Aircraft for a Global Observing System) (Airborne, lower atmosphere); the **ESFRI Landmark ICOS ERIC** (Integrated Carbon Observation System); ARISE (Atmospheric dynamics Research Infrastructure in Europe) and the **ESFRI Landmark EISCAT_3D** (Next generation European Incoherent Scatter radar system) (upper atmosphere); SIOS (Svalbard Integrated Arctic Earth Observing System) (Integrating all observations, terrestrial, marine and atmosphere at Svalbard).

- Exploratory process oriented research, atmospheric chemistry including aerosols: the **ESFRI Project ACTRIS**; EUROCHAMP 2020 (laboratory studies); EUFAR (Airborne platforms for field experiments).

- Modelling development and experiments: IS-ENES (global climate and earth system models).

The atmospheric subdomain landscape is sketched in **Figure 1** in a topic (x-axis) versus altitude (y-axis) graph.

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 informa-

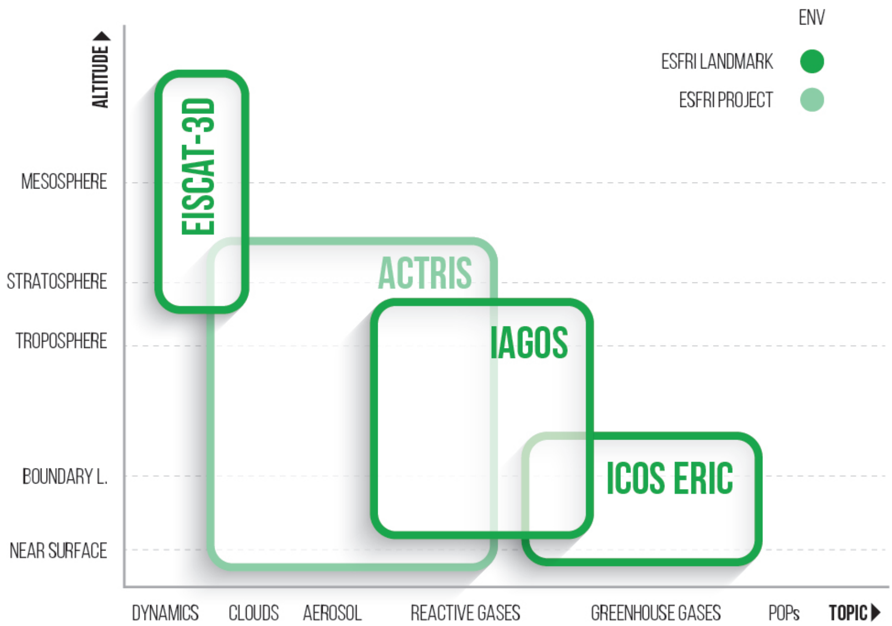



FIGURE 1.
Schematic overview of the ESFRI RI landscape for the atmosphere sub-domain

tion, services, tools and reference methodologies that are used and applied by a very wide community also outside Europe.

An assessment of the user community conducted in 2018 in the framework of the cluster of environmental Research Infrastructures (ENVRI) provided more than 3.000 users and more than 25.000 user requests per year for the Atmosphere Domain RIs. Areas of data use include fundamental research on atmospheric processes, climatological studies on the long-term evolution of the atmosphere and trends of key species, validation of Earth System Models, assimilation of data for numerical weather prediction, validation of satellite products and development of new measurement technologies.

One major user of Atmosphere RIs data products and services is COPERNICUS Atmosphere Monitoring service (CAMS)[13]. The **ESFRI Project ACTRIS**, and the **ESFRI Landmarks 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 forecast of air quality in Europe for European cities, also shown daily on EURONEWS.

## GAPS, CHALLENGES AND FUTURE NEEDS

In response to the status of the existing RIs, specific gaps and challenges have been identified. It is important to study not just components of the atmospheric system but observe as many of those components synergistically as possible to fully understand processes and linkages. A synergistic approach must include the use of *in situ* ground based observations, together with columnar and vertical profile, aircraft and satellite observations and models to study and 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 the geographical coverage by atmospheric observing infrastructures in the Mediterranean including North Africa and Eastern Europe is incomplete. Understanding the atmospheric composition changes and processes is a global issue, and the relevance for Europe is not limited to observations performed on sites located in European regions; there is a responsibility of Europe to explore where further atmospheric observations could be supported, in Africa to start with. Moreover, harmonised measurements on larger geographical scale are crucial and strong international cooperation is needed. A better integration of existing programs and projects in the atmospheric area will help to build and sustain the European component of GEOSS.

Interconnections with other domains – i.e. Health – need to be better explored. Air pollution is a major environmental risk to health. Short-lived atmospheric compounds have recognized adverse health effects at concentrations typically found across Europe and potentially lead to more than 400.000 premature deaths annually in the EU28. In particular, the effect on children's health should be better explored and in this context the role of atmosphere RIs to foster scientific cooperation in this field is of primary importance.

13. COPERNICUS Atmosphere Monitoring service (CAMS) *https://atmosphere.copernicus.eu/*

# HYDROSPHERE

Water is essential for human life and nature and plays a critical role in most natural processes. Water covers about 70% of the Earth's surface and over 97% of it is in oceans, and most of the remaining freshwater is in the form of ice.

**Water is of huge global geopolitical importance and is central to all the key, current environmental issues: climate change, biodiversity, natural hazards, pollution, ecosystem services, and desertification.**

Most water on Earth, including that present in lakes, rivers, deltas/estuaries, lagoons, etc., is part of the hydrological cycle and is inter-linked with the atmosphere, cryosphere, soils, sediments and the rest of the geosphere, as well as with the entire biosphere. Water must therefore be seen and studied in a holistic way.

Climate change, land use and abuse, economic activities such as energy production, industry, agriculture and tourism, urban development and demographic change mostly impact negatively on the status of water and as a result, the ecological and chemical status of EU waters, from mountain springs to coastal zones, is threatened. In addition, more parts of the EU are at risk of water scarcity. Water ecosystems – on whose services our societies depend – become more exposed to extreme events such as floods and droughts. It is essential to better address these challenges on the basis of improved scientific understanding of all relevant processes so as to preserve our resource base and increase its resilience for life, nature, society and to protect human health in the changing climate.

## FRESHWATER:
### ICE, GROUNDWATER, LAKES, RIVERS, ESTUARIES

A holistic view on the water cycle requires integrated, interdisciplinary and trans-sectorial approaches that provide solutions to managing water-related societal risks. Environmental monitoring agencies across Europe continuously collect vast amount of data on freshwater. Linking this routine sampling with high-resolution data from freshwater supersites and remote sensing data would benefit society directly as well as by supporting research in the area. Some research facilities have collected data on snow, ice and freshwater and complementary environmental and ecological information for more than a century. These long time series have been instrumental in understanding the coupling between the water cycle, the changing climate and ecosystems. It is of vital importance to ensure that the long-time series are continued. Experimental facilities for studying complex water-related phenomena – e.g. physical modifications of estuaries, behaviour of substances and energy in mesocosms, etc. – allow physical models to underpin better systemic understanding, often in conjunction with mathematical models.

### II 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** (International Centre for Advanced Studies on River-Sea Systems), supporting interdisciplinary research in river-sea systems, is the only physical pan-European Research Infrastructure devoted to support also research on transitional zones between coastal marine and freshwater areas, together with the **ESFRI Landmark LifeWatch ERIC** (e-Infrastructure for Biodiversity and Ecosystem Research) as the only e-RI, which extends its area of interest also to the whole freshwater environments. 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 Project AnaEE** (Infrastructure for Analysis and Experimentation on Ecosystems, H&F) also offers access to experimental facilities in freshwater environments.

### ▶ GAPS, CHALLENGES AND FUTURE NEEDS

Europe needs a dense, highly instrumented super-sites 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 and 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 Water JPI Strategic Research and Innovation Agenda[14] and the WssTP Strategic Innovation and Research Agenda[15] provide frameworks for collaborative research and innovation efforts. The Water JPI intends to increasingly play a role in facilitating the use of relevant RIs, whereas for example WssTP advocates the use of "real life living labs" where innovative solutions can be tested hence facilitating the scaling up of solutions.

14. Water JPI, 2016
*http://www.waterjpi.eu/images/documents/SRIA%202.0.pdf*

15. WssTP, 2017
*http://wsstp.eu/wp-content/uploads/sites/102/2017/01/WssTP-SIRA_online.pdf*

# MARINE:
## FROM COAST TO DEEP OCEANS AND ICE CAPS

Shelf seas and the world-embracing ocean form a group of dynamic complex systems with a strong interplay of physical, chemical and biological phenomena at multiple spatial and temporal scales. Due to inaccessibility, even their *static* features – e.g. ocean bathymetry – are poorly known. Seas and oceans provide food, energy, and many other resources on which mankind depends. The oceans have a fundamental influence on our climate. Society is increasingly concerned about global change and its regional impacts. Sea level is rising at an accelerating rate, the Arctic sea ice cover is shrinking as high latitude areas are warming rapidly, and storminess is forecast to increase. Since 1955, over 90% of the excess heat trapped by greenhouse gases has been stored in the oceans[16]. The oceans are affected by the increased amount of $CO_2$ in the atmosphere leading to ocean acidification which poses threats for many species. Changes in the thermal structure of water masses are likely to influence currents and stratification. The effects of climate change add to other stresses, such as pollution, in particular [micro]-plastics, and overfishing that are already threatening the biodiversity and health of the seas and oceans.

Last but not least, sources of geo-hazards such as slide prone slopes, active tectonic structures and volcanoes to mention some, lay in marine environment at various depth and distance from the coasts. Wherever they are adjacent to populated regions, to economically developed areas or sites of strategic relevance, they represent threats for the socio-economic fabrics and wellness. Marine observatories provide an essential integration to land-based RIs for a broader vision in the comprehension of the natural phenomena.

Ocean observation is currently a key component of the EU Strategy for Marine and Maritime Research and has become a high priority on the worldwide environmental political agenda.

16. IPCC (2013) WG1 AR5 http://www.ipcc.ch/report/ar5/wg1/

## CURRENT STATUS

Marine RIs consist of up to 800 – increasingly networked – distributed facilities in Europe, serving various domains such as ocean – seafloor, subseafloor and water layers above – and coastal sea monitoring, marine biology research, blue biotechnology innovation, research in aquaculture and ocean engineering. Their observation and data management components form the foundation for a European Ocean Observing System (EOOS), providing the platforms and services to deliver environmental data, information and ultimately knowledge. Marine RIs, including e-RIs, are as diverse as: research vessels[17] and their underwater vehicles for sea access and deep sea exploration/sampling; voluntary vessels for surface and sub-surface monitoring; fixed and mobile, autonomous, including drifting, *in situ* observing systems for seawater column and seabed observation and monitoring; satellites for remote sensing for sea-surface monitoring; marine data centres; land-based facilities for ocean engineering, such as deep wave basins, water circulation canals, sensors tests and calibration laboratories; and experimental facilities for biology and ecosystem studies and for marine genomics, biodiversity, blue biotechnology, aquaculture, mesocosms; virtual research experimental facilities for biodiversity and ecosystem studies integrating data resources from the physical infrastructures and observation systems. Marine research stations, of which there is a high density around Europe, often provide a combination of services to marine researchers.

Key RIs for water-related research are fostered in ESFRI, as reported in **Figure 2**, while there are also other EU projects and initiatives supporting networks that are directly relevant for research.

17. UNESCO (2017), Global Ocean Science Report—The current status of ocean science around the world, L. Valdés et al. (eds), UNESCO Publishing, Paris https://en.unesco.org/gosr

- 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** (European contribution to the international Argo Programme), EuMarineRobots.
- Open ocean fixed point observatories: the **ESFRI Landmark EMSO ERIC** (European Multidisciplinary Seafloor and water-column Observatory).
- Research vessels and underwater vehicles: ARICE, EUROFLEETS.
- Coastal/shelf seas observatories: JERICO-NEXT.
- 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** (A distributed infrastructure for life-science information, H&F), the **ESFRI Landmark EMBRC ERIC** (European Marine Biological Resource Centre, H&F), the **ESFRI Landmark LifeWatch ERIC** – as e-RI – and the **ESFRI Project AnaEE** (H&F).
- Carbon cycle: the **ESFRI Landmark ICOS ERIC** and the **ESFRI Landmark LifeWatch ERIC**, as e-RI.

## GAPS, CHALLENGES AND FUTURE NEEDS

Taking into account recent efforts to define research priorities and infrastructure needs, such as European Marine Board position paper, JPI Oceans SRIA agenda, SEAS-ERA reports, a gap analysis has been performed by the marine community to identify gaps and weaknesses of the present understanding of how the ocean functions and our observing system. Marine regions in open seas are under-sampled, thus additional observatory nodes, together with an acceleration of technological developments, are required – e.g. deeper measurements from Argo floats, Biogeochemical Argo floats and from SMART Cables[18]. The UNESCO Intergovernmental Oceanographic Commission (IOC) is preparing the UN Decade of Ocean Science for Sustainable Development (2021-2030) to improve the scientific knowledge base, in view of humanity's increasing reliance on ecosystem goods and services from the ocean. The current global knowledge base is very weak – e.g. IOC estimates that 99% of habitable marine areas lack basic biodiversity knowledge for their management[19]. However, efforts are on-going to employ newly developed sensors and samplers that can be mounted on observing autonomous platforms – buoys, glider, profiler etc. – or vessels and ships seizing opportunities for more automated sampling and analysis for biochemical and biological parameters. The use of opportunistic sampling needs to be further expanded, e.g. sensors could be further deployed on commercial ships operated by the private and public sector (analogue to **ESFRI Landmark ICOS ERIC**).

Beyond the development of existing or planned individual Research Infrastructures and networks, a more holistic approach is needed for the observing components which are serving many different communities, including but not limited to the scientific community. The observation component is the first crucial part of the system which needs standardisation and interoperability effort to ultimately allow us to better know and understand the functioning of marine ecosystems. Other components will require more sophisticated models. From the perspective of a user of scientific information for utilisation in policy, a large gap is the frequent absence of science-based assessment criteria to evaluate the impact of human activities on environmental status[20] and ecosystem services, indicating a strong need to understand better the multiple cause-effect chains in the marine environmental realm as a contribution to sustainable use of marine and maritime resources.

Economic constraints impose a flexible and multi-use approach, innovation towards cost-effective observing strategies, and prioritisation among possibly conflicting needs. Efforts towards an integrated and sustained EOOS are ongoing with discussions among the community on a specific strategy, implementation plan and sustainable budget. EOOS should build on the wealth of existing RIs capabilities and multi-platform assets already operational across European waters. EOOS would integrate marine observations from the coast to the open ocean and from surface to deep sea; promote multi-stakeholder partnerships for funding observing systems and sharing of data and align with global efforts within a robust framework. The EOOS should also be smart, resilient and adaptable, driven by scientific excellence, stakeholder needs and technological innovation, to fill the need for cross-disciplinary research and multi-stakeholder engagement.

18. ITU/WMO/UNESCO IOC Joint Task Force https://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx

19. IOC, 2018. The United Nations Decade of Ocean Science for Sustainable Development (2021-2030) http://unesdoc.unesco.org/images/0026/002619/261962e.pdf

20. Identified gaps on MSFD assessment elements. PERSEUS Project. ISBN 978-960-9798-01-3. Laroche S. et al., 2013. https://bit.ly/2uppYmC

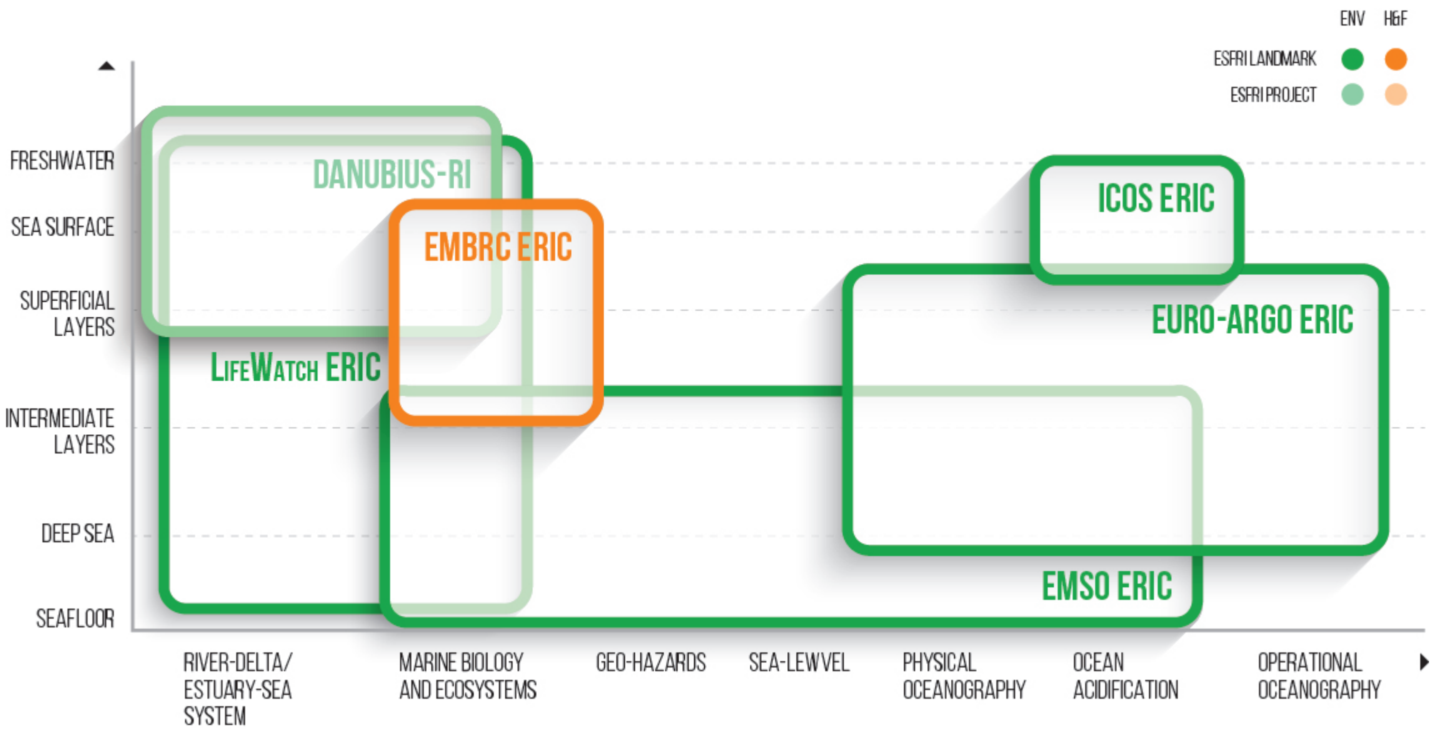



**FIGURE 2.**
Simplified diagram of the observation capabilities of ESFRI Landmarks and Projects respect to the hydrosphere components (Y axis) and to the environmental processes therein (X axis).

# BIOSPHERE: BIODIVERSITY AND ECOSYSTEMS

Biodiversity research integrates the study of the diversity and variability of Life on Earth – namely terrestrial, marine and freshwater ecosystems, and including diversity at genetic, species and ecosystems. Ecosystem functions refer to the structural components of the ecosystems – e.g. water, soil, atmosphere and biota – and how they interact with each other, within ecosystems and across them, and how they interact with societal activities.

**A better understanding of the interconnections, including quantitative relations, between biodiversity and ecosystem services will allow a better response to *Grand Challenges*, namely those included in the Sustainable Development Goals.**

Biodiversity plays a central role in ecosystem functioning and provision of ecosystem services and is thus linked to key *Societal Challenges* such as a secure and safe supply of food and water and other natural resources, human health, energy as well as climate regulation and pollination. The biodiversity and ecosystem research is highly complex not only because of necessary multi-spatial and multi-temporal approaches, but also because associated time scales can range from micro-seconds up to millennia. Therefore, biodiversity and ecosystem research requires a multi- and interdisciplinary integrated approach.

Over the past 50 years or more, ecosystems have changed dramatically due to human pressure. Ecosystems have been affected by soil exploitation, land-use change – for example formation of large monocultures, over-exploitation of natural resources, habitat destruction and contamination. Furthermore, invasive species has resulted in biodiversity loss and disruption of natural communities. As a result, in Europe, a several species are threatened with extinction. For instance, it is estimated that 15% of all mammals are threatened with extinction, 13% of all birds, 37% of all fishes, 19% of all reptiles and 23% of all amphibians. These impacts affect the structure and functioning of ecosystems and consequently their sustainability.

The land-use change which causes habitat destruction and the alien invasive species are the most serious threats to biodiversity, the loss of which is recognised to cause decrease of ecosystem services by affecting ecosystem functioning and stability. The effective strategies to control invasive species include the early detection, regular monitoring of the growth of invasive alien species populations, and prediction of future spread. Research Infrastructures could be instrumental to develop these strategies, providing facilities to mobilize, access and analyse data of citizen science, remote sensing, and develop species distribution modelling for current and future distributions.

In order to protect biodiversity, it is important to also understand the societal drivers, such as demographic, economic, socio-political, cultural and religious, and scientific and technological changes (Millennium Ecosystem Assessment, 2005) as well as their impact on the ecosystems – habitat change, invasive alien species, and overexploitation of species – and thereby indirectly identify reasons for biodiversity loss.

Ecosystem integrity is indispensable to reach the UN Sustainable Development Goals (SDGs)[21]. Goal 15 directly refers to terrestrial ecosystems: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. Furthermore, standardised observations from the terrestrial ecosystem and biodiversity domain comprise essential climate variables (ECVs) and essential biodiversity variables (EBVs) and thus provide knowledge towards the UN Conventions on Climate Change (UNFCCC)[22] and Biological Diversity (CBD)[23].

Long-term observations and monitoring as well as long-term research programs are indispensable for the interpretation of ongoing ecosystem changes, including those responsible for biodiversity loss and erosion.

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

22. UN Convention on Climate Change (UNFCCC) *https://unfccc.int/*

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

## CURRENT STATUS

The European landscape for terrestrial ecosystem and biodiversity RIs covers the complexity of the research agenda (see **Figure 3**). The ESFRI RIs are built on or closely connected to EU-funded projects such as Integrating Activities (IA).

- Observatories and Monitoring Facilities: the **ESFRI Landmark ICOS ERIC**, the **ESFRI Projects DANUBIUS-RI** and **eLTER** (Integrated European Long-Term Ecosystem, critical zone and socio-ecological system Research Infrastructure), the IA InterAct (ongoing), InGOS (until 2015), and SIOS (Svalbard Integrated Arctic Earth Observing System) (Integrating all observations, terrestrial, marine and atmosphere at Svalbard).

- Facilities for *in situ* and in vivo experimentation: The **ESFRI Project AnaEE** (H&F), the IA AQUACOSM.

- Biological collections, Data infrastructures and reference data: the **ESFRI Project DiSSCo** (Distributed System of Scientific Collections), the **ESFRI Landmark ELIXIR** (H&F), and the **ESFRI Project MIRRI** (Microbial Resource Research Infrastructure, H&F), the IAs SYNTHESYS (until 2017).

- e-Infrastructures for analysis and modelling: the **ESFRI Landmark LifeWatch ERIC**, and the IA IS-ENES (ongoing).

The size of the researcher community served by these RIs might be estimated using as proxy the number of researchers engaged with national and international ecological associations, which raises up to 10.000 in Europe and 40.000 worldwide and additional researchers from climate and GHG communities. Other direct users include officers of regional, national and European environmental agencies responsible for national inventories and nature conservation, local and national administration, and environmental NGOs supporting decision making and policy implementation.

The paradigm shift in terrestrial ecological research from searching for a unifying ecosystem theory to tackling specific *Grand Challenges* (and in addition a shift from

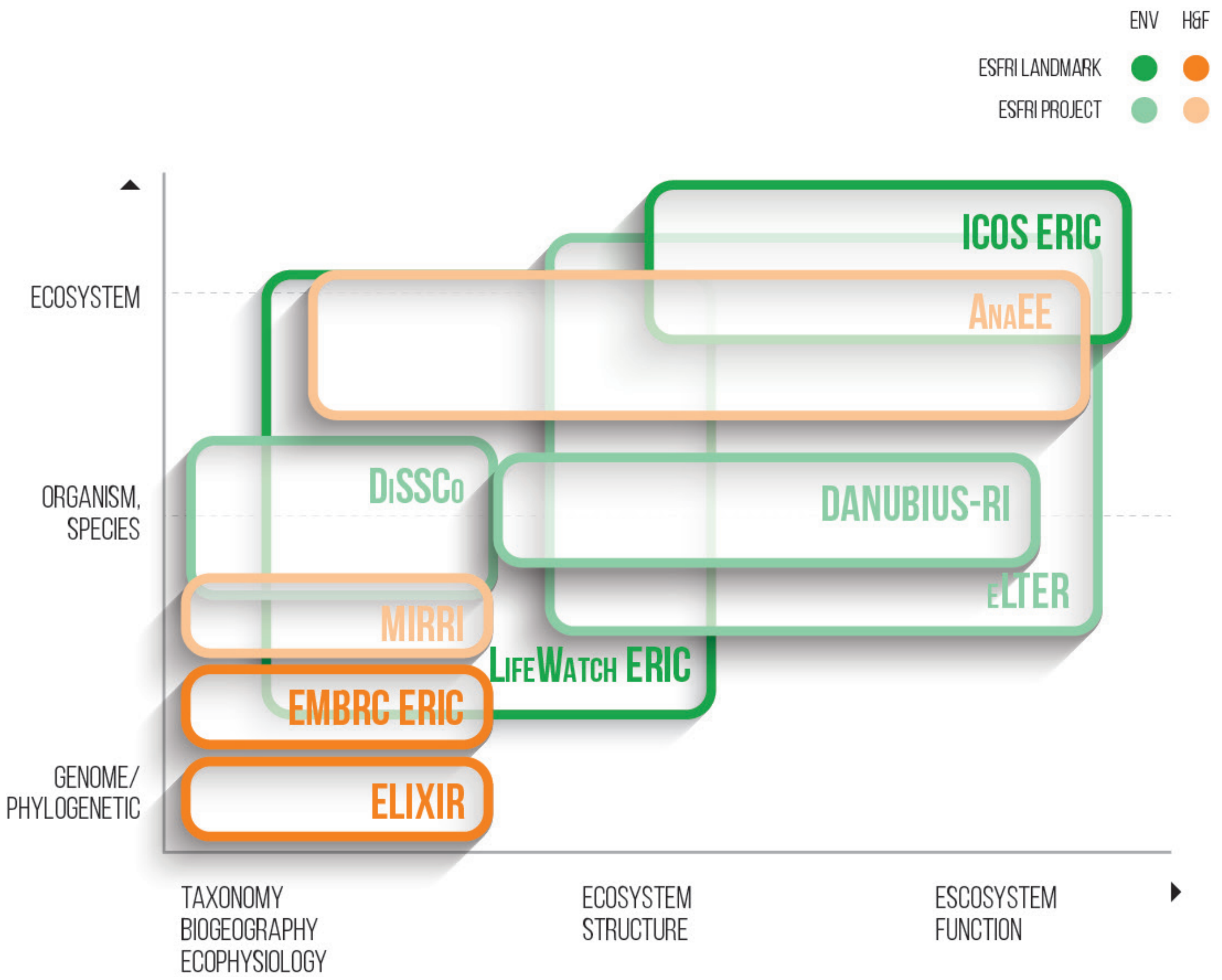



FIGURE 3.
Schematic landscape of biodiversity and ecosystem ESFRI Research Infrastructures.

ecosystem conservation to preservation of ecosystem services) is mirrored by all Research Infrastructures in the domain but differs in the degree of being conducted in the basic concept of individual RIs. With the strongest relation to the approach of ecological integrity, the **ESFRI Project eLTER** is tackling a broad spectrum of ecological challenges, however the theoretical base is starting from understanding ecosystems. The **ESFRI Project AnaEE** (H&F), providing experiments instead of observations, and with stronger focus on agriculture and food security, is starting a bit more specific from a defined set of ecological and societal challenges and has a more anthropocentric objective in the preservation of ecosystem services, food security as well as specific contributions to bioeconomy.

In contrast to the **ESFRI Projects eLTER** and **AnaEE** (H&F) with their basis in the ecological integrity approach or in a broad spectrum of related *Grand Challenges*, the **ESFRI Landmark ICOS ERIC** is following a cross-domain approach that aims to understand 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 **ESFRI Landmark LifeWatch ERIC** has, similar to ICOS, a cross-domain approach and a focus on the *Grand Challenges* of preserving biological diversity and of protecting ecosystem health. The **ESFRI Landmark LifeWatch ERIC** is an e-Infrastructure without own observations and enables knowledge-based solutions to environmental managers by providing access to a multitude of sets of data, services and tools. Specific issues related with biodiversity research, the role of biodiversity in ecosystem functioning and conservation are addressed by the construction and operation of Virtual Research Environments (Virtual Laboratories & Decision-support Applications) where integrated models at the meso- or higher scales are executed.

The digitalisation 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. Of the 8 million species that are estimated to exist, only 1.8 million are currently scientifically described. For some biological groups – insects, nematodes, and microorganisms – only 10% of the species are known, and many species become extinct without being discovered. Many parameters in taxonomy need specialized human efforts. The overall ensemble of RIs in the terrestrial ecosystem and biodiversity field covers comprehensively the scales from molecules to continents and responds to a wide range of environmental challenges.

# GAPS, CHALLENGES AND FUTURE NEEDS

The *Grand Challenges* related to biodiversity, ecosystems and biodiversity are highly inter-related. Land-use change is usually accelerating both loss of biodiversity and climate change by release of CO2 and by creating agricultural monocultures or land degradation.

Firstly, 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 with respect to genomics, species and ecosystem analysis.

Other challenges are the invasive species which can affect native species and habitats, alter the ecosystem primary productivity and thus the carbon sequestration. Consequently, the RIs need to better integrate their data life cycles and to seek common geographical coverage of their observing infrastructures by co-location and a mutual strategy to fill geographical gaps. 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 ecosystem models represent only facets and require further development.

Monitoring biodiversity and ecosystems changes requires also the development and implementation of the Essential Biodiversity Variables[24] as ecological data products underpinned on data and metadata standards, data quality and data preservation would ensure the needed interoperable resources to perform ecological studies and assessments.

The manifold connections to other fields, particularly Health & Food, but also Social Sciences and Energy are obvious. Agriculture and Bioenergy directly affect ecosystem integrity which itself is an important factor for human health, but also for food production. Environmental literacy and behaviour are important interfaces to Social Sciences.

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

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

The solid Earth science is concerned with the internal structure and dynamics of planet Earth and with surface processes. Solid Earth science deals with multiscale physical and chemical processes, from microseconds to billions of years and from nanometres to thousands of kilometres.

**Geology, natural hazards, natural resources and environmental processes, in general, do not respect national boundaries, therefore seamless, trans-national integration of measurements and calibrated data is crucial to enable research and societal applications.**

Progress in Solid Earth science relies on integrating multidisciplinary data acquired through long-term monitoring, new observing systems, and high-level taxonomy data products. The understanding of environmental changes requires unravelling complex and intertwined processes. Solid Earth science contributes to systemic and highly cross-disciplinary investigations, representing an essential component of the investigation of the Earth system. The ash and gas dispersion during a volcanic eruption is a key example of the multidisciplinary observations required to monitor a natural phenomenon and its underlying processes – e.g. seismic activity, ground deformations, magma rheology – and of the cross-disciplinary implications for meteorology, atmospheric sciences, marine sciences, and the life sciences.

In addition to enable fundamental scientific advancement in understanding planet Earth, RIs in the solid Earth domain provide a crucial contribution to two areas of high societal relevance: geo-hazards and geo-resources. In particular, they:

- enable assessing and mitigating the risks caused by natural hazards, such as earthquakes, volcanic eruptions, tsunamis and landslides;

- make available monitoring infrastructures, experimental facilities and expertise for optimising exploration and exploitation of geo-resources and monitoring of natural resources, including geo-energy resources (i.e. geothermal energy, conventional oil and gas, shale gas), underground storage (carbon, gas, nuclear waste), raw materials, minerals and rare earth elements, and for estimating and mitigating the risk of anthropogenic hazards, such as earthquakes possibly induced by the extraction of geo-energy resources;

- provide the monitoring and research background for a correct use of the underground, taking into account considerations of RIs, long-term environmental sustainability and economic viability.

## CURRENT STATUS

The solid Earth domain is represented in ESFRI by a single Research Infrastructure, the **ESFRI Landmark EPOS** (European Plate Observing System). 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. As a result, the **ESFRI Landmark EPOS** integrates several hundreds of individual RIs, distributed in all countries of the Euro-Mediterranean region, with the aim to obtain an efficient and comprehensive multidisciplinary research platform for the Earth sciences in Europe based on novel e-infrastructure concepts for interoperability and provisions of distributed data through Integrated Core Services (ICS) and Thematic Core Services (TCS). In order to enable the required access to inter-disciplinary observations, the **ESFRI Landmark EPOS** established strategic and synergetic alliances and specific TCSs with existing data- and service-providers, such as ESA for the satellite data , the EuroGeoSurveys for the geological data and interpretations, INTERMAGNET for magnetic data and EUREF for reference GNSS data and products.

In addition to the **ESFRI Landmark EPOS**, other geosciences RIs and projects are operated globally or in fields currently not formally included in the EPOS RI framework; on-going work is conducted to ensure the required coordination and integration (**Figure 4**). These include:

- the continental- and ocean-drilling RI and programs (ICDP and IODP/ECORD);

- the collections of exploration data (oil and gas, minerals);

- the underground laboratory facilities established for research on geological waste repositories, now federated by the new initiative EUROL;

- European ERANET programs covering mineral and energy resources, ERA-min[25], coordinating research and development in Europe in the field of mineral prospecting, coordinating and integrating national infrastructures, data management and technical development to support the joint European research efforts with the aim to contribute to European mineral security; ACT, to advance carbon technologies towards the establishment of a carbon-free society; GEOTHERMICA, for the advancement of geothermal and petrothermal technologies for electricity and energy generation and storage;

- Research Infrastructures projects, for access to data, services and infrastructures in seismology and earthquake engineering

25. ERA-min http://www.era-min-eu.org/

SERA; for access to observatories and Research Infrastructures for volcanology EUROVOLC;

- supersites EC projects in GEO, MEDSUV and FUTUREVOLC (Volcano observatories), MARSITE (Near Fault Observatories);

- international organization involved in coordinating national RIs and monitoring networks in seismology and seismic risk, ORFEUS (seismological data) and EMSC (seismological products), key contributor to EPOS;

- research projects on seismic hazard, early warning and risk assessment – SHARE, SAFER, REAKT, MATRIX, STREST;

- e-science Virtual Environment Projects, including VERCE, EUDAT, ENVRI and ENVRI+ (with a strong EPOS participation).

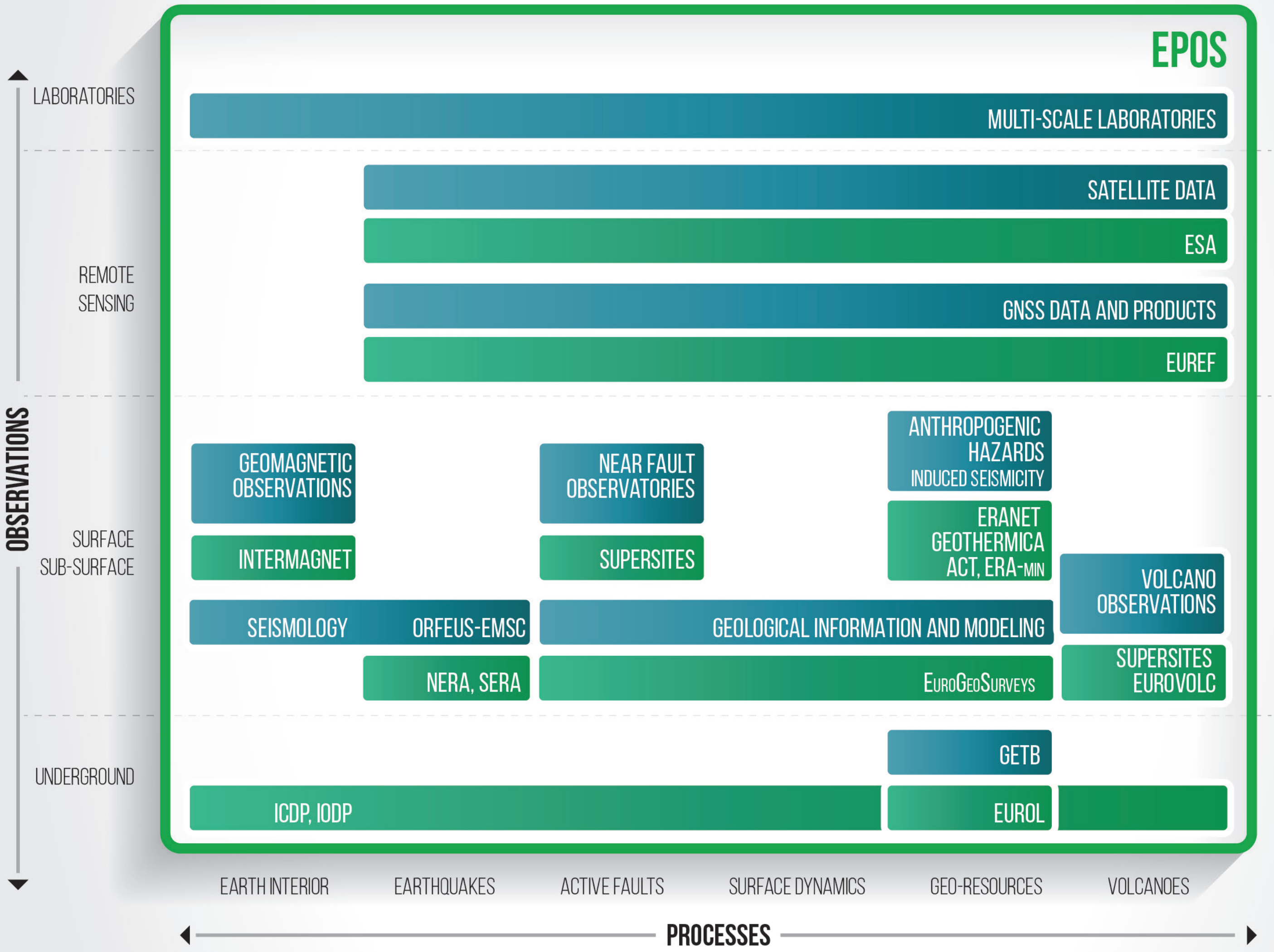



FIGURE 4.
Landscape of solid Earth science platforms and key application areas for the geosphere domain. Blue boxes identify the EPOS Thematic Core Services (TCS). Green boxes refer to other geosciences RIs and projects operated globally or in fields currently not formally included in the EPOS RI framework. (GETB=TCS Geo-Energy Test Beds for low carbon energy).

## GAPS, CHALLENGES AND FUTURE NEEDS

In the future, integration and cooperation in the Geosphere domain needs to concentrate on a few strategic priorities.

The interactions and collaborations between industrial stakeholders and the public sector – such as the European geological surveys – needs to be strengthened. This also involves the accountability of data and data providers as well as the adoption of effective interaction strategies in which the role of scientists is clear. This is mandatory to face ethic issues in communicating science and geo-hazards to society.

Europe uses about 20% of the world's primary metal supply, but produces far less than this (3-8%); the situation is worse for *critical metals* and rare earth elements; new RIs and data are urgent in the fields of geo-resources and mining, in order to achieve meaningful targets of energy and mineral security in Europe; the involvement of laboratories – rock deformation labs, deep underground labs, geophysical exploration data, technologies for environmentally friendly mining, analytical facilities for geochemistry and mineral resources, and modelling facilities are key required ingredients.

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.

Ocean and continental drilling equipment and programmes need to be intensified, this to increase geographical coverage in critical areas; this requires to collect observations on the solid Earth from oceanic regions, including dense ocean-bottom geophysical and seismic monitoring and floating devices.

Finally, the **ESFRI Landmark EPOS** will be completed and it could serve as a European platform for fostering integration and coordination of all observing and surveillance systems and their services at European scale and for increasing global coordination in solid-Earth observing systems, in cooperation with IASPEI, FDSN, IAVCEI, WOVO, GEO and other international programs and organizations.

# VISION AND PERSPECTIVES

The medium to long-term vision (2020-2040) for environmental Research Infrastructures is based on the objective to better facilitate and enable researchers to work in a more integrated manner towards universal understanding of our planet and its behaviour, and to tackle environmental challenges. It is important to study not just individual domains of our planet, but to observe as many of those domains synergistically. This should result in the evolution of a seamless holistic understanding of the Earth's system. Three interdependent resources, that of technological capital, cultural capital and human capital are needed to develop and achieve that vision: *technological resources* which entails the building of monitoring/observational, computational and storage platforms and networks; cultural resources entailing open access to data – requiring rules, licenses and citation agreements on metadata and data; and *human capital* requiring *data scientists* as well as *discipline scientists*.

A federated approach should help to reduce overlaps, to maximise synergies and benefits, and to coordinate Research Infrastructures in order to optimize observing systems ranging from *in situ* and remote sensing data measurement and collection, to data analysis in the laboratory. Concrete actions towards this direction have started already within the ENVRIPLUS (Environmental Research Infrastructures Providing Shared Solutions for Science and Society) project, the cluster of ENV RIs, built around ESFRI roadmap and associated leading e-infrastructures and Integrating Activities, and RIs from other domains as Health & Food for fostering cross-disciplinarity.

ENVRI has proven to be an excellent tool to coordinate Environmental RIs regarding everything from Management, Access policy, Data handling etc. It is of imperative importance that this initiative is continuing.

# CONTENTS



PART2

**LANDSCAPE ANALYSIS - SECTION1**

# HEALTH & FOOD

# HEALTH & FOOD

## KEY MESSAGES

The Health & Food RIs landscape is consolidating firmly in the European Research Area with now 10 Landmarks and 6 Projects covering the vast remit of health, agri-food and the bioeconomy.

To generate readiness to meet current challenges and demands, the Health & Food RIs need to continue cementing their efforts and connecting between them using their different competences and technologies at the service of the user community.

Gaps in the Health & Food landscape can be identified at many levels and it will also be important to connect infrastructure efforts with other domains, as significant innovations and new developments often occur at the boundaries of research areas.

In the field of data, further efforts are required to promote and facilitate the interaction between domains and to avoid fragmentation of the data continuum.

There is a broad consensus that future competitiveness in a globalised knowledge economy depends on research capability. Research Infrastructures (RIs) in the Biological, Agri-Food and Medical Sciences – i.e. Health & Food – continue to establish themselves as research, innovation and skills hubs and as a motor for economic impact. This is reflected in increasing levels of industrial access to RIs, and in their European and global positioning.

The economic impact of investments in large-scale biomedical research, such as the 3.75 billion € investment in the Human Genome Project, has spurred an estimated 900 billion € in economic growth, i.e. a 178-fold return on investment[1]. The bioeconomy on the other hand is estimated to be worth at least 2 trillion € in the EU[2]. The arrival of the digital age allows sharing and collective working on a large and distributed scale. Health & Food RIs are key catalysers of progress and change in this new age. The increasing level of sophistication in instrumentation, tools and techniques means that even very large institutions or laboratories cannot provide and maintain access to all services relevant to the field in question, hence services need to be more specialised and distributed. Distributed RIs offer an interdisciplinary set of skills, complemented by disciplines outside the Biological, Agri-Food and Medical sciences, and are well positioned to address the challenges facing our society today, which see no countries, boundaries or disciplines.

ESFRI has been instrumental and influential in the co-ordination of national decision-making and investment in European RIs in Health & Food. The landscape continues to evolve and it is important to ensure its ability and agility to respond to current and future demands. Much effort has been invested nationally and at EU level in identifying and establishing the current RIs in the ESFRI Roadmap (see **Figure 1**). These key infrastructures are at different stages in their implementation, providing access to a range of key services and giving much visibility to the Health & Food landscape.

Health & Food RIs are also taking an increasing role internationally. The Report of the Group of Senior Officials on Global Research Infrastructures[3] lists the **ESFRI Landmarks BBMRI ERIC** (Biobanking and BioMolecular Resources Research Infrastructure), **ELIXIR** (A distributed infrastructure for life-science information) and **INFRAFRONTIER** (European Research Infrastructure for the generation, phenotyping, archiving and distribution of mouse disease models) as Research Infrastructures of Global Interest recognising their global leadership.

There has been continued progress towards alignment of the Health & Food landscape with the national roadmaps. This is contributing to increased efficiency between existing RIs and will help consolidate existing and new RIs. The landscape requires sustained effort to complement with new RIs, to maximise current services, and to cement new functionalities, integration and interactions with the relevant fields. The Health & Food landscape considers the current and future challenges in Europe, notably in the provision of healthcare and sustainable and healthy food in the context of a changing cli-

1. Economic Impact of the Human Genome Project. Battelle Technology Partnership Practice for United for Medical Research – Tripp, S. & Grueber, M., 2011 https://bit.ly/2NaAzbQ

2. A Bioeconomy Strategy for Europe, 2012 http://ec.europa.eu/research/bioeconomy/

3. GSO Progress Report, 2017 https://ec.europa.eu/research/infrastructures/pdf/gso_progress_report_2017.pdf

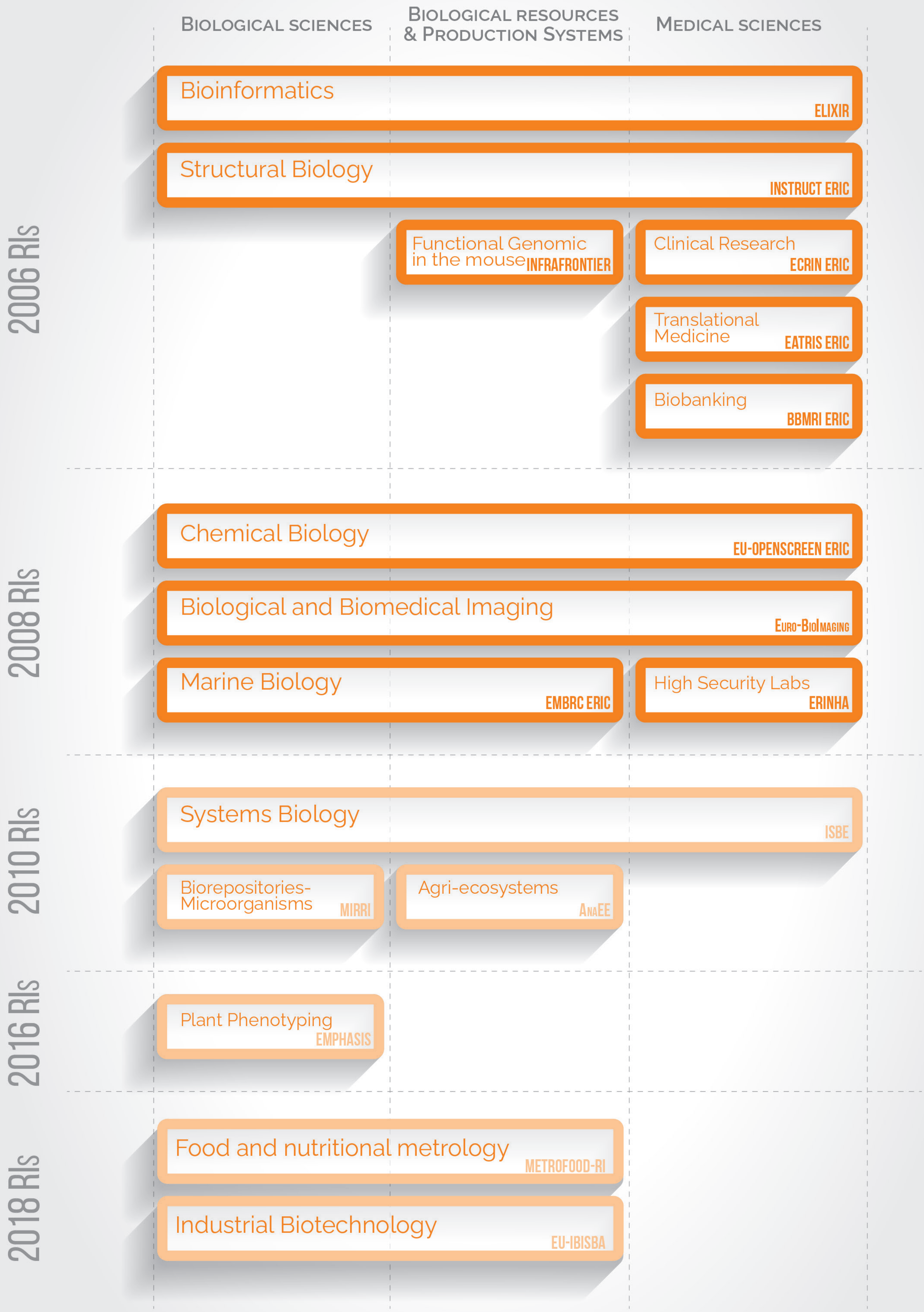



FIGURE 1.
Health & Food Research Infrastructures in ESFRI Roadmap 2018

mate and limited land availability. In order to generate readiness to meet the challenges and demands, the Health & Food RIs need to continue connecting with each other and with the entire scientific landscape, using their different competences and technologies at the service of the user community. Health & Food RIs[4] provide complementary and synergistic infrastructure facilities (see **Figure 2**), and contribute to building the ERA by:

- providing pan-European open access to cutting-edge technology platforms for academia and industry;
- enabling researchers to find new solutions to meet the major societal challenges they face collectively, including the health of the ageing population and the environmentally sustainable supply of affordable and nutritious food;
- promoting interdisciplinary and excellent research in Biological, Agri-Food and Medical Sciences across Europe, alignment and standardising the European research landscape and reducing fragmentation;
- promoting interdisciplinary connections with other domains in Energy, the Environment, Physical Sciences & Engineering, and in Social & Cultural Innovation;
- rapidly translating findings from basic science to new applications in Biology, Agri-Food and Medicine;
- delivering synergies and highly interoperable research processes, creating seamless value chains;
- identifying and accelerating the development and integration of technologies into the infrastructures to meet emerging needs;
- generating opportunities to maximise the competitiveness of Europe's knowledge-based industry and the bioeconomy – e.g. the agricultural, pharmaceutical, biotechnology and food industries, plus advanced equipment manufacturers, as well as development and utilisation of intellectual property;
- providing training and education to current and future Research Infrastructure professionals;
- attracting and retaining world-leading scientists within the ERA.

4. Biological and Medical Sciences Thematic Working Group Report, 2010 *http://ec.europa.eu/research/infrastructures/pdf/bms_report_en.pdf*

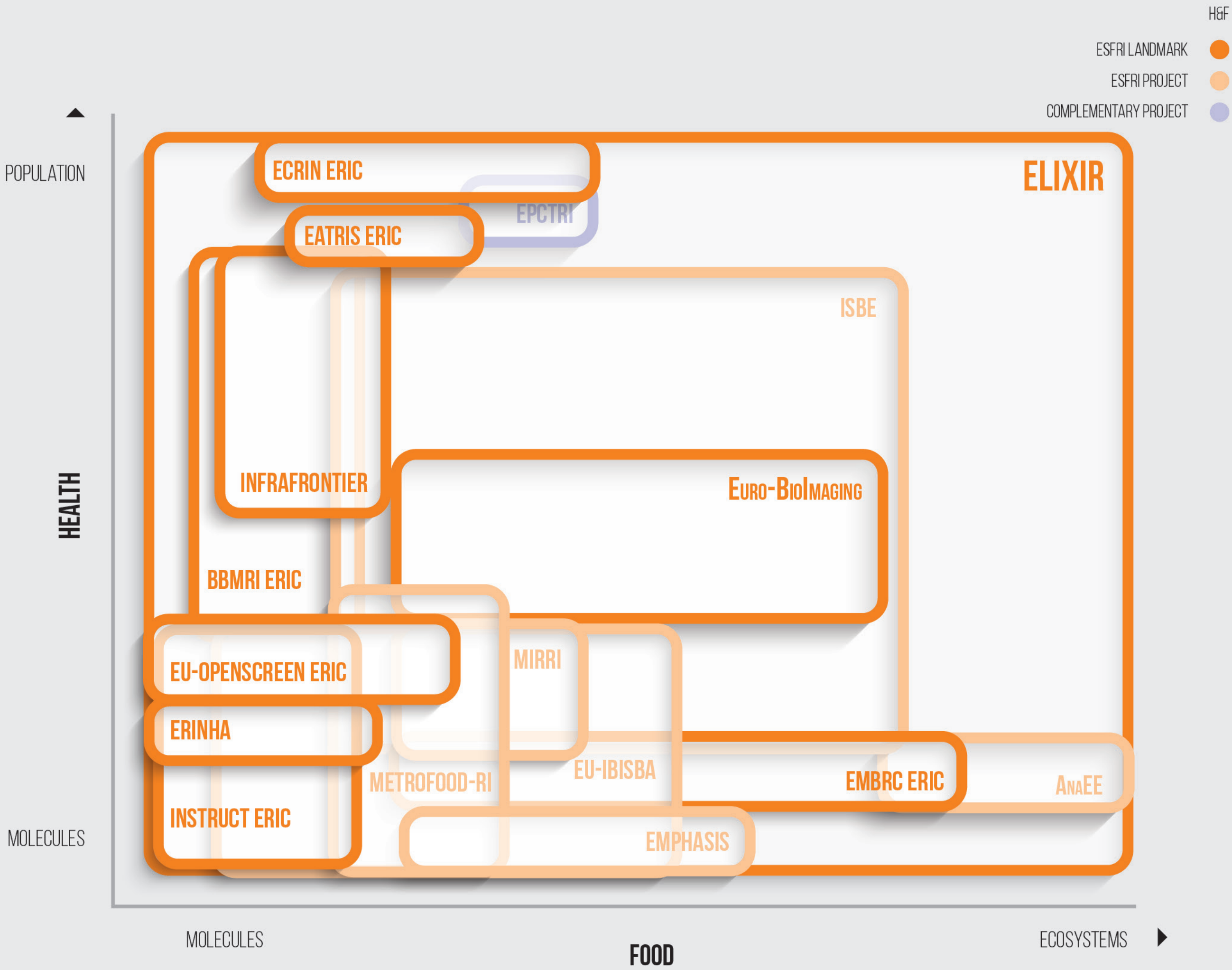



FIGURE 2.
The indicative position of ESFRI RIs relative to the different levels of organisation in the Health & Food domain

# THE HEALTH CHALLENGE

There is a rising demand for health care in Europe and worldwide, brought by an ageing population with a complex disease-pattern and chronic diseases. Modern lifestyles further add to the costs, e.g. through increasing incidence of disease like diabetes type 2, cancer and infectious diseases. Moreover, changes in climate are likely to affect human health in Europe particularly in older people and those with chronic diseases (IPCC, 2014). Increase in the incidence of mental health problems also needs to be addressed. Developing relevant and effective prevention, screening, early diagnosis, treatment and rehabilitation, research questions call for research which is capable to use complex inter- and cross-disciplinary research models, technologies, and bridges between scientific disciplines and society[5,6,7]. The next generation will have demands on the health and care community based on all information which can be accessed. This combined with an overall improved economic situation where tomorrow's elderly will need to get the most effective treatment, prediction of illness and homecare. This is one societal challenge to be addressed and communicated. There is a need to continue bringing together leading healthcare companies across multiple industry sectors, public and private research centres, and top universities, to accelerate entrepreneurship and innovation in healthy living and active ageing for the benefit of all EU citizens[8].

We are in a transition phase moving away from a *one-size-fits-all* approach into customised health care that is tailored to the needs of the individual. Personalised medicine focuses on the patients based on their individual clinical characterization. Precision medicine focuses on identifying which approaches will be effective for which patients based on genetic, environmental, and lifestyle factors. This transition towards customised health care is data- and knowledge-driven. The challenge of data- and knowledge- collection, management and stewardship for precision medicine is already beginning to be met by pan-European infrastructures like the **ESFRI Landmarks ELIXIR, BBMRI ERIC, INFRAFRONTIER** and others (see **Figure 3**), – including ethical, legal and social implications. For proper storage and smart retrieval of these data and knowledge, ICT for health is indispensable. Data relevant to precision medicine are not only generated in the laboratory and clinic. Citizens and patients are increasingly taking advantage of social media and app technologies to share information about their own health and lifestyle. Data shared by patients have already been

5. Advice For 2016/2017 of the Horizon 2020 Advisory Group For Societal Challenge 1. Health, Demographic Change And Wellbeing, 2014
*http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=15073&no=1*

6. Shaping Europe's Vision for Precision Medicine, 2015
*http://www.permed2020.eu/_media/PerMed_SRIA.pdf*

7. The Precision Medicine Initiative Cohort Program – Building a Research Foundation for 21st Century Medicine, 2015
*https://acd.od.nih.gov/documents/reports/DRAFT-PMI-WG-Report-9-11-2015-508.pdf*

8. EIT Health
*https://www.eithealth.eu/*

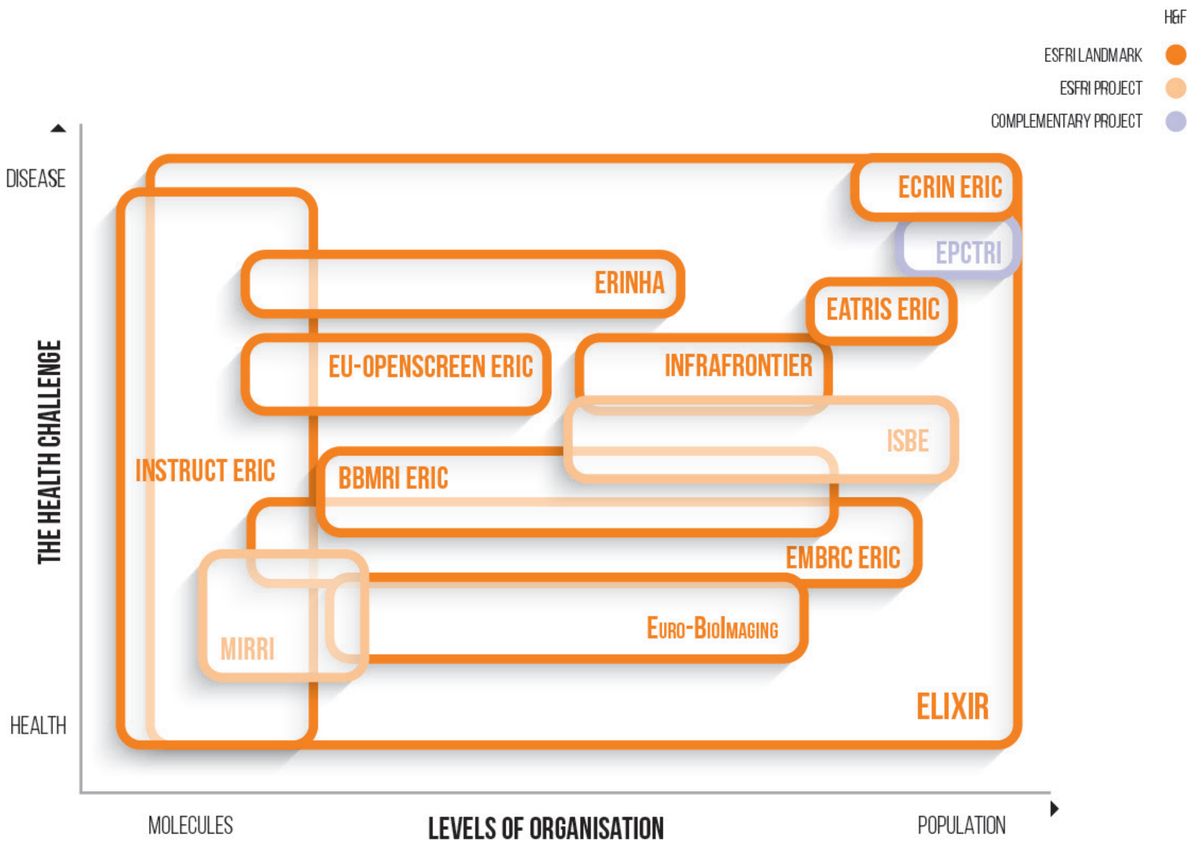



FIGURE 3.
The indicative position of ESFRI Research Infrastructures relative to the different levels of organisation in the Health domain

used effectively for research purposes and it is apparent that this sort of citizen-led collaboration can serve to accelerate clinical research.

The development of increasingly tailored interventions will require smooth translation – the **ESFRI Landmark EATRIS ERIC** (European Advanced Translational Research Infrastructure in Medicine) – and new clinical trial designs to take account of the shift in focus from population to well-defined cohorts of even individuals – the **ESFRI Landmark ECRIN ERIC** (European Clinical Research Infrastructure Network) and the complementary project EPCTRI (European Paediatric Clinical Trial Research Infrastructures), which is focused on paediatric clinical trials. The experience can be extrapolated to other designs involving relatively few patients, e.g. rare diseases. The EU launched a Consultative Group on the European Joint Programme (EJP) for Rare Diseases, in which the **ESFRI Landmarks EATRIS ERIC** and **ECRIN ERIC**, and the complementary project EPCTRI, are actively participating. The aim is to consolidate the transnational research on rare diseases through existing European platforms, and in the framework of the Horizon 2020 work programme 2018-2020, under Societal Challenge 1 - Health, Demographic change, and Well-being. Customised health-care is becoming one of the highly valued new possibilities for science and society. New threats, including pandemics, and exacerbation of diseases thought to be already eradicated, require the developments of innovative treatments and new strategies for the design of new drugs and potent vaccines – the **ESFRI Landmark INSTRUCT ERIC** (Integrated Structural Biology Infrastructure). Improved health-care will inevitably face the problem of the need for new therapies requiring bioinformatics – the **ESFRI Landmark ELIXIR**; experimental analysis of targets – the **ESFRI Landmark INSTRUCT ERIC**; medicinal chemicals and new biologicals – the **ESFRI Landmarks EU-OPENSCREEN ERIC** (European Infrastructure of Open Screening Platforms for Chemical Biology) and **INSTRUCT ERIC;** an integrated approach to modelling disease – the **ESFRI Project ISBE** (Infrastructure for Systems Biology Europe); and state-of-the-art imaging technologies – the **ESFRI Landmark Euro-BioImaging** (European Research Infrastructure for Imaging Technologies in Biological and Biomedical Sciences). In the case of emerging infectious diseases, as recently demonstrated by the Ebola outbreak, high-containment infrastructures will be crucial for new research – category 4 containment, the **ESFRI Landmark ERINHA** (European Research Infrastructure on Highly Pathogenic Agents) – including contained characterisation methods (category 3 and 4 electron microscopy). Important underpinning bioscience developments, such as the Human Cell Atlas, are in preparation. The Human Cell Atlas is an ambitious international programme with active participation by European countries, aiming to facilitate a comprehensive reference maps of all human cells as a basis for understanding human health and diagnosing, monitoring and treating disease[9,10,11,12,13].

9. The Human Cell Atlas
*https://www.humancellatlas.org/*

10. The 2015 Ageing Report
*http://ec.europa.eu/economy_finance/publications/european_economy/2015/pdf/ee3_en.pdf*

11. The Data Mapping Project
*http://www.jpi-dataproject.eu/*

12. EIT Health
*https://www.eithealth.eu/about*

13. Towards Cleaner Air Scientific Assessment Report 2016
*http://www.unece.org/index.php?id=42861*

# THE FOOD CHALLENGE

The global demand for food is predicted to increase 50% by 2030 and 100% by 2050. In many European countries, the growth trends of the yields of major crops, especially wheat, have declined over the past two decades and the variability of crop yields has increased as a consequence of extreme climatic events, such as the summer heat of 2003, which led to 36 billion € economic losses. FAO's 2016 report on the State of Food and Agriculture estimates decrease in yield of major European crops like wheat, maize and soybean under different climate scenarios. We need to produce more food whilst considering the influence of a changing climate, by increasing crop yield, and the efficiency, resilience and sustainability of the food chain, i.e. more product for less water, energy and chemical inputs. Substantial improvements with regard to livestock production are also needed, including new or more efficient strategies for preventing and managing livestock pathogens and the impact of antimicrobial resistance. But food security is also about improving nutritional and health benefits of foods, and making it accessible and affordable, globally, also minimising food waste. The UN sustainable development goals set food waste reduction targets of the following "halve per capita global food waste at the retail and consumer level, and reduce food losses along production and supply chains by 2030". Additionally, the Paris Agreement in 2015 recognised the important role of food production system in a changing climate and offers many opportunities in the food and farming sectors to limit the global temperature increase to well below 2 degrees.

The food system is by far the largest industrial sector in Europe in terms of turnover, value added and employment. In 2014, the activities with the strongest growth were agriculture, forestry and fishing (2.8%) and food services (2.1%) among others. An innovative bioeconomy in support of a *green growth* strategy that combines economic growth, natural resource preservation, highly efficient resource utilisation in well integrated value chains and greenhouse gas reduction is necessary. The bioeconomy is estimated to be worth at least 2 trillion € in the EU and employing around 22 million people. The objective is to secure sufficient supplies of safe, healthy and high quality food and other bio-based products, by developing resource-efficient primary production systems, fostering related ecosystem services and the recovery of bio-diversity, alongside competitive and low carbon supply chains[14,15,16,17,18,19,20,21,22]. The food system fits in the concept of circular economy as a regenerative system that aims to preserve and enhance natural capital, optimises resource yields, and minimises system risks. Embedded in the framework of sustainable development, the goal is to produce goods and services while reducing the consumption and wastage of raw materials, water and energy sources[23]. The *blue economy* is another area with great potential for innovation and growth, representing roughly 5.4 million jobs and generating a gross added value of almost 500 billion € a year[24]. There is a need to continue developing the marine biotechnology pipeline towards Blue Growth, and deliver the long term strategy to support sustainable growth in the marine and maritime sectors[25].

Important steps have been taken with G7 Future of the Seas and Oceans Initiative[26], COP21[27] and FOOD 2030. The realisation of these, among other large initiatives, will require new collaborations between Research Infrastructures and perhaps new configurations and approaches.

Europe is well placed to address these issues. The European RIs currently on the Roadmap constitute the starting point to achieve this ambitious goal for Europe: the **ESFRI Project AnaEE** (Infrastructure for Analysis and Experimentation on Ecosystems) on experimental manipulation of managed and unmanaged terrestrial and aquatic ecosystems, the **ESFRI Project EMPHASIS** (European Infrastructure for Multi-scale Plant Phenomics and Simulation), the **ESFRI Landmark EMBRC ERIC** (European Marine Biological Resource Centre) on marine ecosystems and biological resources, the **ESFRI Landmark ICOS ERIC** (Integrated Carbon Observation System, ENV) on high precision monitoring of greenhouse gas fluxes, other RIs from the ENV domain, the **ESFRI Project MIRRI** (Microbial Resource Research Infrastructure) on microorganisms-oriented services applied to biotechnology and food production, the **ESFRI Landmark Euro-BioImaging** on integrating imaging technologies and services (with links to crop phenotyping), the **ESFRI Landmark ECRIN ERIC** on clinical trials and nutritional trials, the **ESFRI Landmark INSTRUCT ERIC** on the use of structural biology to support plant and animal sciences, the **ESFRI Project ISBE** on integrated approach to food systems, and the **ESFRI Landmark ELIXIR** on life sciences large-scale data and knowledge management – applied to agriculture and bioindustries – and their links to other multidisciplinary RIs (see **Figure 4**).

14. How to feed the world in 2050. Food and Agriculture Organization of the United Nations (FAO), 2009 http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

15. Climate Change 2014, Synthesis Report - IPCC, 2014 http://www.ipcc.ch/report/ar5/syr/

16. A European science plan to sustainably increase food security under climate change. Soussana et al. Global Change Biology 18 (11), p. 3269–3271, 2012

17. European Statistics (Eurostat) - European Commission, 2008 http://ec.europa.eu/eurostat

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

19. Joint Programming Initiative – A Healthy Diet for a Healthy Life (JPI-HDHL) https://www.healthydietforhealthylife.eu/

20. A Bioeconomy Strategy for Europe, 2012 http://ec.europa.eu/research/bioeconomy/index.cfm

21. Sustainable Agriculture, Forestry and Fisheries in the Bioeconomy. A Challenge for Europe. 4th SCAR Foresight Report, 2015 https://ec.europa.eu/research/scar/pdf/ki-01-15-295-enn.pdf

22. Sustainable Development Goals 17 Goals to Transform the World https://www.un.org/sustainabledevelopment/sustainable-development-goals/

23. Circular Economy European Summit http://www.circulareconomysummit.com/

24. Maritime affairs, Integrated maritime policy – Blue Growth https://ec.europa.eu/maritimeaffairs/policy/blue_growth_en

25. The European Marine Biological Research Infrastructure Cluster: An Alliance of European Research Infrastructures to Promote the Blue Bioeconomy - Grand Challenges in Marine Biotechnology, pp 405-421, Piña M. et al., 2018 https://doi.org/10.1007/978-3-319-69075-9_10

26. G7 Future of Seas and Oceans http://www.g7italy.it/sites/default/files/documents/ANNEX 1_WG Future of the Seas and Oceans.pdf

27. COP21 http://www.cop21paris.org/

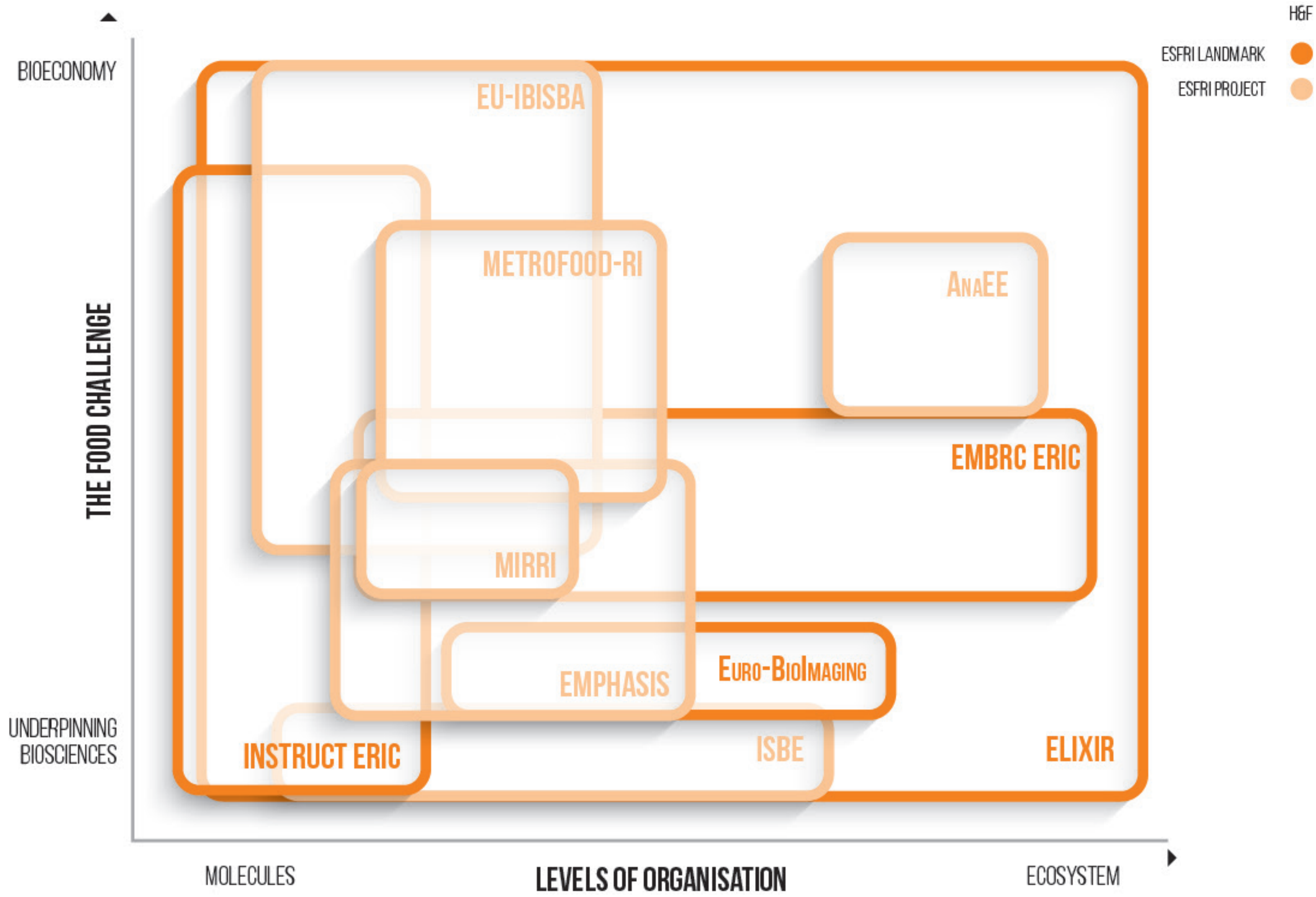



FIGURE 4.
The indicative position of ESFRI Research Infrastructures relative to the different levels of organisation in the Food domain

# THE FAIR DATA REVOLUTION

The Open Data agenda has been driven steadily by the Health & Food distributed infrastructures in collaboration with relevant stakeholders. DNA sequencing technologies have revolutionised the life sciences, from basic biological research right through to biomedical, biotechnology and agri-food applications. High-throughput sequencing technologies now produce billions of bases of nucleotide data per experiment, at a low cost. There are now more opportunities to cross-fertilise different omics platforms, data sets and informatics. Imaging technology is producing vast amounts of data revealing life in unprecedented detail. Structural investigation technologies are also accumulating data at a rate in excess of Moore's law. Cloud computing is estimated to reach a total cumulative gain of 940 billion € in the period 2015-2020. The life science sector is an intensive user of High Performance Computing and it is expected this will increase further[28,29,30]. The data and knowledge generated are contributing to extend the boundaries of frontier and applied research, and to respond to the Health & Food challenges. This will increase opportunities for all stakeholders to be part of the landscape and build competencies, regardless of whether they have the RI in their own country.

ESFRI Health & Food RIs are at the heart of realising the data revolution, by providing pan-European access to the specialised research services and data, suitably open for innovation by industry. A growing number of European and National RIs and projects are established following the EC recommendation on access to and preservation of scientific information[31]. Some e-Infrastructure projects – i.e. OpenAire – offer infrastructure for researchers to support them in complying with the EC Open Access pilot and the ERC Guidelines on Open Access. The European Charter for Access to RIs[32] sets out non-regulatory principles and guidelines for defining access policies for RIs. The Charter promotes interaction with a wide range of social and economic activities, including industry and public services, to maximise the return on investment in RIs and to drive innovation, competitiveness and efficiency. A number of e-RI projects address Data Management Policy in coordination and synergy with Health & Food RIs[33], e.g. BioMedBridges Charter for Data Sharing[34], or in the ERIC process. FAIRDOM[35] is an internationally sustained service to manage project data from instrument to publication since 2008. Establishing good data and model management practices ensures that data and models are findable, accessible, interoperable and reusable (FAIR). The high-level FAIR Guiding Principles[36] were established to precede implementation choices, and do not suggest any specific technology, standard, or implementation-solution. They act as a guide to data publishers and stewards to assist them in evaluating whether their particular implementation choices are rendering their digital research artefacts Findable, Accessible, Interoperable, and Reusable. It is anticipated that these high level principles will enable a broad range of integrative and exploratory behaviours, based on a wide range of technology choices and implementations. Indeed, many repositories are already implementing various aspects of FAIR using a variety of technology choices. ESFRI Health & Food RIs are playing a key role in the promotion and implementation of these principles. In addition, life sciences research relies extensively upon a set of core resources that archive, curate, integrate, analyse, and enable ready access to data, information, and knowledge generated worldwide by hundreds of thousands of researchers. The sustainability of core data resources is being discussed internationally, with the **ESFRI Landmark ELIXIR** playing a key role[37].

The FP7 BioMedBridges and the H2020 CORBEL projects represent a successful joint effort of Health & Food RIs to develop common approaches and standards for data integration in the biological, medical, translational and clinical domains. The **ESFRI Landmark INSTRUCT ERIC** has developed ARIA, a platform for harmonised user access to biological and medical technologies, biological samples and data services required by cutting-edge research. Within CORBEL, the ARIA platform has been further optimised for integrated access to multiple RIs. The current global research data landscape is highly fragmented, by disciplines or by domains, from oceanography, life sciences and health, to agriculture, space and climate. Health & Food RI experts participate actively in the Research Data Alliance[38], a high profile international initiative - over 2.500 membership from 92 countries - aiming at building the social and technical bridges across these areas that enable open sharing of data. Health & Food RIs are also contributing to shape the European Open Science Cloud (EOSC), an EC-led initiative aiming at interconnecting existing Research Infrastructures to offer European researchers and professionals a virtual environment to store, share and re-use their data across disciplines and borders. EOSC will be underpinned by the European Data Infrastructure, deploying the high-bandwidth networks, large scale storage facili-

28. Biology: The big challenges of big data. Marx, V. Nature 498, 255-260, 2013

29. Quantitative Estimates of the Demand for Cloud Computing in Europe and the Likely Barriers to Uptake, 2012 http://ec.europa.eu/information_society/newsroom/cf/dae/document.cfm?doc_id=1115

30. e-IRG White Papers, 2014 http://e-irg.eu/white-papers

31. Commission Recommendation, 2012. https://bit.ly/2okxYvB

32. European Charter for Access to RIs, 2015 https://ec.europa.eu/research/infrastructures/pdf/2016_charterforaccessto-ris.pdf

33. Towards coordination of international support of core data resources for the life sciences. Anderson et al., 2017 https://www.biorxiv.org/content/early/2017/04/27/110825

34. BioMedBridges, Principles of data management and sharing at European RIs. 2014. https://zenodo.org/record/8304/files/BioMedBridges-principles-of-data-management-and-sharing-at-RIs_.pdf

35. FAIRDOM https://www.fairdomhub.org/

36. The FAIR Guiding Principles for scientific data management and stewardship https://www.nature.com/articles/sdata201618

37. Data management: A global coalition to sustain core data https://www.nature.com/articles/543179a.

38. The Research Data Alliance is supported by The Australian Commonwealth Government through the Australian National Data Service supported by the National Collaborative Research Infrastructure Strategy Program and the Education Investment Fund (EIF) Super Science Initiative, the European Commission through the RDA Europe project funded under the 7th Framework Program and the United States of America through the RDA/US activity funded by the National Science Foundation and other U.S. agencies.

ties and super-computer capacity necessary to effectively access and process large datasets stored in the cloud. The **ESFRI Landmarks ELIXIR**, **ECRIN ERIC, INSTRUCT ERIC** and **BBMRI ERIC** are participating actively in EOSC Pilot. The EOSC's Stakeholder Forum in November 2017 attracted all Health & Food RIs to help define EOSC future. A group of EU member states is preparing the GO FAIR initiative, which is a proposal for the practical implementation of the EOSC initiated in the life sciences domain by the ELIXIR node DTL in The Netherlands among others. The current H2020 WP2018-20 for Research Infrastructures includes a call for cluster projects targeted to ESFRI projects and landmarks in all domains: Biomedical Sciences, Environment and Earth Sciences, Physics and Analytical Facilities, Social Sciences and Humanities, Astronomy, Energy. Research Infrastructures can only participate in one cluster. Further efforts may be required to promote and facilitate the interaction between domains and to avoid fragmentation of the data continuum.

The Open Access concept is widely accepted and promoted by ESFRI Landmarks in Health & Food. The **ESFRI Landmark BBMRI ERIC** and its Common Service ELSI aim at facilitating and supporting cross-border exchanges of human biological resources and data attached for research uses, whilst giving proper consideration of ethical, legal and social issues. The **ESFRI Landmark INSTRUCT ERIC** has adopted a data policy that specifically encourages its users to make their data open and mandates the development of the required tools. The **ESFRI Landmark ELIXIR**, together with the **ESFRI Landmark CLARIN ERIC** (Common Language Resources and Technology Infrastructure, SCI) and **ESFRI Landmark DARIAH ERIC** (Digital Research Infrastructure for the Arts and Humanities, SCI), in the social sciences and humanities, and the DASISH cluster project, have endorsed the eduGAIN Data Protection Code of Conduct. Health & Food RIs are actively managing all aspects related to the implementation of the new General Data Protection Regulation (GDPR), effective from May 2018. The GDPR applies to both automated personal data and to manual filing systems where personal data are accessible according to specific criteria.

# INTERCONNECTED SERVICES AND CAPABILITIES

The Health & Food RI landscape is made up of a vast number of national infrastructures interconnected at different levels. Many of the framework programme Integrating Activities (IA) have provided the foundation and primary integration for more complex RIs, as communities mature and the case for higher integration and connection is refined.

For instance, the **ESFRI Landmark INSTRUCT ERIC** integrates a series of IA projects of specialised structural technologies and tools, i.e. X ray diffraction, NMR, EM and Mass Spec (Bio-NMR, BioStructX, PrimeX, PCUBE) pushing beyond the horizon of each individual technology. The **ESFRI Project EMPHASIS** integrates IA projects EPPN and EPPN2020, facilitating access to 31 key plant phenotyping installations, developing novel technologies and methods for environmental and plant measurements, tools for statistical analysis and information systems, and integrating phenotyping facilities and users in the EU and internationally. The combination of research capability and capacity of ESFRI RIs and IAs enhances the landscape and accelerates the transfer of data and technologies into services and innovation.

The Health & Food RIs constitute an advanced level of integration at pan-EU scale, bringing together facilities, services and resources for research, and taking them to a new level of expertise and synergy. ESFRI in its incubator role has enabled the current Health & Food RIs to significantly change the infrastructure landscape: they are in a unique position to offer complementary or sequential processes and services in different fields. This is the model of the **ESFRI Landmarks INFRAFRONTIER**, **INSTRUCT ERIC, EATRIS ERIC** and **ECRIN ERIC** together with EPCTRI**,** in association with the **ESFRI Landmarks BBMRI ERIC** and **ELIXIR**. In early stage drug discovery, the **ESFRI Landmarks EU-OPENSCREEN ERIC** and **INSTRUCT ERIC** provide a platform for identifying candidate compound hits for target pipelines; the **ESFRI Landmark INFRAFRONTIER** provides animal models to test hypotheses preliminary to human testing; the **ESFRI Landmarks INSTRUCT ERIC** and **EATRIS ERIC** provide the translational pre-clinical and early clinical research facilities; and the **ESFRI Landmark ECRIN ERIC** provides the clinical infrastructure for the clinical research on diagnostic and therapeutic procedures and clinical trials of drugs and devices in patients. The Complementary Project EPCTRI, offers a facility to deliver clinical trials involving children with uniform standards across Europe. EPCTRI and the **ESFRI Landmark ECRIN ERIC** have aligned their efforts at strategic and operational level, for mutual benefit. The H2020-funded project PedCRIN is helping to consolidate these efforts. It is expected that similar integrated service pipelines will be established in other areas of the Health & Food landscape, e.g. marine biotechnology, industrial biotechnology, and sustainable agri-food systems, where the **ESFRI Landmark EMBRC ERIC**, and the **ESFRI Projects AnaEE, EMPHASIS, EU-IBISBA** (Industrial Biotechnology Innovation and Synthetic Biology Accelerator), **METROFOOD-RI** (Infrastructure for promoting Metrology in Food and Nutrition) and **MIRRI** will play a significant role.

Integrating technologies at different levels of complexity is allowing RIs to tackle problems using a systems approach. The **ESFRI Project ISBE** is an example of a RI with a role in integrating life sciences technologies, data and services between the Health & Food RIs, with complementarities with ESFRI Landmarks and Projects, like the **ESFRI Landmark ELIXIR.** An example of integration of services at thematic level can be that for diagnosing rare diseases, as critical amount of data is gathered and shared from different countries in Europe that otherwise would not be available. Meta- or global infrastructures with a thematic and/or a technological focus are key elements of the landscape.

# GAPS, CHALLENGES AND FUTURE NEEDS

There are some significant gaps to be filled and connections to be enabled across the pan-European landscape of infrastructures in Health & Food. There is a need for a pan-EU approach on food and nutrition as well as in sustainable agriculture and bio-economy, building a natural link between the two complex medical and agriculture fields. Gaps can be identified at many levels and in order to complete the landscape, it will also be important to connect infrastructure efforts within Health & Food and with other domains. Significant innovations and new developments often occur at the boundaries of research areas, and Health & Food Strategic RIs have already established effective connections between them and across other ESFRI domains. As the landscape keeps evolving, new connections will and need to be made; ESFRI Landmarks and Projects in all domains have a key role to play as a driver in promoting and facilitating effective and fruitful connections, as well as in supporting the ERA.

These new connections need to be pursued to maximise current efforts by ESFRI RIs and build on the technical and thematic knowledge gained in ESFRI Clusters, to deliver new knowledge and new services, and enhanced socio-economic impact. Different levels of integration and connections will continue to build the infrastructure landscape in the Health & Food sector, towards true interdisciplinarity and convergence (see **Figure 5**).

Boundary areas have the potential to provide a new level of integration and organisation. It is proposed that boundary areas can lead to the formation of Interdisciplinary Clusters in order to realize the added value of RIs being connected not only to new RIs but also to other relevant initiatives. Interactions with stakeholders like the healthcare and agri-food sectors and industry will benefit from those formations. This is important in order to continue building the ERA, capitalising on the generated knowledge and translating these into the benefits for society.

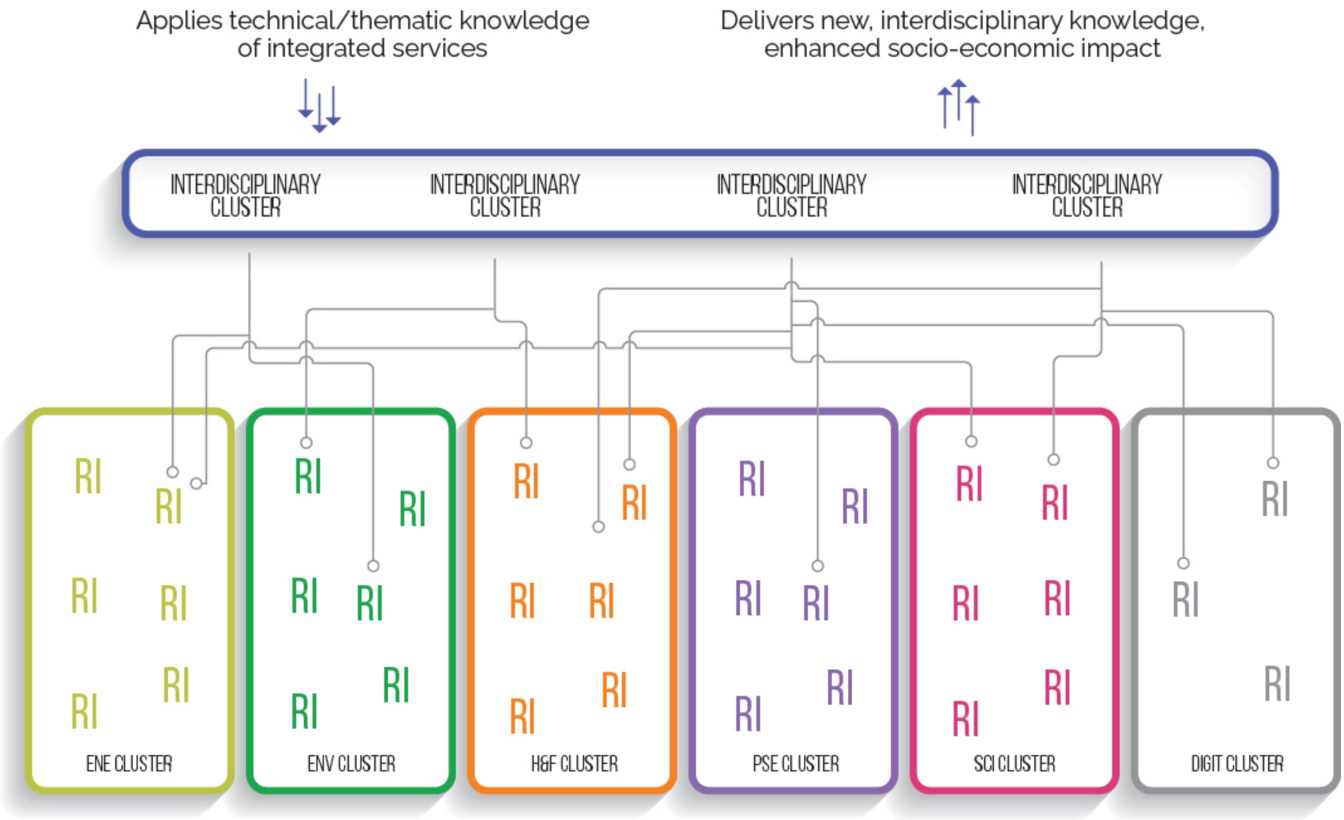



**FIGURE 5.**
Interdisciplinary clusters - new connections in the ESFRI RIs landscape

# GAPS AND CONNECTIONS IN FOOD

In the context of a changing environment, an increasing human population and pressure on land, a concerted effort to continue bringing together national facilities at 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. Continued RI efforts at EU-level are needed to provide livestock genetic resources, phenotyping and breeding, including large farm animals, poultry and fish; genetic resources for adaptation to climate change and protein production; genomic selection and genetic modification and sustainable intensification for higher feed efficiency, precision livestock farming and precision feeding; platform of technologies and capabilities for epidemiological modelling and surveillance, including host-pathogen interactions and vaccinology towards countering the threats of animal-borne disease. There is a need to proactively combine 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. New efforts should include integrated facilities for bio-imaging, 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, e.g. building on AQUAEXCEL[39], NADIR[40] and VetBioNet[41]. Animal genotype-to-phenotype infrastructures and capability at pan-EU level will have a positive impact on global food production and on European competitiveness, and enhance international effort in this important field.

Food related diseases are costly; the EU national health systems are the most under pressure. The key is to fully understand the interrelation between nutrition and health, particularly the digestive process and the role of food consumption, including the gut microflora, food pathogens, immunology and many other factors, that together can help develop new strategies to deliver healthy and nutritious food and encourage favourable changes in consumption patterns. Regulatory demands relating to health and novel foods impose comprehensive safety assessment procedures and scientific evidence. European research base and expertise in nutrition and food science is unique but it remains highly fragmented and, in some areas and countries, it is below the critical mass[42,43,44].

New infrastructure efforts are needed at EU-level in the field of *food, nutrition and processing*. There is a need to connect RIs across EU and globally, and across the entire food chain. Food systems cover a number of intertwined important areas, spanning social, cultural, economic, geo-political, and environmental dimensions, and involving a great diversity of stakeholders. There is a role for Research Infrastructures to be able to connect food systems and stakeholders. The **ESFRI Projects AnaEE, METROFOOD-RI, EMPHASIS**, and other EU initiatives like the EC-funded project Richfields contribute to achieve this aim, from sustainable food production to consumer behaviour. The **ESFRI Landmark EMBRC ERIC** supports fundamental and applied research activities towards sustainable solutions in the food sector, as well as in health and the environment.

Connections to food and feed production systems are key. The **ESFRI Project EMPHASIS** is central to this stage, currently establishing connections to relevant ESFRI Projects and Landmarks as well as other infrastructures and large scale initiatives. The International Wheat Yield Partnership (IWYP), led by public funders of UK, France, USA, Canada, Australia, India, Mexico is a global mechanism established in 2012 bringing together funding from public and private research organisations from around the world with the goal to raise the genetic yield potential of wheat by 50% in 20 years. This important gap area is of interest to many EU countries and current efforts to connect relevant infrastructures and large scale initiatives should continue[45,46].

The **ESFRI Project METROFOOD-RI** aims at providing 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 agro-food, sustainable development, food safety, quality, traceability and authenticity, environmental safety, and human health. This gap area is vast and there are in addition several IA addressing complementary aspects on food and nutrition, which are breaking ground for future infrastructure in nutrition and health, e.g. FoodManufuture EuroFIR, NuGO, Food-4Me, Eurogene, EURRECA, QuaLiFY, and EuroDISH[47,48]. In addition, the combination of fundamental science, translational research and clinical trials, positioned alongside a major clinical gastroenterology service and tissue repository, will ensure a seamless interface between research, clinical practice and the pharmaceutical and biotechnology industries, also cross linking with RIs at the boundary areas.

Food production and its accessibility are increasing worldwide. Legal and ethical issues are critical and have to be addressed as well as information and communication. Nanotechnologies create the possibility of foods with new flavours and textures, and also healthier food products with reduced salt, fat or sugar content or increased vitamin and nutrient content, using nanoencapsulation. Due regard needs to be given to safety and sustainability aspects in their broadest sense as well as to public perception and stakeholder engagement in align-

39. Aquaexcel http://www.aquaexcel.eu/

40. NADIR - The Network of Animal Disease Infectiology Research Facilities https://www.nadir-project.eu/

41. VetBionet http://www.vetbionet.eu/

42. JRC Foresight study, Tomorrow's healthy society – Research priorities for foods and diets, 2014 https://ec.europa.eu/jrc/sites/jrcsh/files/jrc-study-tomorrow-healthly-society.pdf

43. 3rd and 4th SCAR foresight exercises https://ec.europa.eu/research/scar/pdf/ki-01-15-295-enn.pdf

44. ETP Food for Life Implementation Plan, 2018 http://etp.fooddrinkeurope.eu/

45. The International Wheat Yield Partnership (IWYP) http://iwyp.org/

46. Wheat Initiative http://www.wheatinitiative.org/

47. EuroDISH http://www.eurodish.eu/

48. Precision agriculture and the future of farming in Europe http://www.europarl.europa.eu/RegData/etudes/STUD/2016/581892/EPRS_STU(2016)581892_EN.pdf

ment with the principles of Responsible Research and Innovation. These principles apply to all Health & Food areas but are flagged here for their relevance in the nanotechnology field.

The increasing digitalisation of agricultural practices is realising the production of plant and animal products with ever higher efficiency and ever lower environmental impact – Precision agriculture and the future of farming in Europe. Precision agriculture is a modern farming management concept using digital techniques to monitor and optimise agricultural production processes. Beyond sustainable food production, precision agriculture offers technologies for producing more food with less input, e.g. sensor-based monitoring systems provide farmers with better information and early warnings on the status of crops, and improved yield forecasts. Precision agriculture also plays a major role in animal husbandry. The **ESFRI Projects EMPHASIS** and **AnaEE** aim to collaborate in bringing innovative solutions for a sustainable intensification of agriculture. By integrating the study of plant phenomics and agricultural ecology they hope to foster the development of novel scientific concepts, sensors and integrated models[49]. 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. Legal and ethical issues are critical as well as information and communication.

Health & Food RIs and their connections with ENV SWG and ENE SWG RIs are critical to address issues associated with *agriculture and land-use change*, food and non-food systems, and bioenergy. The **ESFRI Project AnaEE** is working with the **ESFRI Landmarks ICOS ERIC** (Integrated Carbon Observation System, ENV), **LifeWatch ERIC** (e-Infrastructure for Biodiversity and Ecosystem Research, ENV), and others in the EC projects ENVRI and ENVRI+, Common Operations of Environmental RIs linking across e-infrastructure initiatives. The links to the social sciences are also important. The global demand for food includes challenges regarding efficiency, resilience and sustainability. The field of bioenergy and biorenewables in particular links to energy and environmental facilities.

49. European infrastructures for sustainable agriculture. Roy et al. (2017) https://www.nature.com/articles/s41477-017-0027-3

The sustainable production and conversion of biological raw materials for use as sources of renewable energy, materials and chemicals can provide alternatives for diminishing fossil resources and drive the growth of the knowledge based bio-economy. Addressing the demand for sustainable supplies of materials, fuels and food through biological means required the use of biological resources towards environmental and economic sustainability. An effort at European level is required 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. The **ESFRI Project EU-IBISBA** proposes a distributed RI on industrial biotechnology with applications in energy (liquid biofuels), chemicals (organic acids), materials (bioplastics) and ingredients for the food, feed, cosmetics and pharma sectors (enzymes, antioxidants, antibiotics). The **ESFRI Project EU-IBISBA** aims to deliver translational research in industrial biotech, allowing researchers to access cutting-edge technology, infrastructure and expertise to move projects up to TRL6. The **ESFRI Project EU-IBISBA** has the potential to accelerate TRL2 to TRL6 processes, and in reducing time to market. It will interact with and connect to existing infrastructures such as the **ESFRI Projects ISBE** and **MIRRI**, the **ESFRI Landmarks BBMRI ERIC**, **ELIXIR**, **INSTRUCT ERIC**, and **EU-OPENSCREEN ERIC**, and other RIs in the environment, and energy sectors. The infrastructure uses synthetic biology as one of their approaches. Synthetic biology applies engineering to the biosciences, seeking to design and construct/modify new or existing biological parts and systems to deliver novel functions that do not exist in nature. The field is expected to impact many sectors of the economy, and to provide tools to better tackle areas of great social and environmental interest, including health, energy and food security[50]. Synthetic biology is both highly interdisciplinary and technically and scientifically demanding. It and also addresses a range of social, economic, ethical, and legal issues.

50. ERA-Net SynBio https://www.erasynbio.eu/

## GAPS AND CONNECTIONS IN HEALTH

The future of health research offers high potential to patients, to citizens, and the economy. The move in the sector towards precision and stratified medicines and personalised healthcare at much lower cost to the consumer brings with it a need to test new technologies and provide multi-scale facilities as test-beds for pharmaceutical and biopharmaceutical (therapeutics) manufacturing. These activities apply primarily to industries for technological development based on academic input and evidence. Investment to date has focused more on fundamental science and discovery, meaning that there is a gap between discovery and actual manufacture. This area should constitute an excellent platform of technology development and include the complete manufacturing process from a scientific, engineering, regulatory and supply chain perspective, with the ultimate aim of providing affordable access to innovative therapies in collaboration with the **ESFRI Landmarks EATRIS ERIC**, **ECRIN ERIC**, and **EU-OPENSCREEN ERIC** and other relevant RIs, and Innovative Medicines Initiative (IMI2). Research in this area is expected to be highly innovative and will lead to three key benefits: better diagnosis and earlier interventions, more efficient drug development, and more effective therapies. Existing infrastructures such as the **ESFRI Landmarks BBMRI ERIC**, **EATRIS ERIC**, **ECRIN ERIC**, **ELIXIR**, **ERINHA** and others could connect aiming at providing a full pipeline for drug development.

Advances in the sector of personalised health care require computational approaches, and integration with innovations in biomedical engineering, analytical research, and other relevant fields as well as with social, ethical and regulatory aspects. The challenge of *antimicrobial resistance* and pandemics also calls for an integrated effort. Next generation sequencing technologies and mass spectrometry platforms for genomic, transcriptomic, proteomic, metabolomics and metagenomics applications, coupled with advanced imaging, set the basis for personalised and stratified drug discovery and development. Combined high-end technology platforms with specialised expertise, bringing together hospitals, research centres and the private sector in an integrated network that will offer a point of single access for the development of next generation medicines. All ESFRI Health & Food Landmarks and Projects with applications in health have the capacity to play a significant role in enabling research activities towards developing tailored healthcare interventions and robust models for prevention and treatment strategies, bridging the gap between genomic information and clinical practice.

New therapies are needed in order to cure and treat *complex diseases.* Challenges exist in the development of new applications and new modes of treatment approaches in *imaging, diagnostics and novel therapeutics*. The **ESFRI Landmarks INSTRUCT ERIC**, **Euro-BioImaging**, **INFRAFRONTIER**, **EATRIS ERIC** and **ECRIN ERIC** are of relevance. Interdisciplinary interactions will be critical in order to handle upcoming issues and implications – e.g. in the *ageing population* and neuroscience research[51]. Links of relevance are the Joint Programming Initiative "More Years, Better Lives – The Potential and Challenges of Demographic Change" seeking to map data sources on ageing at the European and national levels[52] and the Knowledge and Innovation Community initiative EIT Health, promoting innovation in healthy living and active ageing[53]. New advances in technologies, such as nanotechnologies, are having impacts on therapeutics, diagnostics, imaging and regenerative medicine, particularly in cardiovascular diseases, diabetes and cancer. Due regard needs to be given to public perception and stakeholder engagement and the principles of Responsible Research and Innovation. Tools for health planning are required. A Health information System is supported by the EC DG SANTE as a joint action to harmonise health indicators and surveillance tools across Europe, and to host health-related databases including population based and clinical registries for diseases, biobanks, health protocols as well as metadata for health determinants.

51.
The 2015 Ageing Report
*http://ec.europa.eu/economy_finance/publications/european_economy/2015/pdf/ee3_en.pdf*

52.
The Data Mapping Project
*http://www.jpi-dataproject.eu/*

53.
EIT Health
*https://www.eithealth.eu/about*

*Longitudinal population* studies and cohorts are an invaluable resource for research, in health and disease conditions. These studies gather data over a long period of time and provide a rich resource with connections to several domains. In particular, this is an area to explore together with the ESFRI Social & Cultural Innovation SWG and its Research Infrastructures, which flagged "integration of biosocial data and resources – longitudinal and cohort studies" in their landscape as an important area of connection to Health & Food Research Infrastructures. There is a need to enable a Research Infrastructure environment that will facilitate research on the *human health and wellbeing* at all stages in development, including ageing, nutrition and behavioural studies, and their connections to the social sciences and humanities. There are also geographic, economic and environmental drivers affecting human health and wellbeing. 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 pan-European level. At the heart of this approach is the exposome, taking a holistic view throughout the human lifetime on the effect of exposures to diet, lifestyle, and the environment on human health and disease. The exposome coupled with advanced genetic and medical approaches represents an opportunity to tackle this complex issue by connecting to the landscape of Health & Food RIs and other domains. Ongoing EU projects and networks on human biomonitoring (HBM4EU and EMEP) are important steps to bring together relevant parties[54].

Health & Food RIs provide a framework for applications in other domains, such as anthropological studies, using biobanking, omics, and metabolomics. Cohorts include biological material of specific diagnoses and general populations either longitudinal or case by case. Multidisciplinary databases contain data of different aspects related to the addressed hypothesis. The combination of these has the potential to enable better understanding of disease and the identification of disease mechanisms.

54.
Towards Cleaner Air Scientific Assessment Report 2016
*http://www.unece.org/index.php?id=42861*

# VISION AND PERSPECTIVES

ESFRI has been instrumental and influential in the co-ordination of national decision-making and investment in European RIs in Health & Food. The landscape continues to evolve and it is important to ensure its ability and agility to respond to current and future demands. Significant innovations and new developments often occur at the boundaries of research areas. To continue cementing the critical role of distributed RIs in Health & Food as they progress in their lifecycle, it will also be important to connect infrastructure efforts with other domains. This is territory largely unexplored and where Health & Food RIs have the potential to pioneer new ways of working and realise true interdisciplinarity.

There is a need to develop well-established procedures for the systematic assessment of the social and economic impact of Health & Food RIs, to demonstrate effective use of resources and accountability for public money, to inform future decision making and evidence for policy-making, to demonstrate evidence of societal and economic benefits and to ensure their long term sustainability. Overall, this will help demonstrate the collective impact that the distributed RIs in Health & Food have had in shaping the landscape of research infrastructures in the last 12 years since the first ESFRI Roadmap was published, and will signal their potential to transform the landscape in the years to come.

# CONTENTS



PART2

**LANDSCAPE ANALYSIS - SECTION1**

# PHYSICAL SCIENCES & ENGINEERING

# PHYSICAL SCIENCES & ENGINEERING

Research Infrastructures are integral part of the day-to-day activity of Physical Sciences & Engineering. Historically and today the PSE RIs are integrated in the way research is done in these disciplines, and major advances in knowledge are achieved by the research performed at RIs. However, the RIs are much more than research tools; they are truly *Hubs of Knowledge & Innovation* with a complete multidisciplinary approach and a systematic impact on many areas beyond Physical Sciences and Engineering.

To date there are few assessments of the socio-economic impact of RIs over their lifecycle[1,2,3]. There are even fewer studies that take into account the wider impact on society; benefits which are not directly economic, such as health, a safer and fairer society, and a cleaner environment. Indeed, the methodology for such studies is still a subject of debate. However, the PSE RIs enable a vast range of science and engineering research that has an impact on almost all the identified areas of societal challenge, including health and the aging population; cleaner energy and a greener environment; better transport and improved cities; improved communications; national and personal security.

A major challenge that confronts scientists and policymakers is the increasing cost of the tools needed for achieving progress at the frontiers. Basic research as conducted today in these areas is truly international. About 30% (in some cases much more than 50%) of the users of the large and medium sized RIs are from outside the country where the facility is located. Support for the operations of these facilities has historically been provided by the host country or region with a policy of free and open access by the international scientific community and with beam-time and observation-time allocated based upon the merit of the proposed research.

Inside the PSE domain we identify three thematic subareas: **ASTRONOMY AND ASTROPARTICLE PHYSICS, PARTICLE AND NUCLEAR PHYSICS** and **ANALYTICAL PHYSICS**. In the following, the three areas will be described, with the corresponding RIs available, and the identified gaps and challenges for the near future.

**Astronomy and Astroparticle Physics** is evolving over recent years towards a multi-observatory approach. This new approach is contributing to our holistic understanding of the universe and its components to an unprecedented degree. Also beneficial and deep-rooted are the interactions with **Particle Physics** through the common theoretical framework and via *multi-messenger*, multi-instruments studies, covering an extraordinary range of electromagnetic wavelengths, different particles and most recently gravitational waves. Fast data analysis, together with an early alert network system, makes possible a direct observation of the same event by multiple observatories, thus elucidating the same phenomena with complementary techniques. The convergence of the different disciplines and different messengers is providing a very fertile approach and new results, which directly impact on the understanding of the physical world, from infinitely small to extremely large scales. The Astronomy and Astroparticle Physics community involves more than 12.500 scientists[4].

**Particle Physics** aims not only at understanding the elementary constituents of matter, but also at building a coherent theoretical framework including all fundamental forces, which would allow us to understand the evolution of the universe from its earliest instants. Probing the limits of the Standard Model of particle physics and beyond, therefore involves understanding gravitation as well as elucidating the *Dark Sector* of the Universe: Dark Energy and Dark Matter. The tools to achieve this goal are manifold, from the highest energy particle colliders and highest intensity beams to extremely low background detectors and the observation of cosmic messengers at the interface with astrophysics and cosmology, as well as ultra-high-precision experiments at the frontier with atomic physics. Some 13.000 scientists are registered as users of CERN alone.

**Nuclear Physics** is the study of atomic nuclei and nuclear matter and of the fundamental forces responsible for their properties and behaviour. It aims at studying the fundamental properties of nuclei from their building blocks, protons and neutrons, and understanding the emergent complexity in terms of the strong interaction from the underlying quark and gluon and their degrees of freedom within Quantum Chromodynamics (QCD). This requires detailed knowledge of the structure of hadrons, of the nature of the residual forces between nucleons resulting from their constituents and of the limits of the existence of bound nuclei and ultimately of hadrons themselves.

The significant global effort in basic nuclear physics research involves around 13.000 scientists and support staff with funding of

1. The importance of physics to the economies of Europe https://www.eps.org/default.aspx

2. Long-Term Sustainability of Research Infrastructures, ESFRI Scripta Vol.2, October 2017 http://www.esfri.eu/sites/default/files/u4/ESFRI_SCRIPTA_TWO_PAGES_19102017_1.pdf

3. SUSTAINABLE European Research Infrastructures https://ec.europa.eu/research/infrastructures/pdf/swd-infrastructures_323-2017.pdf

4. This number includes only the members of the International Astronomical Union

approximately 2 billion € per year. Investment in basic science results in long-term economic benefits. Advances in nuclear physics techniques and accelerator technology have made significant contributions to national and societal priorities, including new approaches in energy, national security, industry, and medicine. The discoveries and technical advancements that result from nuclear physics research make important contributions to other scientific fields and national and societal priorities. The forefront research facilities attract and train a next generation of scientists for research and national needs.

**Analytical Physics** includes the fine analysis of matter by scattering of beams and by spectroscopy, the nanofabrication of complex materials and systems and the *in operando* study of their functionalities. Europe is extremely competitive in this field with several world-leader **Analytical Research Infrastructures (ARIs)** facilities including sources of photon, neutron, electron and ion beams such as **Synchrotron Radiation (SR)** storage rings, **Free-Electron Lasers (FELs)**, **Neutron Scattering (NS),** advanced **Electron Microscopes (EM)**, **Nuclear Magnetic Resonance (NMR)**, high-performance lasers (**Ultra Short Pulse and High Intensity Lasers**) and **High Magnetic Fields (HMF)**.

The size of the current user community for **Synchrotron Radiation** facilities was estimated in 2017 as at least 24.000[5]. The current user community for **Free-Electron Lasers** is in its infancy and is probably less than 1.000. The size of the current user community for **Neutron Scattering** in Europe has been estimated as over 5.577 distinct users in 2017, based on data provided by the facilities[6]. The size of the current user community for **Electron Microscopy** in the physical sciences Europe was estimated[7] as 5.000 excluding proprietary industrial users. This number is likely doubled if users in structural biology are considered because of the sudden proliferation of Cryo-EM users following technological leaps in recent years which enable unprecedented resolution. The current user community for **Ultra Short Pulse and High Intensity Lasers** in Europe mainly comes under the umbrella of the LaserLab Europe network which now undergoes its 4$^{th}$ edition. This has a population of about 3.500 individuals from about 50 laboratories across Europe. The **ESFRI Landmark ELI** (Extreme Light Infrastructure) offers significantly enhanced research opportunities to the global academic and industrial community of users and with the increased availability of state-of-the-art beamlines, there is a potential for the growth of the scientific community. The size of the current user community for **High Magnetic Fields** in Europe can be estimated as 2.500 users and slowly growing based on the current number of users of the **ESFRI Landmark EMFL** (European Magnetic Field Laboratory). Adding up the numbers of users above quoted, a sum of approximately 45.000, including multiple users, is obtained. To the best of our knowledge, there is no quantitative study of cross-technique use across Europe, though the estimate of cross-facility use is of the order of 10%[8] wherever there are co-located facilities – for example SR and neutron scattering facilities on the same campus.

There is a tendency to develop clusters of activity and to set up complementary facilities, both large and small in scale, around **Analytical Research Infrastructures**, notably at research campuses like in Grenoble, Hamburg, Harwell, PSI Villigen, Paris-Saclay, Trieste, Barcelona and Lund. This, in turn, attracts partnerships with universities and industries which create effective hubs for research and innovation across a very wide range of disciplines and can make very significant contributions to the local economy. In most cases, ARIs also develop technologies or products as bio-products or derivatives of their core technology development. For example, in the field of laser technologies, the following areas developed: i) remote sensing for airport security and food safety; ii) medicine and medical imaging, in particular related to cancer therapy; iii) photonic devices and new laser technologies. One of the resounding success stories is Cobalt Light Systems Ltd. an STFC spin-off company, which produces the Insight100 machine[9], a bottled liquid screener that is now being used in most airports worldwide.

This Landscape Analysis does not cover the research facilities for engineering or purely applied research as they escape the exact definition of RI, often operating as test facilities or technology demonstrators. Nevertheless, there are areas - like the cleanrooms for Nanoscience and Nano-Engineering – that support both the applied industrial end users, and fundamental research programs – e.g. in the development of emerging technologies as Artificial Intelligence, Quantum Technologies and Computing.

5. Brochure for the launch of LEAPS, November 13$^{th}$ 2017 https://www.leaps-initiative.eu/

6. Neutron Users in Europe. Facility based insights and scientific trends - Brightness project https://bit.ly/2uqQZpS

7. As part of a survey of pan-European EM requirements for state of the art installations within the ESTEEM2 consortium. This figure excludes the life sciences and users of standard instruments who are likely to be at least equal to this number. It is important to recognise that an increase in demand for transitional access between the ESTEEM and ESTEEM2, INFRA projects, the latter offering 3.300 user days over a four-year period indicates unsatisfied bandwidth and hence provides support for consolidated (and more efficient) infrastructures and for an overall expansion of EM provision

8. Estimates of dual-use of facilities have been made in Grenoble and at Harwell

9. Insight100 machine https://www.cobaltlight.com/products/insight100series/

# ASTRONOMY AND ASTROPARTICLE PHYSICS

**Astronomy and Astroparticle Physics** deal with the understanding of the universe and its components: from its still not well known beginnings to its growing complexity, with the formation and evolution of galaxies, stars and planetary systems, until the emergence of life. It relies on various kinds 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 spread well beyond the historical optical domain, to the whole electromagnetic spectrum from radio astronomy to the observation of gamma-rays, and new messengers such as gravitational waves and neutrinos. *Multi-messenger* astronomy, with its multi-wavelength, multi-instrument studies, is the new frontier to study the evolution and present phenomena of the Universe. Underground physics investigates the rarest phenomena to discover dark matter and the nature of neutrino mass.

The main science drivers are:

- understand the origin of the universe, its main constituents and the extreme conditions it hosts;
- observe the formation of galaxies and their evolution;
- understand the formation of stars and planets;
- understand the solar system and the conditions enabling life, searching for other planetary systems in our galaxy.

The recent observation of gravitational waves is the dawn of gravitational wave astronomy, a highlight which opens a new window for observation of stellar bodies and phenomena. Exoplanetary research also builds up as an inter/multidisciplinary field where a *multi-messenger* approach – e.g. landers, sample return – is taking place.

The science drivers of Astronomy and Astroparticle Physics merge with those of Particle and Nuclear Physics, linking the physics from the infinitively large to the infinitively small, giving a holistic view of the overall Research Infrastructure investment in the Physical Sciences & Engineering field.

## CURRENT STATUS

Research in Europe in this area remains at the leading edge. The intergovernmental organisations ESO[10] (European Southern Observatory) and ESA[11] (European Space Agency) enable Europe to compete at the global level in ground and space-based astronomy. Another key factor is the strong organisation of communities at national and European levels. The ASTRONET[12] and ASPERA[13] ERA-NETs have strengthened a Europe-wide collaboration between research communities and funders and are the key players proposing strategies. ASTRONET covers research from the Sun and Solar System to the limits of the observable universe, and the ERA-NET is giving rise to a co-ordinating Consortium. The APPEC Consortium[14] coordinates Astroparticle Physics research. ASTRONET and ASPERA/APPEC continuously update comprehensive studies of all the present and future activities based on scientific goals and merit.

The ASTRONET and ASPERA/APPEC Infrastructure Roadmaps, which include ESFRI Roadmap facilities, are being implemented in spite of the serious impact of the recent financial restrictions. The suite of ground-based telescopes is delivering new science. The European Southern Observatory's Very Large Telescope (VLT)[15] is the world-standard. The ALMA[16] 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)[17] and the Joint Institute for VLBI ERIC (JIVE)[18] in the European VLBI Network[19], are pathfinders for the **ESFRI Landmark SKA** (Square Kilometre Array). SKA, a global collaboration with Europe in a leading role, has established a dual location in Australia and South Africa. High-energy gamma-ray Cherenkov telescopes HESS[20] and MAGIC[21] developed the observation of TeV scale photon sources into a full-fledged astronomy. The **ESFRI Landmark ELT** (Extremely Large Telescope) – ESO's giant optical-infrared telescope – was approved in 2012 and is now under construction in Chile. The **ESFRI Landmark CTA** (Cherenkov Telescope Array) is setting up the infrastructure of its two hosting sites at ESO Paranal in Chile and at the IAC La Palma, Spain. The **ESFRI Project KM3NeT 2.0** (KM3 Neutrino Telescope 2.0) is installing the first set of strings at the two Mediterranean sites of Capo Passero (Italy) and Toulon (France), aiming at higher luminosity than the IceCube[22]. The European ground-based solar community successfully proposed the **ESFRI Project EST** (European Solar Telescope) to the 2016 update of the ESFRI Roadmap.

Two ASTRONET panels, the European Telescope Strategy Review Committee and the European Radio telescope Review Committee, respectively recommended

10. European Southern Observatory http://www.eso.org/public/

11. European Space Agency http://www.esa.int/ESA

12. ASTRONET http://www.astronet-eu.org/

13. ASPERA http://www.aspera-eu.org/

14. APPEC http://www.appec.org/

15. European Southern Observatory's Very Large Telescope (VLT) http://www.eso.org/public/unitedkingdom/teles-instr/paranal-observatory/vlt/

16. ALMA http://www.almaobservatory.org/en/home/

17. LOFAR http://www.lofar.org/

18. Joint Institute for VLBI ERIC http://www.jive.eu/

19. European VLBI Network http://www.evlbi.org/

20. HESS https://www.mpi-hd.mpg.de/hfm/HESS/

21. MAGIC https://wwwmagic.mpp.mpg.de/

22. IceCube https://icecube.wisc.edu

to optimize the science impact and cost effectiveness of small and medium size facilities[23], and reviewed the existing European radio telescopes in the context of the **ESFRI Landmark SKA.** The optical/infrared, radio, planetary and solar communities are federated respectively by OPTICON, RADIONet, EuroPlaNet and PRE-EST, succeeding SOLARNET-I3 in 2017. The APPEC 2017-2026 resource-aware roadmap recommends a strong coordination among the EU agencies involved in Astroparticle Physics in the four main research areas of *multi-messenger* astronomy, neutrino physics, dark matter searches and cosmology (CMB, dark energy). Four European networks focus on gravitational wave antennas, underground laboratories, ultra-high energy cosmic rays and dark energy.

The global network of gravitational wave interferometers (GWIC) includes advanced VIRGO[24] (EU), advanced LIGO[25] (US) and KAGRA[26] (Japan) and the forthcoming INDIGO[27] (India); all are sharing data, analysis and publications. A European FP7 design study was carried out for a novel underground 10 km-arm interferometer concept called the Einstein Telescope. The first direct observation in September 2015 of gravitational waves from the merger of a black-hole pair at LIGO and furthermore the possibility of studying the direction of the signals thanks to joining VIRGO with LIGO in data taking, set the course for a new era of gravitational and *multi-messenger* astronomy.

The network of *underground laboratories* hosts increasingly large detectors, the Gran Sasso (Italy) being the largest equipment world-wide. The ultrahigh energy cosmic ray community is gathered in Europe around the Auger Observatory in Argentina. Finally, there is a large European ground-based dark energy community with major participation in the US-led Large Synoptic Survey Telescope (LSST)[28], which is complementary to the EU-led EUCLID[29] space mission.

Excellent science continues to emerge from space missions. Herschel[30] and Planck[31] provided truly spectacular far-infrared/sub-millimetre mapping of the cold Universe and of the cosmic microwave background. Gaia performs a 3D-image of our galaxy and of star velocities. In addition, the ESA Cosmic Vision selection process has set the scene for small, medium and large projects covering: the study of the Sun (Solar Orbiter[32], launched in 2019), of Mercure (BepiColombo[33], 2018) and of Jupiter's icy moons looking for biology markers (JUICE[34], 2022), exoplanetary studies (CHEOPS 2019, PLATO 2026, ARIEL 2028), the search for dark energy (EUCLID), the study of the hot and energetic universe (ATHENA) and the study of the gravitational wave Universe (LISA)[35], this last planned to be launched by 2034, with in addition the Exomars programme (Trace Gas Orbitor[36] 2016, robotic exploration 2020). There is also an important European participation in space missions through bi- or multilateral agreements, for instance for searching for antimatter in space (AMS on the ISS) and gamma-rays (FERMI). Europe's premier space astrophysics research is planned out into the distant future thanks to the substantial stability in funding for ESA that allows maximising returns for the agencies and structuring the community as well as industry. International collaboration is also well established, in particular on the James Webb Space Telescope (WEBB/JWST)[37] near-infrared telescope, which will be launched in 2018.

The Astronomy ESFRI & Research Infrastructure Cluster project (ASTERICS) develops the cross-cutting synergies and common challenges shared by the Astronomy and Astroparticle ESFRI RIs: the **ESFRI Landmarks ELT**, **SKA**, and **CTA**, and the **ESFRI Project KM3NeT 2.0**, with liaison building up with the **ESFRI Project EST**.

A summary of the main Research Infrastructures in Astronomy and Astroparticle Physics field is shown in **Figure 1** and ESFRI contribution is depicted in **Figure 2**.

## GAPS, CHALLENGES AND FUTURE NEEDS

The programme of development of new facilities is basically on track, but timelines get longer as the cost and complexity of projects increase. One challenge is to propose projects which remain doable while at the forefront to fulfil science needs. Moreover, the funding of backend instruments for the large facilities and of data science is not always included in the Research Infrastructure cost estimate, whereas the field already feels *Big Data* challenges.

The evolution of Astronomy and Astroparticle Physics projects clearly goes towards internationalisation in the construction as well as the operation of Research Infrastructures. ALMA and the **ESFRI Landmark SKA** have been the first global astronomy infrastructures. The novel *multi-messenger* paradigm implies the observation and interpretation of transient phenomena alerts and follow up by a network of telescopes and underground or underwater/ice detectors. The first detection of gravitational waves sources by the LIGO-VIRGO Consortium led to their astrophysical interpretation and their astronomical follow-up. Interest

23. Report by the European Telescope Strategic Review Committee on Europe's 2-4 m telescopes over the decade to 2020 *http://www.astronet-eu.org/sites/default/files/plaquettet2_4m-final-2.pdf*

24. VIRGO *http://www.virgo-gw.eu/*

25. LIGO *https://www.ligo.caltech.edu/*

26. KAGRA *http://gwcenter.icrr.u-tokyo.ac.jp/en/*

27. INDIGO *http://gw-indigo.org/tiki-index.php*

28. Large Synoptic Survey Telescope *https://www.lsst.org/*

29. EUCLID *http://sci.esa.int/euclid/*

30. Herschel space mission *http://sci.esa.int/herschel/*

31. Planck space mission *https://www.cosmos.esa.int/web/planck*

32. Solar Orbiter *https://www.asi.it/en*

33. BepiColombo *http://sci.esa.int/bepicolombo/*

34. JUICE *http://sci.esa.int/juice/*

35. LISA *https://www.elisascience.org/*

36. Trace Gas Orbiter *http://exploration.esa.int/mars/46475-trace-gas-orbiter/*

37. WEBB/JWST *https://www.jwst.nasa.gov/*

in gravitational-wave astroparticle/astrophysics is growing fast with the approved ESA LISA mission, the Pulsar Timing Arrays with LOFAR and in the future with **ESFRI Landmark SKA**, and developments of the Einstein Telescope.

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. ASTRONET and APPEC representing the major EU agencies/institutions operating in Astrophysics and Astroparticle Physics respectively have large overlaps in the Research Infrastructures they deal with. They are establishing contacts trying to develop a more solid coordination to fully exploit the synergy present in their roadmap visions.

The ASTERICS Cluster supports and accelerate the implementation of the ESFRI telescopes, to enhance their performances beyond the state-of-the-art, and to see them interoperating as an integrated, multi-wavelength and *multi-messenger* facility. It demonstrates the power of building synergies and common endeavours between the ESFRI RIs, and the necessity to establish a framework to continue to do so beyond the current Cluster projects.

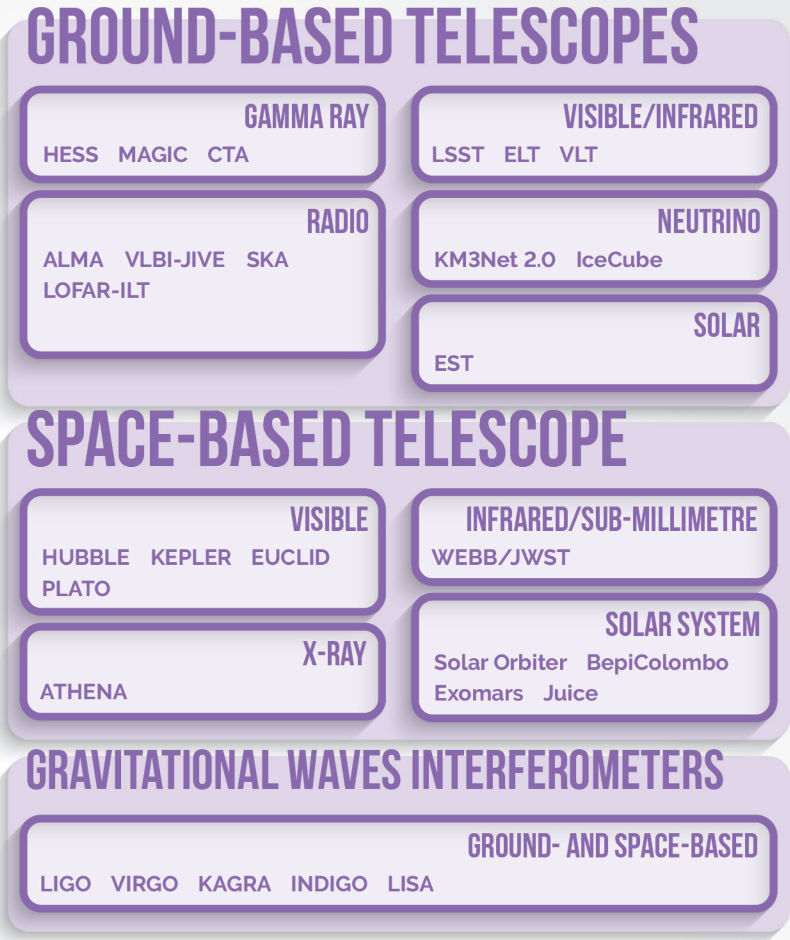



**FIGURE 1.**
Main Research Infrastructures in Astronomy and Astroparticle Physics

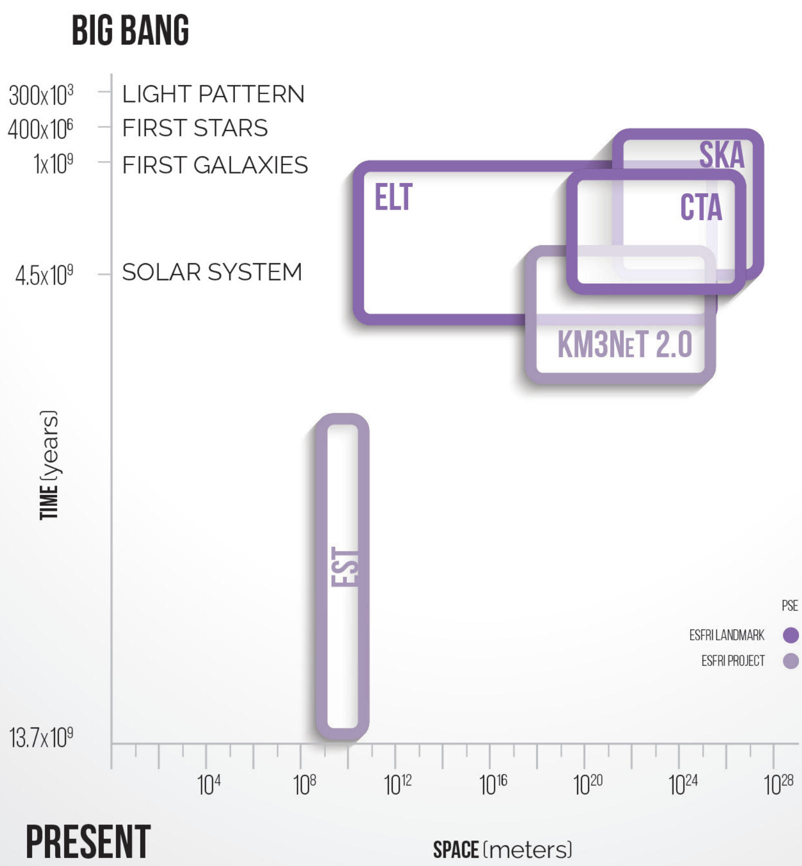



**FIGURE 2.**
Space and time domain of investigation of ESFRI Projects and Landmarks in Astronomy and Astroparticle Physics

# PARTICLE AND NUCLEAR PHYSICS

During the last 10 years, major discoveries have shaped our vision of the building blocks of matter, their properties, their interactions and their role in the evolution of the Universe. With the discovery of the Higgs boson, the Standard Model of **Particle Physics** provides an internally consistent picture of the known elementary particles which is nevertheless known to be incomplete, since it leaves several major questions unanswered. The presence of Dark Matter in current cosmological models, and the fact that gravity is not included in the Standard Model, are two examples which push searches for physics beyond the Standard Model.

New physics models which address these questions can, for example, lead to deviations Standard Model in consistency tests or in the properties of the Higgs boson at the sub per cent level, and/or predict new particles or forces which manifest at the higher energies than currently accessible. Reaching high precision and extending the energy range are therefore crucial.

Searches for Dark Matter continue at colliders, direct detection experiment and via indirect observation via astrophysics. So far none of these have revealed any signature of new particles, though theoretical as well as experimental efforts are continuously pushing the limits. Other promising areas to look for deviations from the Standard Model include high precision measurements in flavour physics in the quark and charged lepton sectors, and the search of broken symmetries in the neutrino sector.

A key goal for **Nuclear Physics** is to develop a comprehensive understanding and a predictive theory of complex nuclei. Worldwide, this goal has driven the development of various cutting edge facilities for experiments with short-lived rare isotopes in order to provide data and discover new phenomena against which theoretical predictions have to be tested. Rare isotope beams (RIB) are obtained by complementary techniques, either through the isotope-separation-on-line (ISOL) process or through in-flight production. Such beams will allow for nuclear physics research studies aiming at answering several fundamental questions related to the phases of strongly interacting matter and their role in astrophysics, the nature of the strong force that binds protons and neutrons into stable and rare isotopes, the nature of neutron stars and dense matter, the nuclear reactions that drive stars and stellar explosions. Nuclear structure and dynamics have not only reached the discovery frontier, but are also entering into a high precision frontier with higher beam intensities and purity, along with better efficiency and sensitivity of instruments, in order to focus on essential observables to validate and guide our theoretical developments.

## CURRENT STATUS

The current Particle Physics landscape is guided by the 2013 European Strategy for Particle Physics (ESPP)[38], which has been closely followed providing a coherent and broad scientific programme. The Large Hadron Collider (LHC) at CERN[39] is the major infrastructure for particle physics, with more than 7.000 physicists working on its different experiments. By the end of 2018, the LHC is in its second running period and will have accumulated an integrated luminosity of 150 $fb^{-1}$, corresponding to acquiring the data of roughly $10^{15}$ collisions and a stored data volume well in excess of 250 PB. In 2019-2020 a long shutdown is foreseen with major detector upgrades of the LHC experiments. It is foreseen to accumulate another 150 $fb^{-1}$ in this configuration until the high-luminosity phase of the LHC will start around 2025. The **ESFRI Landmark HL-LHC** (High-Luminosity Large Hadron Collider) requires an upgrade of the accelerator complex, which has already started, and also refurbishment of the ATLAS and CMS detectors in order to maximise their scientific output in a much harsher environment.

In the field of flavour physics, the measurements provided by the LHCb experiment will be complemented and cross-checked by the results from the BELLE-2 experiments at the SuperKEKB[40] collider at KEK in Japan. Data taking of this experiment will start in 2019 and use rather low energy electron-positron beams yet at the highest intensities with the aim to accumulate an integrated luminosity of 50 $ab^{-1}$.

The CERN neutrino platform is a framework that allows European physicists to work on neutrino detector development. In this context, collaboration is ongoing with the next generation long baseline accelerator-based neutrino experiments: DUNE in the US (Fermi National Accelerator Laboratory FNAL[41] and Sanford Underground Research Facility[42]) and Hyper-Kamiokande[43] in Japan.

These experiments with increased beam intensities, and improved detectors, will allow unprecedented precision in measurements of neutrino oscillations and CP violation. Detector R&D as well as prototype construction for these experiments is ongoing. Accelerator based neutrino experiments are complemented by the upcoming reactor-based experiment, JUNO located in China, and measurements with atmospheric neutrinos by the ORCA-site of the **ESFRI Project KM3NeT 2.0** collaboration. Other neutrino properties are measured in Europe by smaller infrastructures, such as KATRIN at KIT for aiming at a direct neutrino

38. European Strategy for Particle Physics (ESPP) https://cds.cern.ch/record/1567258/files/esc-e-106.pdf

39. HL-LHC https://home.cern/topics/high-luminosity-lhc

40. SuperKEKB http://www-superkekb.kek.jp/index.html

41. Fermi National Accelerator Laboratory (FNAL) http://www.fnal.gov/

42. Sanford Underground Research Facility https://sanfordlab.org

43. Hyper-Kamiokande http://www.hyperk.org

mass measurement, and GERDA, CUORE at LNGS or SuperNemo (LSM) for determining the Dirac or Majorana nature of neutrino. European particle physicists are also pursuing precision measurements in the charged-lepton sector, at PSI and at infrastructures in other regions (US, Japan).

Complementing the searches for new physics at the LHC, experiments directly searching for Dark Matter based on various techniques such as liquid noble gas or cryogenic detectors are hosted in underground laboratories. The most stringent limits are currently provided by the XENON collaboration (LNGS), with developments ongoing on large liquid Argon based detectors (DARKSIDE) and low mass searches with cryogenic detectors.

The first generation of radioactive beam (RIB) facilities based on the complementary methods of, in flight separation (GANIL and GSI) and the ISOL approach (ISOLDE and SPIRAL1) have enabled tremendous progress in the study of exotic nuclei to be made. Both in-flight separation and the ISOL approach, combined with different post-processing of the radioactive nuclei, will form the pillars of the RIB facility network in Europe.

Major advances in the field are expected to come through the studies of extended reach in proton-to-neutron ratio of new or upgraded facilities, including the Radioactive Isotope Beam Factory (RIBF) at Rikagaku Kenkyusho (RIKEN), the **ESFRI Landmark FAIR** (Facility for Antiproton and Ion Research) at Darmstadt, the HIE-ISOLDE facility at CERN, the **ESFRI Landmark SPIRAL2** (Système de Production d'Ions Radioactifs en Ligne de 2e génération) at Grand Accelerateur National D'ions Lourds (GANIL), the facility for the Study and Production of Exotic Species (SPES) at INFN-Legnaro, the Isotope Separation and Acceleration II (ISACII) at TRIUMF, and the Facility for Rare Isotope Beams (FRIB, USA) with capabilities for fast, stopped, and unique reaccelerated beams. All these facilities provide or will provide new and important insights into the structure of nuclei and are expected to discover new phenomena that will lead to major progress towards a unified description of nuclei. Other accelerator-based probes are also important for nuclear physics research in Europe. The ELI-NP (Extreme Light Infrastructure - Nuclear Physics) facility is one of the three pillars of the pan-European **ESFRI Landmark ELI** aiming at the use of extreme electromagnetic fields for nuclear physics research.

Investigation of nuclei produced at the upcoming nuclear physics research facilities requires development of state-of-the-art detectors and detection techniques. The Advanced Gamma Tracking Array (AGATA)[44] represents a revolution in the way gamma-ray spectroscopy is performed and it will have a wide range of uses in nuclear physics from studying how elements are synthesised in stars to the understanding of the underlying shell structure of the newly discovered super-heavy elements. The basic technology of the array will also bring developments in medical imaging and diagnostic machines that produce three-dimensional images of people's bodies, providing information about the functioning of internal organs and detecting disease and tumours.

The production of exotic nuclei is closely linked to the availability of separators and spectrometers in order to select and identify the nuclei or reactions of interest. Addressing these objectives is a driving force for existing or future facilities, such as the Japan Proton Accelerator Research Complex (J-PARC), the international **ESFRI Landmark FAIR** at Darmstadt, the 12 GeV Continuous Electron Beam Accelerator Facility (CEBAF) Upgrade at the Jefferson Lab, the Mainz Microtron (MAMI), A Large Ion Collider Experiment (ALICE) at CERN, and RHIC II at Brookhaven National Laboratory (BNL), the Nuclotron-based Ion Collider fAcility (NICA) or The Super Heavy Element Factory (SHE Factory) at the Joint Institute for Nuclear Research (JINR) in Dubna (Russia).

A summary of the main Research Infrastructures in Particle and Nuclear Physics field is shown in **Figure 3** and ESFRI contribution is depicted in **Figure 4**.

44. Advanced Gamma Tracking Array (AGATA) *https://www.agata.org/*

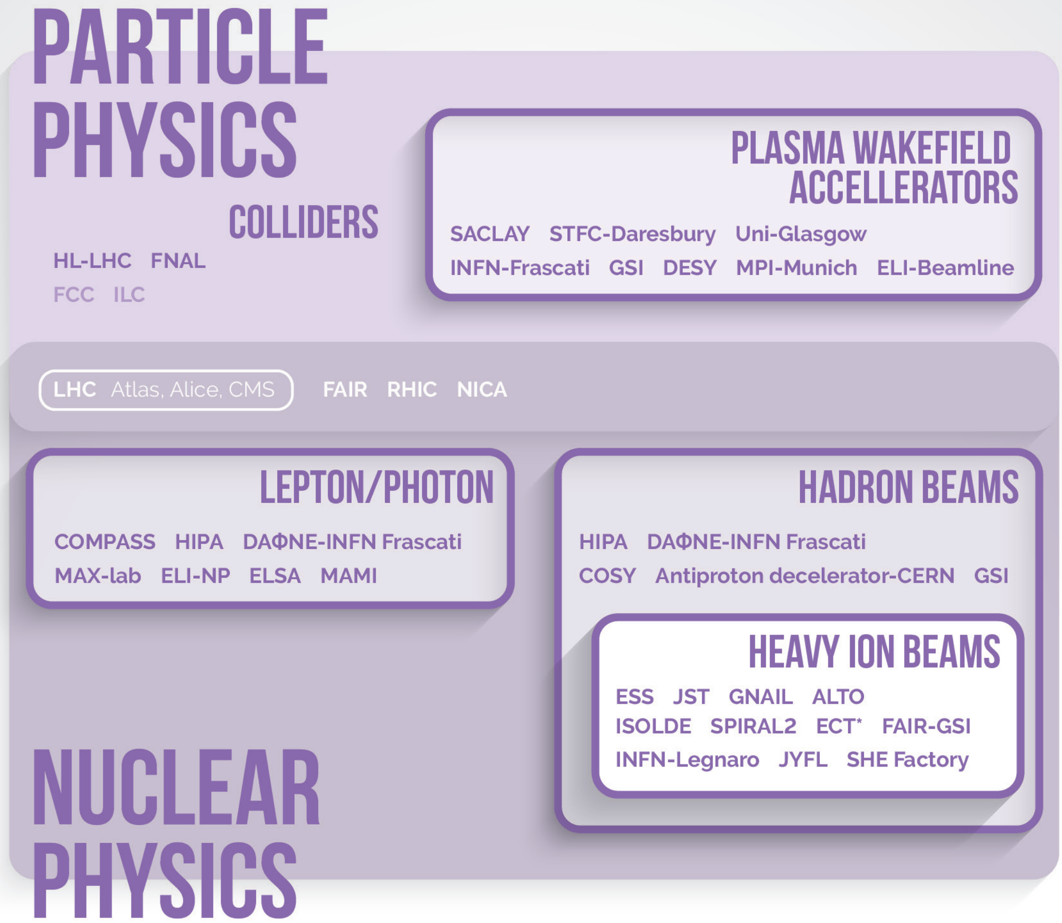



**FIGURE 3.**
Major Research Infrastructures in Particle and Nuclear Physics

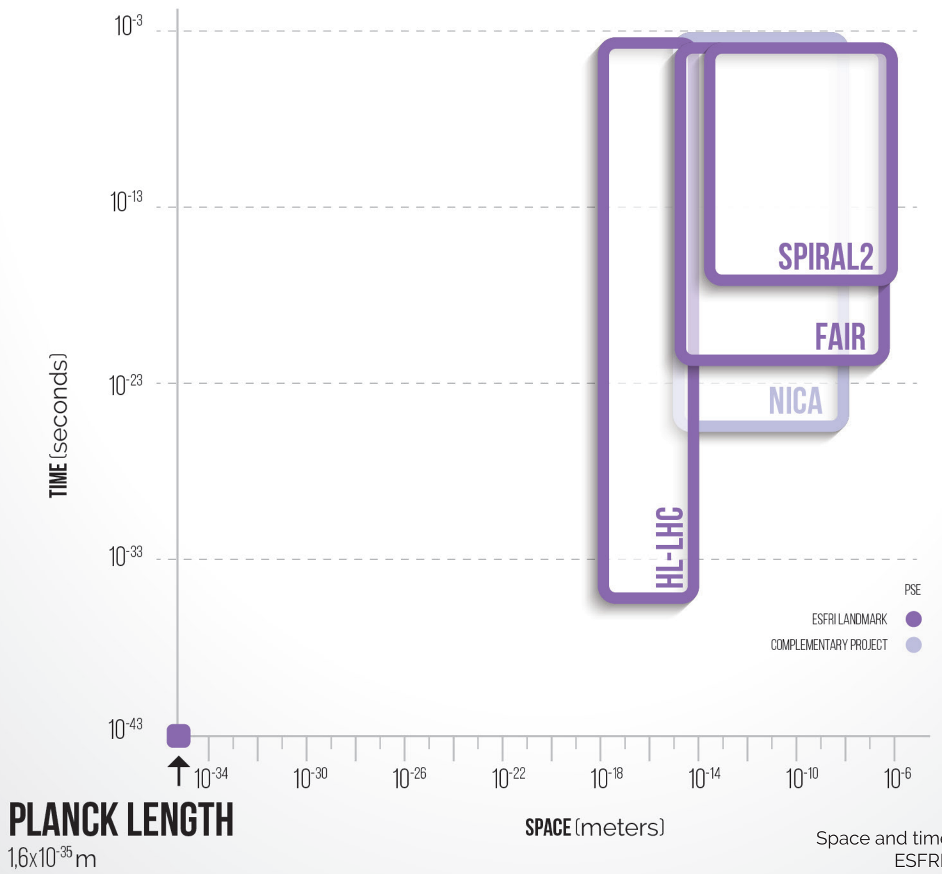



**FIGURE 4.**
Space and time domain of investigation of ESFRI Projects and Landmarks in Particle and Nuclear Physics

## GAPS, CHALLENGES AND FUTURE NEEDS

For the near term future, the HL-LHC will be the main particle physics accelerator infrastructure, allowing detailed study of the Higgs sector and searches for new physics with 3000 $fb^{-1}$ of data expected for ATLAS and CMS by 2035. On a similar timescale an International Linear Collider (ILC)[45] providing electron-positron collisions at a few hundred GeV energy, is a possible project to be hosted in Japan as a worldwide international collaboration. This would allow important studies of the Higgs sector and other precision measurements complementary to the HL-LHC. The ILC has long been on the strategic list of projects foreseen in particle physics, and a signal from the Japanese community indicating whether or not Japan would host such a project is expected by the end of 2018.

Further future projects would address the two main requirements for particle physics: an increase in precision and in energy. Several initiatives in accelerator R&D are addressing these challenges. In order to reach higher energies for an electron-positron linear collider, R&D for the CLIC concept using beam driven acceleration has been pursued at CERN initially aiming at energies in the multi-TeV range. However, the highest reach in energy is obtained from proton colliders, where the big challenge is the development of high field magnets, currently part of an ambitious R&D programme. Conceptual studies for a 100 km collider with about 100 TeV collision energy – the Future Circular Collider Study (FCC)[46] are underway at CERN. Such a collider would open a new window on searches for new physics and allow a conclusive study of the Higgs self-coupling. A possible stepping stone could be to install the required high field magnets in the LHC tunnel to double the LHC collision energy (HE-LHC), or to have an electron-positron collider in the FCC tunnel (FCC-ee), both of which are included in the FCC studies. There may also be interesting options to combine these technologies to collide electrons with protons, which may provide significant improvement in Higgs coupling measurements. Beyond these studies, innovative R&D programmes are ongoing on the concept of laser-plasma acceleration. Several techniques are studied in major European laboratories (Germany, Italy, UK, France and Portugal) and through the EUPRAXIA[47] design study as well as through the AWAKE[48] project at CERN.

Given the lack of theoretical guidance on where new physics could be realized, it is important to, as much as possible, cover all options. A new Physics Beyond Colliders[49] initiative is looking at ways of profiting from the CERN infrastructure and expertise to leave no stone unturned in the search for new physics. For example, studies include searches for axion-like particles in beam dump based experiments benefitting from the upgrade of the LHC injectors. By the end of 2018 documents on all the above projects will be available for the next ESPP discussion, from which a set of recommendations will be released in 2020 to define the strategy for particle physics research for the proceeding 5-10 years.

For Nuclear Physics on a long term perspective a novel ISOL facility in Europe (EURISOL) is needed, which will provide wide range of beams with much higher intensities compared to what is available at present. Meanwhile, by integrating the ongoing efforts and developments at the major ISOL facilities of HIE-ISOLDE, SPES and SPIRAL2, the planned ISOL@MYRRHA facility, and the existing JYFL and ALTO and COPIN facilities and the planned ELI-IGISOL facility an advantage should be taken use the synergies and complementarities between them and build a programme of research to bridge the gap between present facilities and ultimate EURISOL facility.

Based on the collaboration between nuclear physicists and plasma physicists, the ELI project will develop laser–plasma electron accelerators, based on the wakefield principle, and ion beams accelerators. Such devices have the potential to accelerate a range of particle and ion species in table-top distances. These innovative acceleration methods will open new perspectives for a range of applications such as: more efficient production of radioisotopes required for nuclear medicine and beams for testing the latest designs of sensors for use in medical imaging, new methods for identification and remote characterization of nuclear materials with applications in homeland security and nuclear material management, testing of materials for space science.

Research and development programmes, are being pursued to investigate the concept of precision storage rings to search for charged particle electric dipole moments (EDM), based on the ongoing studies at COSY; the design of a polariser ring to produce high intensity polarized antiproton beams as one upgrade option for HESR at FAIR; the implementation of sympathetic laser cooling techniques to cool systems like the proton, antiproton and highly charged ions to temperatures as low as a few mK; the design of advanced high intensity lasers for precision spectroscopy of exotic atoms, such as antihydrogen, muonic hydrogen, pionic helium, and muonium.

45. International Linear Collider
*http://www.linearcollider.org/*

46. Future Circular Collider Study
*https://fcc.web.cern.ch/Pages/default.aspx*

47. EUPRAXIA
*http://www.eupraxia-project.eu/*

48. AWAKE
*https://cds.cern.ch/record/2221183/files/SPSC-SR-194.pdf*

49. Physics Beyond Colliders
*http://pbc.web.cern.ch/*

# ANALYTICAL PHYSICS

**Analytical Research Infrastructures** primarily comprise powerful sources of photon or particle beams. Light sources based on electron accelerators with storage rings for **Synchrotron Radiation** or **Free-Electron Lasers** provide brilliant soft to hard X-ray beams enabling nanoprobes of the structure and chemical composition of materials, including trace analysis down to ppb concentration, over many length scales – from atomic to macroscopic ($10^{-10}$ - $10^{-1}$ m) – and time scales – from femtoseconds (fs, $10^{-15}$ s for FELs) or picoseconds (ps, $10^{-12}$ s for SR) to milliseconds (ms, $10^{-3}$ s) or steady states. **Neutron Scattering** sources based on proton accelerators or nuclear reactors provide unique and complementary probes of the structure of materials, particularly for light elements such as H and subtle magnetism, and lower energy scales for slow dynamics – typically ~µs. Moreover, the neutrons constitute, because of their high penetration power, a single probe for analysis on large volumes, or non-destructively on small internal volumes in an industrial piece for example.

The broadly distributed laser spectroscopy, high resolution **Electron Microscopy** and **High Magnetic Field** facilities also operate as ARIs. EM complements SR, FELs and NS, probing down to 50 picometers (pm, $10^{-12}$ m) spatial resolutions with element specificity, comparable energy resolution (10 meV or less) and temporal resolutions that can approach 10 fs. **Laser RIs** probe or manipulate matter with ultra-short or ultra-high intensity pulses from ~ 100 attoseconds (as, $10^{-18}$ s) to 100 fs with millijoule (mJ) to tens of joule (J) energies, or cover the complementary time-energy region up to 10 kilojoule (kJ) and 10 nanosecond (ns, $10^{-9}$ s). Materials may also be manipulated using HMFs to provide unique insights into electronic and magnetic phenomena.

The very broad range of analytic capabilities provided by ARIs provides an equally broad range of drivers across many areas of fundamental and applied science: structure and function of biological macromolecules implicated in disease and therapy; materials for cleaner, greener transport, energy and chemical synthesis; complex electronic and magnetic materials, for next generation ICT; synthesis and performance of materials during manufacture and under *operando* conditions; environmental systems and planetary science; and climate, natural and cultural heritage artefacts.

Integration of European ARIs is occurring at different levels, impacting materials science and nanoscience both for fundamental research and for innovation: the CERIC-ERIC[50] is a distributed RI providing access to fine analysis with complementary methods – electrons, neutrons, X-rays, synchrotron-light; the EU IA Initiative NFFA-Europe[51] offers integrated access to nano-foundry, characterization, theory and fine analysis at major European facilities and research institutions.

## II CURRENT STATUS

### SYNCHROTRON RADIATION AND FREE ELECTRON LASER FACILITIES

There are currently twelve SR facilities and six FELs open for transnational access across Europe (**Table 1** and **Table 2**). Among SR facilities most have storage ring energies of 3 GeV and are among the best in class in the world – while the **ESFRI Landmark ESRF EBS** (European Synchrotron Radiation Facility Extremely Brilliant Source) have helped maintain it as best in class of any SR facility in the world and the 6 GeV facility PETRA III has also undergone extensive upgrades[52]. Most recently, Europe has seen first operations of the MAX IV Facility[53] based on novel, disruptive MultiBend Achromats (MBA) technology for the storage ring that will offer unprecedented brightness and coherence. The **ESFRI Landmark ESRF EBS** will provide 100-fold increase in brilliance and coherence – significantly closer to the physical (diffraction) limit for hard X-rays – by 2019 through a MBA upgrade, several other national facilities also plan MBA upgrades in the period 2020-2025. Complementary improvements in detector technology have also been transformative, while accelerated throughput and increased remote access in techniques such as crystallography, and construction of more beamlines at some national facilities helps meet the increasing demand for access.

50. Central European Research Infrastructure Consortium CERIC ERIC
http://www.ceric-eric.eu/

51. NFFA-Europe
http://nffa.eu

52. PETRA
http://photon-science.desy.de/facilities/petra_iii/index_eng.html

53. MAX IV
https://www.maxiv.lu.se/

| FACILITY | LOCATION | ELECTRON ENERGY (GeV) | EMITTANCE (nm rad) | FULLY SCHEDULED BEAMLINES (CONSTRUCTION/COMMISSIONING) | START OF USER OPERATIONS |
|---|---|---|---|---|---|
| **ESRF (EBS)** | GRENOBLE (FR) | 6 | 4 (0.13) | 30+14 CRGS* | 1994 (2020) |
| **PETRA III** | HAMBURG (DE) | 6 | 1.1 | 16 (24) | 2010 |
| **ALBA** | BARCELONA (ES) | 3 | 3.6 | 7 | 2012 |
| **DIAMOND** | HARWELL (UK) | 3 | 2.7 | 31 (33) | 2007 |
| **MAX IV** | LUND (SE) | 3 | 0.34 | 16 (29) | 2016 |
| | | 1.5 | 9 | 0 (5) | 2016 |
| **SOLEIL** | ST. AUBIN (FR) | 2.75 | 3.74 | 29 | 2008 |
| **SWISS LIGHT SOURCE** | PSI, VILLIGEN (CH) | 2.4 | 4.4 | 16 | 2001 |
| **ELETTRA** | TRIESTE (IT) | 2.0/2.4 | 7.0/9.7 | 26 (2) | 1994 |
| **BESSY II** | BERLIN (DE) | 1.7 | 6.4 | 47 (31) | 1998 |
| **SOLARIS** | CRACOW (PL) | 1.5 | 6 | 2 | 2018 |
| **ASTRID2** | AARHUS (DK) | 0.58 | 12 | 10 | 2014 |
| **MLS** | BERLIN (DE) | 0.24-0.6 | 100 | 11 | 2008 |

*Collaborating Research Groups managing quota of access

**TABLE 1.**
Summary of European SR facilities

| FACILITY | FELS LINES OPERATING IN PARALLEL | LOCATION | START USER OPERATION | ELECTRON ENERGY | PHOTON ENERGY | PULSE PROPERTIES | NUMBER OF END STATIONS |
|---|---|---|---|---|---|---|---|
| **European XFEL** | SASE-1<br>SASE-2<br>SASE-3 | HAMBURG / SCHENEFELD, GERMANY | 2017<br>2018<br>2018 | 8.5-17.5 GeV | 3.0 to >20 keV<br>3.0 to >20 keV<br>0.25-3.0 keV | 1-100 fs<br>10x2.700 pulse/s | 2<br>2<br>2 |
| **SwissFEL** | ARAMIS<br>ATHOS | VILLIGEN, SWITZERLAND | 2018<br>2020 | 2.1-5.8 GeV | 4.0-15 keV<br>0.25-2.0 keV | 5-100 fs<br>100 Hz | 2<br>2 |
| **FERMI** | FERMI-1<br>FERMI-2 | TRIESTE, ITALY | 2012<br>2016 | 1.5-1.8 GeV | 15-90 eV<br>80-400 eV | 20-90 fs<br>10-50 Hz | 5 |
| **FLASH** | FLASH<br>FLASH-2 | HAMBURG, GERMANY | 2005<br>2016 | 1.25 GeV | 30-300 eV<br>30-300 eV | 20-150 fs<br>10x800 pulses/s | 4<br>3 |
| **CLIO** | CLIO | PARIS, FRANCE | 1993 | 40 MeV | 10-400 meV | 0.5-5 ps<br>60 MHz<br>pulsed: 25 Hz | |
| **ELBE** | FELBE<br>TELBE | DRESDEN, GERMANY | 2005<br>2016 | 40 MeV | 0.5-250 meV | 0.5-30 ps<br>13 MHz cw | 7<br>1 |
| **FELIX** | FELIX 1/2<br>FLARE<br>FELICE | NIJMEGEN, NETHERLANDS | 1993<br>2013<br>2007 | 15-50 MeV<br>10-15 MeV<br>15-50 MeV | 8-400 meV<br>0.8-12 meV<br>12-250 meV | 0.5-200 ps<br>1/3 GHz<br>pulsed: 20 Hz | 12<br>4<br>2 |
| **TARLA** | | ANKARA, TURKEY | 2019 | 40 MeV | 5-400 meV | 0.5-30 ps<br>13 MHz cw | |

**TABLE 2.**
Summary of European FELs, in operation or under construction

The **ESFRI Landmark European XFEL** (European X-Ray Free-Electron Laser) and SwissFEL[54] are hard X-ray FEL facilities that saw their first experiments in 2017, complementing a suite of complementary IR, UV or soft X-ray FEL user facilities already in operation. The TARLA facility is being built in Turkey and further projects are planned (MAX IV-FEL, POLFEL).

CALIPSOplus[55] supports co-ordinating activity for SR and FEL facilities, overlapping with the remit of the European Cluster of Advanced Laser Light Sources (EUCALL)[56]. The League of European Accelerator-based Photon Sources (LEAPS)[57] co-ordinates activity for SR and FEL facilities, FEL activities join forces in the consortium FELs of Europe[58] and the EC funded the PaNdata[59] initiative for integrated data infrastructure for European photon and neutron facilities, and for the future EOSC is under discussion.

## NEUTRON SCATTERING FACILITIES

Thirteen NS facilities operate in Europe, comprising two world-leading sources – the **ESFRI Landmark ILL** (Institut Max von Laue-Paul Langevin), and the accelerator-based ISIS neutron and muon Facility[60] – and an array of high quality medium flux facilities (**Table 3**). This landscape will change greatly in the next decade: the future neutron source for Europe, the **ESFRI Landmark European Spallation Source ERIC** begins its user program on world-leading instruments initially planned for 2023 while two reactor-based facilities – BER-II[61] and Orphée-LLB[62] – will stop in 2019. ILL whose current agreement between the partners expires in 2023, is one of the key facilities to maintain at a very high level the European community of neutron scientists and users, especially before ESS reaches its nominal operation. These evolutions of the European neutron landscape will lead to a significant shortfall in the provision of neutron facilities relative to needs from the start of the next decade[63]. EC currently supports such facilities, including integrating activity, through SINE2020[64].

| FACILITY | LOCATION | SOURCE | POWER (MW) | FULLY SCHEDULED INSTRUMENTS | START (END) USER OPERATIONS |
|---|---|---|---|---|---|
| **ILL** | GRENOBLE (FR) | REACTOR | 57 | 30+10 CRGs* | 1971 |
| **ISIS** | HARWELL (UK) | SPALLATION | 0.2 | 21+10 CRGs* | 1984 |
| **LLB** | SACLAY (FR) | REACTOR | 14 | 21 | 1981 (2020) |
| **FRM-II (MLZ)** | GARCHING (DE) | REACTOR | 20 | 25 | 2004 |
| **BER-II** | BERLIN (DE) | REACTOR | 10 | 10 | 1973 (2019) |
| **SINQ** | VILLIGEN (CH) | SPALLATION | 1 | 13 | 1996 |
| **JEEP II** | KJELLER (NO) | REACTOR | 2 | 2 | 1967 |
| **REZ** | REZ (CZ) | REACTOR | 10 | 8 | 1957 |
| **BNC** | BUDAPEST (HU) | REACTOR | 10 | 15 | 1959 |
| **DELFT** | DELFT (NL) | REACTOR | 2 | 4 | 1963 |
| **SACAVEM** | SACAVEM (PT) | REACTOR | 1 | 3 | 1961 (2016) |
| **VIENNA** | VIENNA (AT) | REACTOR | 0.25 | 4 CRGs* | 1962 |
| **ESS** | LUND (SE) | SPALLATION | 5 | 15** | 2023 |

* Collaborating Research Groups managing quota of access
** Instruments under design and construction to be operational in the period 2022-2028

TABLE 3.
Summary of European Neutron Scattering facilities

54.
SwissFEL
https://www.psi.ch/swissfel/

55.
CALIPSOplus
http://www.calipsoplus.eu/

56.
EUCALL
https://www.eucall.eu/

57.
LEAPS
https://leaps.desy.de/

58.
FELs of Europe
https://www.fels-of-europe.eu/

59.
PaNdata
http://pan-data.eu/

60.
ISIS Muon and Neutron Source
https://www.isis.stfc.ac.uk/Pages/home.aspx

61.
Research Reactor BER II
https://www.helmholtz-berlin.de/quellen/ber/ber2/index_en.html

62.
Orphée-LLB
http://www-llb.cea.fr/en/Web/hpr_web/HPRWEB1.php

63.
Neutron scattering facilities in Europe - Present status and future perspectives Author. ESFRI Physical Sciences and Engineering Strategy Working Group - Neutron Landscape Group, ESFRI Scripta Volume 1, 2016
http://www.esfri.eu/sites/default/files/u4/NGL_CombinedReport_230816_Complete%20document_0209-1.pdf

64.
ENSA Brochure, 2017
https://www.sine2020.eu/news-and-media/ensa-brochure---second-edition.html

### ELECTRON MICROSCOPY FACILITIES

About 100 mid- to high-end EM instruments operate in Europe (most of which include aberration correction of the probe forming or imaging optics). From these 15 leading laboratories and some SMEs form a networked infrastructure, ESTEEM2 (FP7)[65], to be replaced by ESTEEM3 (H2020). An EU Design Study (DREAM) to explore the creation of a pan-European Research Infrastructure for advanced EM at a scale similar to SR and Neutron facilities is being planned, including two of the highest spatial resolution microscopes in the world (at Juelich[66] and Harwell[67,68]) and several instruments capable of providing sub 10 meV energy resolution (Daresbury[69] and Orsay[70]). The recent development of direct electron detectors has helped to revolutionise the use of cryo-EM in structural biology, with an exponential growth in installations that increasingly complement X-ray protein crystallography, and in the physical sciences through faster frame-rates and significantly improved detector resolution.

### HIGH PERFORMANCE LASERS

Laser RIs are distributed across Europe with user access and joint R&D coordinated mainly through the EU integrated Initiative Laser-Lab IV (LLIV)[71] with 33 organisations from 16 countries and also part of EUCALL. The **ESFRI Landmark ELI**, which aims to host the highest performance laser systems worldwide, is currently developing at three sites with complementary capability to each other and the rest of LLIV: the ELI-ALPS[72] pillar combines USP and UHI at very high repetition rates; the ELI Beamlines pillar[73] will provide ultra-short secondary radiation (X and $\gamma$-rays) and particle (electrons, ions) sources; ELI-Nuclear Physics[74] offers a unique combination of the most powerful laser sources worldwide (2 x 10 PW) with a fully tuneable $\gamma$-ray source (up to 19.5 MeV).

### HIGH MAGNETIC FIELDS

All high magnetic field activities in Europe are organised through the **ESFRI Landmark EMFL** facilities, 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) field, under commissioning in 2018 (Grenoble and Nijmegen) while in Toulouse, a semi-destructive pulsed field installation now offers fields of 100-200 T. All HMF facilities have been either fully renewed since 2000 or have had major upgrades and are internationally competitive. Two of them are directly coupled to a THz FEL (Nijmegen and Dresden), allowing unique joint operation.

### GENERAL

European activity should also be considered as part of a network of global partnerships, both among our nearest neighbours (for example Russia, which has a number of existing and planned facilities available for international users such as the IBR-2 reactor[75] and the support of the Commision through the Cremlin project[76], as well as the middle East with initiatives such as SESAME[77]).

A summary of the main Analytical Research facilities representing the Analytical Physics Landscape is reported in **Figure 5** and ESFRI contribution in **Figure 6**.

65. ESTEEM 2 *http://esteem2.eu/*

66. ER-C *http://www.er-c.org/centre/centre.htm*

67. Harwell ePSIC *http://www.diamond.ac.uk/Science/Integrated-facilities/ePSIC.html*

68. Harwell eBIC *http://www.diamond.ac.uk/Science/Integrated-facilities/eBIC.html*

69. SuperSTEM-Daresbury *http://www.superstem.com/*

70. LPS-Orsay *http://www.lps.u-psud.fr*

71. LASERLAB *https://www.laserlab-europe.eu/*

72. ELI-ALPS *https://www.eli-hu.hu*

73. ELI-BEAMS *https://www.eli-beams.eu*

74. ELI-Nuclear Physics *http://www.eli-np.ro/*

75. IBR-2 reactor *http://ibr-2.jinr.ru/*

76. Cremlin project *https://www.cremlin.eu/project/*

77. SESAME *http://www.sesame.org.jo/sesame/*

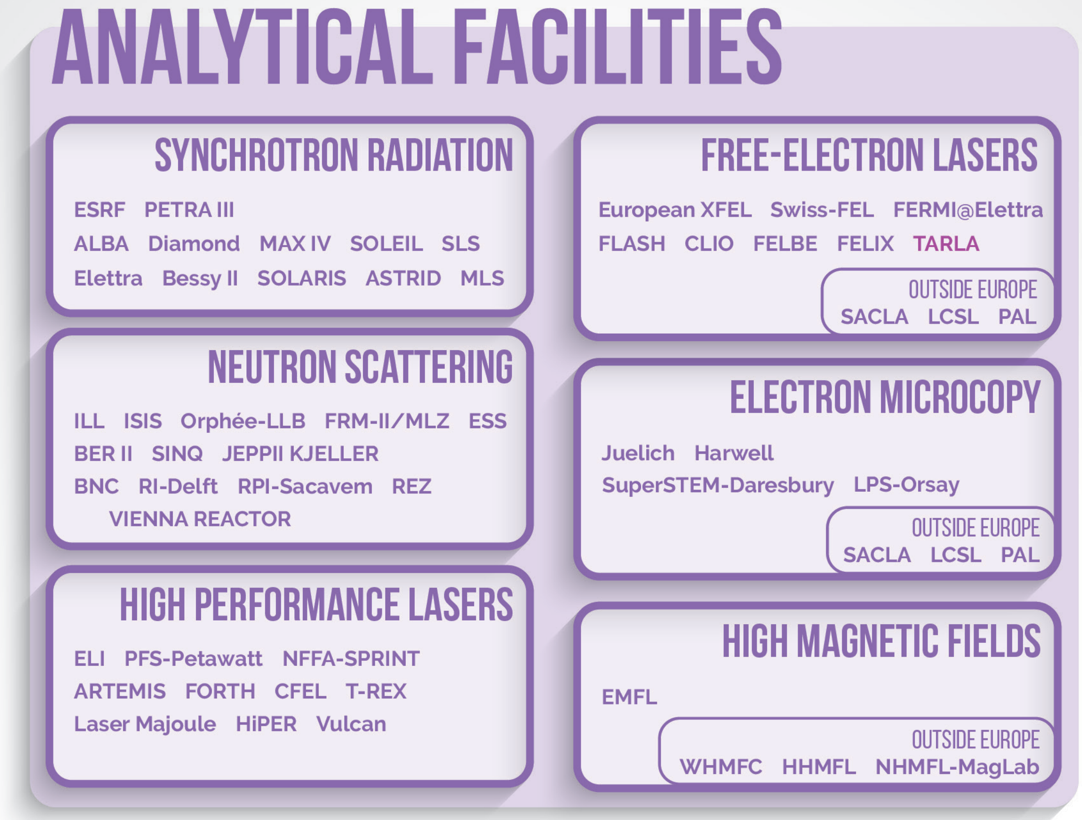



**FIGURE 5.**
Main Research Infrastructures in Analytical Physics

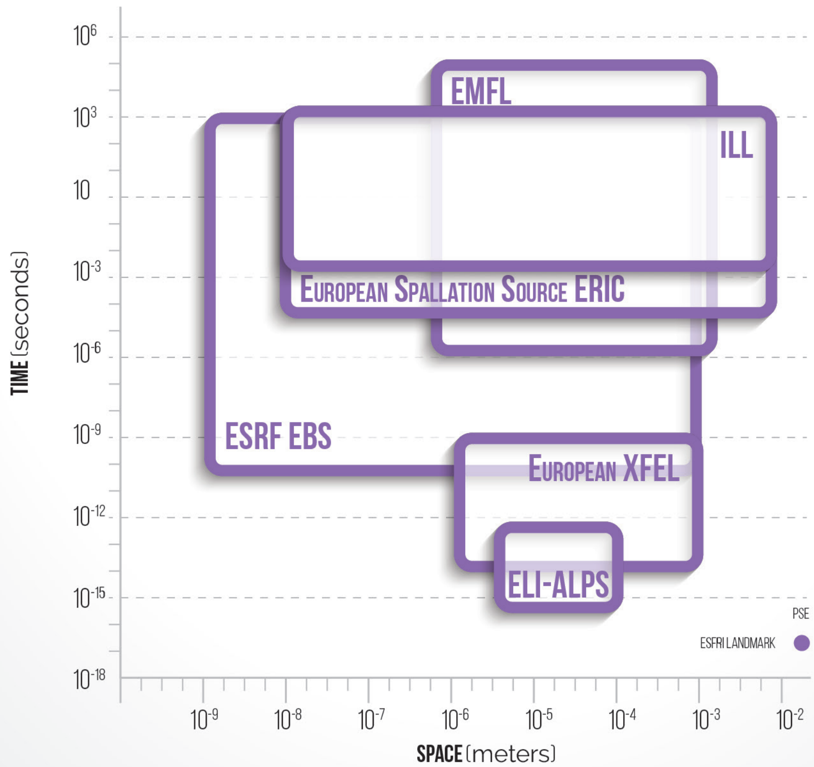



**FIGURE 6.**
Space and time domain of investigation of ESFRI Projects and Landmarks in Analytical Physics

# GAPS, CHALLENGES AND FUTURE NEEDS

Brighter sources and faster detectors produce larger, often more complex data sets that are becoming more challenging to process and analyse, both during the experiment to make informed decisions about how best to proceed, and afterwards, increasingly across multiple probes. This requires not only significant investment in hardware to transfer, store and process data but also coherent development of software with greater exploitation of AI techniques, and many more people – data scientists – expert in such methods.

Many ARIs require more powerful, compact accelerator sources and better detectors, both of which could involve highly synergic collaborations across types of RIs. There are technical challenges specific to individual types of ARI: diffraction limited storage rings for SR for harder X-rays offering coherent imaging down to 10's of nm, and study of fluctuations to 100 ps; new medium-power high-brilliance NS installations; coherent pulsed sources for EM that operate in both stroboscopic and single shot modes, also requiring detector development. Improvements to high performance lasers will require new materials for robust optical components, a new generation of online, single-shot, *in situ* diagnostics of the laser fields, to control the experimental environment fully, and increase laser peak power at least 100 times by shortening pulses or superposing beams from several sources to create and study electron-positron pairs from the vacuum. For HFM, co-ordinated development across RIs (CERN, NS, etc.) is needed to develop a 30+ T high $T_c$ superconducting (HTSC) magnet and address the very high electricity costs of operation, as well extend fields to the region 55-60 T, closer to the point where charge carriers in HTSC materials decouple.

Increasing demand for SR facilities could be met over the next decade through the upgrade of existing facilities and building additional national or regional facilities. Exploitation of complementary FEL facilities is still at a relatively early stage but likely to grow strongly in this period. A co-ordinated European plan to provide sufficient NS capacity before the ESS ramps up should be developed. The very strong growth in demand for Cryo-EM will require an increase in the number of instruments and the development of higher throughput methods. For high-performance lasers a key challenge is to transform existing networks into more robust and reliable user-oriented operations at or approaching 24/7.

# CONTENTS



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) enhance research into the historical, social, economic, political and cultural contexts of the European Union, providing data and knowledge to support its strategies.

The data collected and provided by SCI RIs contribute 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 social and economic policies and societal trends in and across Europe. These insights are fundamental to understand European society and to answer to emerging challenges moving forward.

Data from social sciences and structures that create, collect, assemble and curate such relevant data are fundamental to the further development of the social science research community of Europe. The statistical literacy and research potential of the next generation of social scientists is nurtured using the resources of networked social science data archives and cross-national surveys. The research outputs of Europe's social scientists have 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), the Global Science Forum (GSF) and the European Commission (EC), with important contributions arising from the social sciences.

Public statistics, major scientific surveys, management data and data from opinion polls represent essential sources of knowledge for the social sciences. The development of European indicators on society via longitudinal surveys is a challenging goal to provide a key instrument for constructing Europe.

Research in the humanities provides a better understanding of our society, both diachronically through historical research to answer questions of how we become what we are – by which mechanisms was this driven – and how we can elaborate this knowledge for shaping the future development of our society; and synchronically by monitoring the media to detect what is currently happening in our society – how we react to the major challenges – how societal challenges beside us can be addressed. 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 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.

Future surveys of the impact of SSH research and RIs will make use of the Social Impact Open Repository (SIOR)[1] allowing researchers to upload qualitative and quantitative testimonies of the social impact of their research, making use of specific indicators[2]. This system also enables funding agencies and citizens to monitor the way in which research impacts society positively, for instance through the reduction of early school leaving. It shows especially the directions of innovation in SSH research are going and how these are integrating with other sciences. The availability of this information will also provide guidelines for SSH research groups and projects to increase political and social impact, as well as a body of evidence to demonstrate the results.

The SSH target community is substantial: 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 11% in arts and humanities. The ISSC World Social Science Report 2016 estimates that more than 30% of the researchers in the higher education system are in SSH disciplines, however with substantial variation among countries. This accounts for more than 500.000 researchers employed – Full Time Equivalent (FTE) – in higher education in the European Union. In contrast, the spending for SSH is substantially lower than 30% of the overall research spending and often lower than 20% in many countries, according to figures given in the same report[4].

1. Social Impact Open Repository
http://sior.ub.edu/jspui/

2. Social impact: Europe must fund social sciences. Flecha R., Soler-Gallart M., Sordé T. – Nature, 2015, Vol. 528 (7581): 193.
http://www.nature.com/articles/528193d

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

4. ISSC World Social Science Report 2016
http://unesdoc.unesco.org/images/0024/002458/245825e.pdf

# EMERGING DRIVERS

## BIG DATA

The speed and versatility of electronic communication and the growth of digital media and tools, as well as their accessibility, 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 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. Such data may be generated by machines through the operation of sensing and imaging devices – e.g. Radio-Frequency Identifiers, imaging equipment; by robotic analysis – e.g. genome wide scans; by social media interactions – e.g. Twitter feeds; mass-recordings of video magnetic tapes – e.g. video cassettes from last centuries art projects; or from the recording of administrative processes – e.g. hospital records, tax and benefit claims. In 2012, digital content grew to over 2.8 Zettabytes (ZB, $10^{21}$ bytes) to 8.5 ZB by 2015[5]. *Big Data* technologies, tools, and services that turn this information overload into information gains are the next opportunity for competitive advantage, and Language Technology (LT) is a core *Big Data* technology. Growth in the volume and variety of data is mostly due to the accumulation of unstructured text data; in fact, up to 80% of all data is unstructured text data[6]. Moreover, the translation technology segment will continue to dominate the European LT market. RIs in LT are indispensable in breaking new ground. 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 data sources. They can, for example, be used to extract information about preferences, 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.

While data types are many and varied, their value for research relates to the depth of their content and the extent of their coverage and the possibility to link data from different sources, which in turn is a function of the processes by which such data are generated. For example, supermarket store card data derived from specific and self-selecting customers who shop at particular stores and feel motivated to use a store card to gain a loyalty bonus. With data from millions of shoppers, in particular when linked to social surveys or administrative sources, the information generated can be used to explore dietary patterns and to relate these information to geographical indicators of social deprivation. 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.

Before the research value of *Big Data* for SSH can be realised, three important conditions must be met. First, the data must be accessible for research purposes, often through their availability, digitalisation and normalisation; second, the best possible metadata and methods need to be used to extract and interpret the information; and third, there should be clarity about how the data have been generated. While the first condition seems obvious to researchers, data holders may place restrictive conditions on research when individual-related data or commercial interests are involved. In addition, linking data from different sources substantially increases their scientific potential but raises many practical issues to be addressed: technical connected to data integration, and legal related to data protection.

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

6. Unstructured Data and the 80 Percent Rule
*http://breakthroughanalysis.com/2008/08/01/unstructured-data-and-the-80-percent-rule/*

# NEW MEANS FOR COMMUNICATING AND DISSEMINATING RESEARCH

The mechanism for dissemination of research results emerges as one of the most important predictors of extra-academic impact. Open Access has gained momentum with the involvement of Governments from different countries and the support of funding agencies for research in order to create a strong Open Access Landscape in Europe.

Open Access is just one component of Open Science – the movement to give access to data, research and publications and open up the whole research cycle for participation and collaboration. Initiatives such as the European Open Science Cloud (EOSC)[7], or the Open Access mandate that goes along with the Horizon 2020 Framework[8], are strong messages to the whole scientific community. Yet, the development of Open Access for publications in SSH seems to lag behind other scientific disciplines. For example, the Directory of Open Access Journals indicates that only 41% of the journals[9] – representing 23% of the articles – belong to the SSH area. One of the reasons explaining this divergence could be that a large part of the scientific production in SSH disciplines is published in books and not journals. Even if quantitative social research is often coming closer to other sciences in terms of methodological approaches, books still play an important role in the dissemination of knowledge for those disciplines. Open Access for academic books in SSH develops under different conditions than those we know for articles in the natural or hard sciences. The challenges are different in technical and economic terms as well as in usage, and there are many initiatives in different European countries, by the publishers, the libraries or the scientific communities themselves, which need to be better coordinated in the future.

The dissemination is increasingly not limited to the publications but to the data underlying publications. The request to make primary sources of SSH data available is increasing, both from funding agencies and publishers. This trend in open science not just for publications, but for data as well, requires new and enhanced capabilities to store and access different type of data in the future.

The EOSC aspires to become the European stakeholder-driven infrastructure for science and innovation. It will not only be a data repository, but will also comprise technical elements of connectivity, hardware, repositories, data formats and Application Programming Interfaces (APIs) and it will offer access to a wide range of user-oriented services, data-management, associated HPC analytics environments, stewardship services and, notably, expertise.

# 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 makes way for promising interactions. Disciplinary boundaries are 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. 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 eloquent example of that evolution. 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.

**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. To cite just one example, the extraction of oil from bituminous sands and shales in Canada is expected to move every year more than two times the total mass of annual river sediments in the whole world. While the environmental impact of such extraction can be estimated by natural sciences, it requires the social sciences to analyse and understand the decision-making processes that lead to or can avoid such massive changes in the environment. This change has been accentuated by recent developments in the way of managing science. Horizon 2020, which is not structured by disciplinary fields, but by societal challenges – e.g. health and well-being, climate changes – is the paradigmatic example of this transformation of the science system in Europe. This new approach poses the question of hybrid 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** (European Research Infrastructure for Heritage Science) which combines material science methods with interpretative schemes of history of art to rejuvenate the field of heritage studies.

7.
European Open Science Cloud
https://ec.europa.eu/research/openscience/index.cfm?pg=open-science-cloud

8.
H2020 Programme Guidelines to the Rules on Open Access to Scientific Publications and Open Access to Research Data in Horizon 2020
http://ec.europa.eu/research/participants/data/ref/h2020/grants_manual/hi/oa_pilot/h2020-hi-oa-pilot-guide_en.pdf

9.
Directory of Open Access Journals
https://doaj.org/

# CURRENT STATUS

The digital aspect of the currently most prominent 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.

The **ESFRI Landmark CESSDA ERIC** (Consortium of European Social Science Data Archives) is a distributed Research Infrastructure that provides and facilitates researchers' access to high quality social science data and supports their use of this data. The CESSDA Work Plan 2017 informs about significant improvements in information retrieval across the range of relevant service providers and other sources. In this regard, the CESSDA Product and Service Catalogue (PaSC) will be made fully operational in 2018, and a new retrieval tool is under development. Other improvements are in the areas of metadata management, technical architecture, PID policy, and outreach to new scientific cohorts through workshops on data discovery, collaborative data management, etcetera. CESSDA does not disseminate data itself, it coordinates the activities of the national data service providers across Europe. In total it holds, curates and provides access to several thousands of separate data collections, supporting a European-wide user community. CESSDA operates within a global data environment, with reciprocal data access arrangements and agreements established with other data holding organisations worldwide.

The **ESFRI Landmark ESS ERIC** (European Social Survey) is an academically driven long-term pan-European survey designed to chart and explain the interaction between Europe's changing institutions and the attitudes, beliefs and behaviour patterns of its diverse populations. ESS recently announced 100k registered users. The ERIC updated its Multilevel Data resource in June 2017. Italy, Slovakia and Spain were the final countries to confirm that they will take part in Round 8 (2016/17) of the European Social Survey alongside 21 other European countries. ESS has a broad scientific network and is widely used for academic publications: 109.063 users were registered by the end of August 2017; 76.677 users have downloaded ESS data from all over the world by end of August 2017. Bibliometric data from a google scholar analysis shows 3.140 ESS publications and citations based on ESS data recorded in the period 2003-2015; 2.821 outputs and publications are registered in the ESS online bibliography as of 5 September 2017[10]. In addition, HypeStat[11] states: europeansocialsurvey.org receives about 650 unique visitors and 2.210 (3.40 per visitor) page views per day.

The **ESFRI Landmark SHARE ERIC** (Survey of Health, Ageing and Retirement in Europe) is the upgrade into a long-term Research Infrastructure of a multidisciplinary and cross-national panel database of micro data on health, socio-economic status and social and family networks of about 110.000 Europeans aged 50 or over. SHARE covers 27 European countries and Israel. The main data collection of Wave 7 is under way in all these countries. As the largest pan-European Social Science Panel Study, SHARE broke a new country record – there have never been more countries in one wave. 6.400 SHARE users were recorded in February 2017. Furthermore, new country teams in Romania, Cyprus and Slovakia were established between 2016 and 2017. SHARE had more than 7.000 users by July 2017. Overall 1.836 publications were produced with SHARE data, 815 were peer reviewed articles[12].

The **ESFRI Landmark CLARIN ERIC** (Common Language Resources and Technology Infrastructure) 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.

10. ESS User Statistics
http://www.europeansocialsurvey.org/about/user_statistics.html

11. HypeStat
https://hypestat.com/

12. SHARE Project
http://www.share-project.org/

In 2018, CLARIN has 20 Members, two Observers and one third country institution (Carnegie Mellon University, USA). CLARIN has a global vision, although the focussed user community is European (EU and Associated States). In 2018, CLARIN has more than 40 centres and more than 160 institutes. Europeana[13] has 800.000 resources listed in CLARIN's Virtual Language Observatory (VLO). The number of monthly visits to the CLARIN website is slowly growing since January 2015. In addition, there is a steady increase in the number of visits to the Discovery Service – used during single-sign on to CLARIN service providers. This can most probably be explained by the increase of the number of services available and their growing popularity.

The **ESFRI Landmark DARIAH ERIC** (Digital Research Infrastructure for the Arts and Humanities) is aiming at enhancing and supporting digitally enabled research and teaching across the Arts and Humanities. During 2017, DARIAH launched its Teaching Platform in Digital Arts and Humanities.

The **ESFRI Landmarks CLARIN ERIC** and **DARIAH ERIC** have collaborated on the relaunch of the Digital Humanities Course Registry. Recent workshops have focused on Data Management, Software Sustainability, Research Ethics, Access, Staff Training, Impact, etc. Numerous universities and libraries joined as cooperating partners in the first half of 2017.

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 enables 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. Based on the preliminary work done in the framework of the H2020 IPERION-CH project started in May 2015, the **ESFRI Project E-RIHS** is currently in the Preparatory Phase which will be used to address legal status and governance/management organization. This will lead to the foundation of an ERIC – or another suitable legal form – to be launched in 2020. Further developments are planned for connecting and including partners and facilities outside the EU, and gradually reaching the status of a global distributed Research Infrastructure.

13. Europeana
https://www.europeana.eu

# GAPS, CHALLENGES AND FUTURE NEEDS

The development of high speed data connection together with storage capacities and information processing software has provided access to massive amounts of data, 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 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.

Data storage and digital interactivity, have opened up new opportunities in terms of appropriation and handling of research resources. Consequently, we have seen a diversification in the locations of digital resource production which have resulted in the creation of many 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* 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, among which we point out the following.

**THE PREDICTIVE CAPACITY OF BIG DATA.** The challenge is to understand if and how a large amount of data can improve and enhance predictive capacity regarding social phenomena. One concern is that *Big Data* might lead to causality being overlooked, since this perspective relies on correlations and trends whose underlying cause may not be clear.

**BIG DATA AND THE ROLE OF THEORY.** The advent of *Big Data* has often been accompanied by concerns about the end of theory and about a kind of knowledge that is only data-driven. The question is to understand if the use of *Big Data* can contribute to the generation of interpretative patterns of past, present and future social, political or cultural reality, or identification of the limits of machine learning for humanist and sociological knowledge.

**BIG DATA AND DATA PROTECTION ISSUES.** The use of *Big Data* in research does not only refer to the issues of privacy protection, but also concerns about access and possession of such data and in many cases also copyright issues. Solutions at national and European level must be found in order to enable researchers to use *Big Data*, given the ethical and legal challenges.

**METHODOLOGICAL CHALLENGES OF BIG DATA.** The scientific community has some concerns about the validity and the reliability of *Big Data*: the discussion is how to use them in a controlled way in order to produce scientifically relevant inferences.

**BIG DATA ANALYSIS.** Especially in the field of opinion mining and sentiment analysis, treatment and analysis of *Big Data* rely on automatic procedures more or less monitored by the researcher and on algorithms of machine learning through which the software is able to classify a large amount of textual information. This raises classic methodological problems in a new form: the inspection and thus the control and evaluation of data analysis procedures.

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.

## INTEGRATION OF BIO-SOCIAL DATA

Interdisciplinary research cutting across SSH has the potential to supply increasingly rapid insights into the influence of socio-economic and environmental conditions on biological changes. These have long-lasting consequences for our behaviours, health and socioeconomic well-being through the life cycle. There is a need to understand the pathways and mechanisms involved in these reciprocal feedbacks over the range from cells to society. Bringing together interdisciplinary teams to address these research issues and ensuring that our longitudinal and cohort studies are augmented and enhanced to enable such research, provides new opportunities for scientific discovery.

Bringing together data from diverse sources, spanning genomics, blood analyses and biomarkers, health and other administrative records, and business or transaction data, and linking all of these into the rich longitudinal cohort and panel studies presents several major challenges to ensure accessibility and usage. Many researchers would benefit enormously from having complex data pre-processed and summarised in useful ways.

Existing RIs, such as the **ESFRI Landmark ELIXIR** (A distributed infrastructure for life-science information, H&F) and **ESFRI Landmark SHARE ERIC**, indicate that there is significant potential at the pan-European level to integrate a range of biomedical and socio-economic data resources during the lifecycle. In the same way, the surveys and data provided by the emerging project GGP will contribute to the analysis of generational differences in values and gender roles that are highly relevant for policy debates.

Further development in this area of the European research landscape will provide fertile ground for trailblazing research with huge potential benefits for the health and well-being of populations.

## PROMOTING AN INTERNATIONAL APPROACH TO REAL-TIME DATA ANALYTICS

Historically, data that have been used for research in the social, economic and behavioural sciences have been designed and/or collected specifically for that purpose. In recent years, however, new forms of data not originally intended for research use, such as transactional and administrative data, internet data (derived from social media and other online interactions), tracking data (monitoring the movement of people and objects), and image/video data (aerial, satellite and land-based), have emerged as important supplement resources and alternatives to traditional datasets. In quantitative humanities, however, the analysis of resources that were not created for specific research questions has a long tradition. The problem of non-tailored resources arises newly since large amounts of digital resources are available to researchers. The troubling gap is emerging in our ability to capture and explore these new forms and amounts of data for the purposes of research. This gap is arising because:

- the prevalence of new forms of data will increase exponentially as technologies and digital capabilities evolve and it is imperative for the SSH community to take a leading role in establishing a robust, quality assuring, secure and sustainable infrastructure for utilising them;

- technological and methodological advances must be made in order to realise the potential of real-time analytics for research in SSH;

- much of the value of new forms of data lies in the potential for linkage and calibration with other data and the derived opportunities for addressing novel research questions aa well as re-examining open questions through a new lens;

- current training and capacity-building provisions are insufficient to meet the growing demand from researchers at all stages of their careers to utilise new forms of data;

- new forms of data and their subsequent uses pose novel ethical, quality and privacy questions that must be explored to ensure that these technologies are deployed in a responsible way.

Europe has to implement standards with respect to privacy and security issues in Research Infrastructures. The recently established General Data Protection Regulation (GDPR) could bring clarity and benefit to research across the SSH and associated disciplines – e.g. medical sciences, health research etc. The new GDPR is an opportunity to develop and establish a lead in regard to privacy and security issues concerning Research Infrastructures.

## RIs FOR SOCIAL MEDIA – ARCHIVING WEB

Since the mid-1990s the web has become an integrated part of society, culture, business, and politics, and national web archives have been established to preserve this part of the digital cultural heritage. But for the scholar who wants to study the web across borders, national web archives become an obstacle since they delimit the borderless information flow on the web by national barriers. Thus, a transnational Research Infrastructure should be established with a view to: i) developing a more efficient and attractive European Research Area; ii) ensuring the researcher free access to the digital cultural heritage from different nations; and iii) increasing the potential for fostering innovative partnerships with the software development industry for studies of *Big Data*.

## RIs FOR HUMANITIES AND CULTURAL INNOVATION

Contemporary technologies offer great opportunities to revitalize and make available on a large scale cultural items which represent a collective treasure for Europe in terms of identity, citizenship, diversity, cultural growth, and economic potential. The effort in that direction should be conceived in two different ways:

- Cultural items – manuscripts, papyri, books, movies, music, paintings, monuments, etc. – in their material reality, are complex physical objects that are in need of material analysis, dating, preservation and restoration. Viewed in this way, they are relevant for RIs which aim to support the analysis of physical objects in general.

- Making a material object part of our cultural heritage largely depends on the collective awareness of its existence and on the value vested in it. In this respect, RIs devoted to the dissemination (digitisation, 3D-reconstitution, etc.) of those objects are crucially needed to the maintenance of our cultural heritage.

An enormous amount of diverse materials is widely distributed across Europe: they are often difficult to access from outside local communities, and sometimes at risk of deterioration. The main challenge of RIs is to provide users access (educators, museums and exhibition curators, public) to such treasures and heritage, and to the state-of-the-art analysis carried out by experts and researchers, also by exploiting digital media and archives.

National museums and integrating Research Infrastructures such as the European Cultural Heritage Online (ECHO)[14] and Europeana[15] have made important efforts to digitize libraries and collections. ECHO was established in 2002 to create a research driven IT infrastructure for the humanities. It works on digitisation of cultural heritage and develops research driven tools and workflows for analysis and publication of scholarly data linked to primary sources. ECHO features more than 70 collections from more than 24 countries worldwide. Europeana is a European network representing more than 3,300 institutions and aggregators and provides cultural heritage collections to all in the form of more than 30 million digitised objects and descriptive data.

However, making these treasures accessible in digital form is only the first step in ensuring their uptake by the target audience. The vast bulk of the cultural heritage accumulated through centuries of European history is a formidable resource of rich material for new and far-reaching analyses, typically in languages no longer spoken. Therefore, the mere availability of this heritage no longer

14. European Cultural Heritage Online (ECHO) *http://echo.mpiwg-berlin.mpg.de/home*

15. Europeana *http://www.europeana.eu/portal/*

guarantees that current scholars, let alone the general public, will be able to internalise it through conventional methods, i.e., reading about this heritage and annotating it. Thus, new methods of intelligent information mining and text analytics are needed that should be capable of automatically processing the content of the massive amount of cultural heritage treasures and making them accessible to present day audiences. In response, initiatives have been made by setting up projects to record and possibly revitalize endangered languages, in which social media can also play an important role[16]. It may be noted that CLARIN has examples from a very large number of languages, and that more than 1.500 languages are represented with 5 examples or more.

Meeting this challenge requires significant interdisciplinary efforts to integrate competences from different expert fields, bring together the most advanced facilities and make their resources available on a large scale. Infrastructures such as the Cultural Heritage Advanced Research Infrastructure (CHARISMA) contributed to the development of joint activities in the field of conservation of cultural heritage. CHARISMA covers joint research, transnational access and networking of twenty-one organizations that provide access to advanced facilities, develop research and applications on artwork materials for the conservation of cultural heritage and open up larger perspectives to heritage conservation activities in Europe. It has defined and consolidated the background for the **ESFRI Project E-RIHS**.

Additionally, in the archaeological sciences the ARIADNE network developed out of the vital need to develop infrastructures for the management and integration of archaeological data at a European level. As a digital infrastructure for archaeological research ARIADNE brings together and integrates existing archaeological research data infrastructures so that researchers can use the various distributed datasets and technologies. ARIADNE has strong ties to the **ESFRI Landmark DARIAH ERIC**.

16. The Endangered Languages Project
*http://www.endangeredlanguages.com/*

## 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 attractive and compatible on a global scale.

The accessibility of digital research data – e.g. survey data in the Social Sciences, digitized and annotated cultural heritage in the humanities – 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 is there still a possible gap between different standards for certain kinds of data – depending on the source from which they were derived – between European infrastructures and non-European 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.

Digital tools and functions have to be potentially newly programmed 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 newly 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 to ten years ago where data could disappear when a researcher retired. Currently not only data are stored in sustainable, long-lasting and secure archives, but the current RIs – e.g. the **ESFRI Landmarks CLARIN ERIC** and **CESSDA ERIC** – also use innovative 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 one part of Europe if other parts are missing. For those 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 infrastructures only have 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 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 Landmark SSH RIs. 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 infrastructures to build and maintain what could be called a *Knowledge Sharing Infrastructure* is important. Knowledge Sharing 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.

# HIGH STRATEGIC POTENTIAL AREAS OF RESEARCH IN THE FIELD OF SOCIAL AND CULTURAL INNOVATION

## RELIGIOUS STUDIES

Religious studies have become very relevant not only for researchers, but also social actors and decision makers since positive knowledge on religions is a prerequisite to develop informed dialogue and effective policy in the evolving multicultural society. The economic and demographic crisis affecting Europe, as well as the concurrent immigration from other parts of the world, destabilizes the perception of the European society also in terms of an evolving religious landscape. New forms of orthodoxy appear and social discontent and radicalism are expressed frequently in religious terms which is also a threat to social cohesion in the EU. At the same time, religion has played a central role in social integration throughout the history of humankind and it is important to understand its evolution in a changing European society. In this context, specialized research in the broad field of religious and related sociological studies is of high potential strategic value for addressing the challenges of the evolving European societal landscape and dialogue with the neighbouring countries. To effectively address these challenges, scholars and other users who deal with issues related to religions need open access to libraries, archives, human and digital resources, as well as the dedicated services, at a higher level than typically available today at the existing national research centres and laboratories, or at excellence clusters. Cooperation of scholars in religious studies, like in the H2020-funded *Research Infrastructure on Religious Studies initiative* (RelReS)[1] project, can be of high potential strategic value for creating a diachronic understanding of the historical development of religions and for enabling the appropriate elaboration of tools to manage inter-religious stress.

## DIGITAL SERVICES FOR OPEN SCIENCE

Scholarly communication practices in the social sciences and humanities need to be reinforced in order to implement Open Science principles. There is a fragmented and generally sub-critical level of activity corresponding to traditional university presses, other scholarly-led publishers, publication platforms, libraries, service providers and research networks that limits the high innovative potential of this area and its contribution to the effective implementation of the goals of Open Science. Specific challenges of the social sciences and humanities domain need to be addressed: publication typologies – research monographs, critical editions – multilingualism, strong connections of research with local communities. This generates a need of advanced interoperability across the sector and its perspective integration into the EOSC. The need of creating a robust open scholarly communication system capable of contributing to Open Science is evident as well as the opportunity to build it on existing know-how, technologies, infrastructures, business models and funding streams. Cooperation on the development of pan-European services in this field, like in the H2020-funded *Design for Open access Publications in European Research Areas for Social Sciences and Humanities* (OPERAS-D)[2] project, can be of high potential strategic value for promoting better accessibility and interoperability of SCI data and services.

1. Research Infrastructure on Religious Studies – RelReS
https://cordis.europa.eu/project/rcn/213376_en.html

2. Design for Open access Publications in European Research Areas for Social Sciences and Humanities – OPERAS-D
https://cordis.europa.eu/project/rcn/206231_en.html

# CONTENTS



PART2

**LANDSCAPE ANALYSIS - SECTION1**

# DATA, COMPUTING AND DIGITAL RESEARCH INFRASTRUCTURES

# DATA, COMPUTING AND DIGITAL RESEARCH INFRASTRUCTURES

In research, as in all fields of society, Information and Communications Technology (ICT) has become a key enabling factor for progress. ICT is also changing the *modus operandi* of research by providing new possibilities for geographically distributed collaboration and sharing. Data-driven science, as well as more and more open access to data and scientific results, is transforming not only how research is conducted, but its overall reach.

Today, all large-scale Research Infrastructures are already dependent on ICT resources. This dependence has increased the need to find synergies and to develop ways to tackle the ICT challenges at a generic level, providing effective and cost efficient services that can be of wide and general use. The pan-European e-Infrastructures for networking, high-performance computing (supercomputing) and high-throughput computing (clusters built from more commodity-type hardware) are already well-established and provide production services used by international research and Research Infrastructures projects. Also, data and cloud infrastructures are developing fast and consolidation and integration of such initiatives is taking place, partly inspired by the description of the European e-Infrastructure *Commons* as proposed by the e-Infrastructure Reflection Group (e-IRG). The European Commission enforces the collaboration between researchers, Research Infrastructures and e-Infrastructures by the European Open Science Cloud (EOSC) declaration and the Electronic Data Infrastructure (EDI) definition as a combination of very fast networking and exascale computing.

The e-Infrastructure landscape described below paves the way for common solutions for shared needs and requirements. Having a general, common layer of supporting e-Infrastructures – *horizontal* e-Infrastructures – also allows for a refocus on science for the disciplinary Research Infrastructures. *Horizontal* e-Infrastructures shared by thematic infrastructures are an important facilitator of cross-disciplinary work, thereby enabling the study of fundamentally new research questions. Here, it should be noted that the development of ICT is very fast and further innovation and development of e-Infrastructure services of all types is essential to make sure that the needs of the European research and Research Infrastructures communities can also be tackled in the future.

Beyond e-Infrastructures and digital devices for network, computation and data management, it is also of a major importance to develop specific Research Infrastructures in the domain of computer sciences, supporting the experimentation of disruptive systems including e-Infrastructures, hard-middle-softwares, protocols, computing and cybersecurity issues. This is best done as a co-design effort between all stakeholders where new needs of the researchers lead the way to innovation efforts.

The European e-Infrastructure landscape includes a networking infrastructure, computing facilities and data infrastructures. The European e-Infrastructure ecosystem fully includes national, regional and institutional e-Infrastructures. It should be noted that the pan-European e-Infrastructure services are often being provided by national e-Infrastructures in a collaborative setting, and the European initiatives are dependent on the existence of strong, persistent and synergic national e-Infrastructure nodes.

In the subfields a brief introduction of the major pan-European *horizontal* e-Infrastructure initiatives is given and some examples of services provided are listed. The EOSC and EDI initiatives are highlighted in the corresponding sections. A more complete account of available services can be found in the e-IRG Guidelines Document 2017[1].

The subfields in the e-Infrastructures domain are **NETWORKING INFRASTRUCTURES** and **COMPUTING, DATA AND CLOUD INFRASTRUCTURES**.

1. Guide to e-Infrastructure requirements for European Research Infrastructures, e-IRG support document, 2017 *http://e-irg.eu/documents/10920/363494/2017-Supportdocument.pdf*

# NETWORKING INFRASTRUCTURES

## CURRENT STATUS

GÉANT[2] manages the pan-European research and education network which links together and offers transnational access to RIs and research resources by providing interconnectivity between National Research and Education Networks (NRENs) across 43 European countries. The NRENs connect universities, research institutes, and sometimes other public institutions in each country. The access to NREN resources is managed nationally and the policy differs slightly from country to country. In addition to pan-European connectivity, the GÉANT network has international connections to a large set of partner networks worldwide, enabling international collaboration on research and education. Most large-scale Research Infrastructures can connect to the local NREN and thus access GÉANT enabling worldwide communications. Projects can also work with their NREN and GÉANT for international point to point links to connect parts of the Research Infrastructures that are distributed over Europe or beyond. If the project or infrastructure is distributed across national boundaries, GÉANT can help coordinate with the relevant local NRENs and advise on appropriate technical solutions. GÉANT also provides important services for researchers, such as innovation test beds.

GÉANT delivers a range of networking services at the international level. Most of these services match those offered at national level by the NRENs. The GÉANT NREN Compendium[3] gives an overview of all NRENs, their services and the contact information. The connectivity delivered by GÉANT is supported by a comprehensive range of network monitoring and management services for e.g. optimizing network performance and continuous monitoring. Users can also benefit from the range of GÉANT network monitoring, security and support services employed by NRENs to assure optimum performance for projects and institutions.

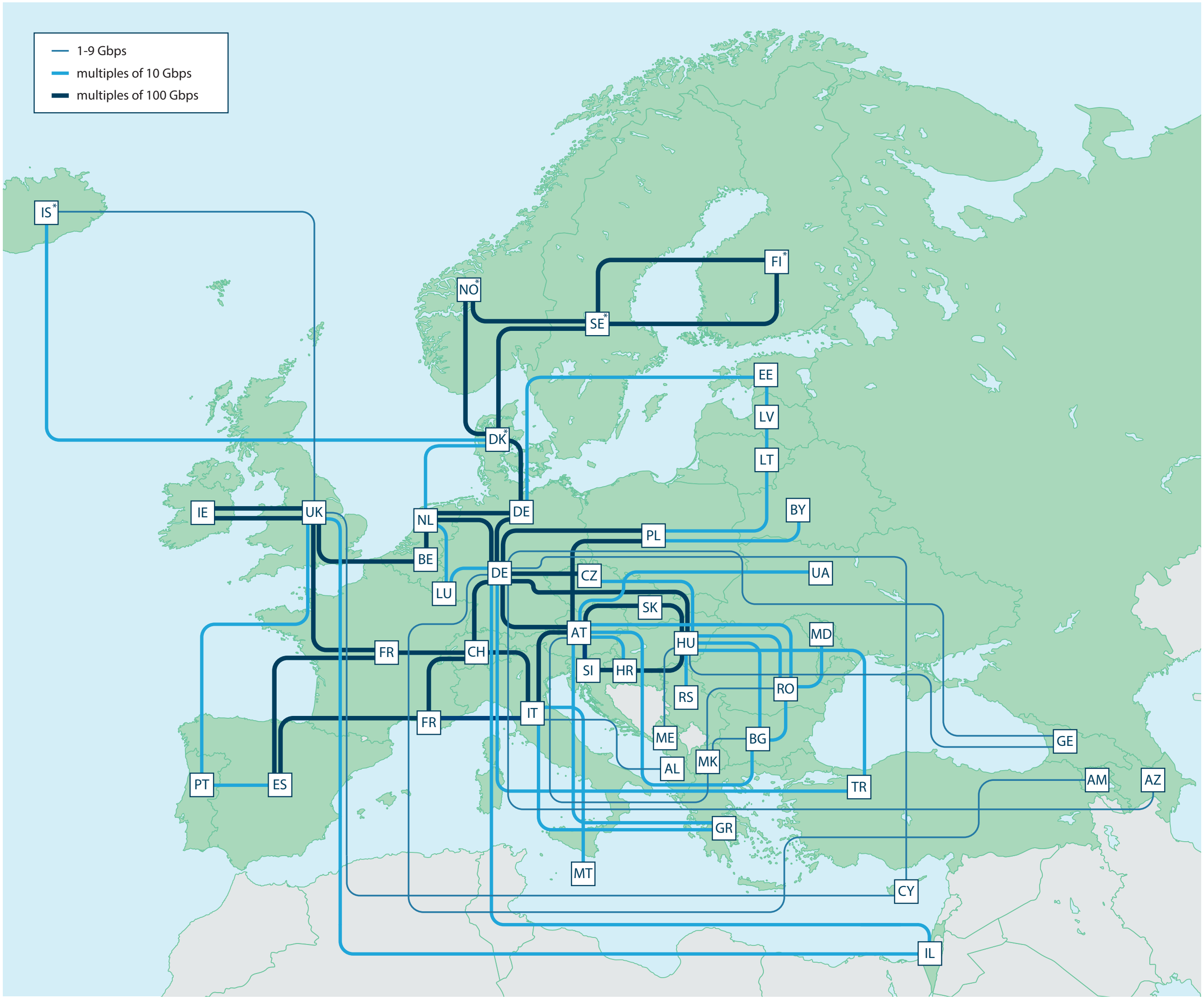
Leading research is today often conducted in a highly distributed and mobile environment where researchers freely collaborate across boundaries. The research communities need to manage access to their services from participants in many organisations and individual researchers need to easily and securely access multiple tools, services and datasets. Trust and identity therefore take up a pivotal position in the e-Infrastructure ecosystem. Here, federated authorization and authentication services simplify access to inter-organisational resources, allowing controlled and secure access. By forming a layer connecting the power of the network with computing, data and cloud infrastructures, such services enable safe and secure research throughout Europe and beyond. In this context, a number of services for the research community are provided to the research community by GÉANT. These services include eduroam that facilitates access to wireless networks in campuses around the world and eduGAIN that provides a framework for interoperation between digital identity federations.

2. GÉANT
*https://www.geant.org/*

3. GÉANT NREN Compendium
*https://compendium.geant.org/#!/*

GÉANT

GÉANT's pan-European **research and education network** interconnects Europe's National Research and Education Networks (NRENs).
Together we connect over **50 million users** at 10,000 institutions across Europe.




GÉANT's pan-European network is funded by the GÉANT Project (GN4-2), which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement 731122. Connectivity to the Eastern Partnership countries (AM, AZ, BY, GE, MD, UA) is provided through the EaPConnect project, with 95% funding from the European Commission DG NEAR under grant agreement 2015-356353. The map shows topology as at January 2018. The GN4-2 and EaPConnect partners are listed below.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| AL Albania | BE Belgium | CY Cyprus | EE Estonia | GE Georgia | IE Ireland | LT Lithuania | ME Montenegro | NO Norway* | RS Serbia | TR Turkey |
| AM Armenia | BG Bulgaria | CZ Czech Republic | ES Spain | GR Greece | IL Israel | LU Luxembourg | MK F.Y.R Macedonia | PL Poland | SE Sweden* | UK United Kingdom |
| AT Austria | BY Belarus | DE Germany | FI Finland* | HR Croatia | IS Iceland* | LV Latvia | MT Malta | PT Portugal | SI Slovenia | UA Ukraine |
| AZ Azerbaijan | CH Switzerland | DK Denmark* | FR France | HU Hungary | IT Italy | MD Moldova | NL Netherlands | RO Romania | SK Slovakia | |

*Connections between these countries are part of NORDUnet (the Nordic regional network)

**FIGURE 1.**
This map has been downloaded from the GÉANT website. Last update: January 2018
*https://www.geant.org/Resources/Documents/G%C3%89ANT_Topology_Map_January_2018.pdf*

# COMPUTING, DATA AND CLOUD INFRASTRUCTURES

## CURRENT STATUS

The most well-established pan-European computing infrastructures are EGI[4] in the area of high-throughput computing and cloud infrastructures, and the **ESFRI Landmark PRACE** (Partnership for Advanced Computing in Europe) in the area of High-Performance Computing (HPC) infrastructure. EUDAT[5] and OpenAIRE are the initiatives that focus on data Infrastructures. Helix Nebula, GÉANT and EGI offer cloud services.

These e-Infrastructures represent the core of the European e-Infrastructures however this landscape may change in the coming years under the influence of the EOSC and EDI initiatives of the EC. The EOSC Declaration[6] states that the EOSC infrastructure will be developed as a data infrastructure *Commons* serving the needs of scientists. It should provide both common functions and localised services delegated to community level. Indeed, the EOSC will federate existing resources across national data centres, European e-Infrastructures and Research Infrastructures; service provision will be based on local- to-central subsidiarity – e.g. national and disciplinary nodes connected to nodes of pan-European level; it will top-up mature capacity through the acquisition of resources at pan-European level by EOSC operators, to serve a wider number of researchers in Europe. Users should contribute to define the main common functionalities needed by their own community. A continuous dialogue to build trust and agreements among funders, users and service providers is necessary for sustainability. The EC has included a number of calls for proposals to build the EOSC in its Research Infrastructures and e-Infrastructures Work Programmes 2016-2017 and 2018-2020. It is anticipated that in the framework of these calls current e-Infrastructures, as mentioned here, will cooperate ever more closely, such as EGI and EUDAT in the EOSCHub project.

4.
EGI
https://www.egi.eu/

5.
EUROPEAN DATA INITIATIVE
https://www.eudat.eu/european-data-initiative

6.
EOSC Declaration
https://ec.europa.eu/research/openscience/pdf/eosc_declaration.pdf

The supercomputing landscape will be enhanced in the coming years through the EuroHPC initiative. EuroHPC is part of EDI and aims at providing exascale computing in Europe. On 23rd March 2017, seven European countries signed an agreement to start a European HPC programme that will eventually lead to European exascale supercomputers called EuroHPC. Meanwhile, eight more MS have joined the declaration. Those Member States agreed to work together and with the European Commission in the context of a multi-government agreement called EuroHPC for acquiring and deploying by 2022/2023 a pan-European integrated pre-exascale supercomputing and a data infrastructure that will support data-intensive advanced applications and services. It is a response to the surging demand from scientists, industry and the public sector for access to leading-edge computing capacity to cope with vast amounts of data produced in almost all scientific and engineering domains. The EuroHPC joint undertaking will provide EU level coordination and adequate financial resources to support the development and procurement of such infrastructure. This infrastructure will be accessible to public and private users for research purposes; paying services to industry may also be provided (under conditions TBD). The EuroHPC has proposed, by the end of 2017, a legal instrument that provides a procurement framework for the exascale supercomputing and data infrastructure.

EGI is an international collaboration that federates the digital capabilities, resources and expertise of national and international research communities in Europe and worldwide. EGI's main goal is to empower researchers from all disciplines to collaborate and to carry out data- and compute-intensive science and innovation. EGI is coordinated by the EGI Foundation and has participants from national representatives (NGIs), EIROforums and ERICs. EGI provides open solutions offered through a service catalogue that has been evolving for many years. The EGI Federated Cloud Solution offers a standards-based and open infrastructure to deploy on-demand IT services that can manage and process datasets of public or commercial relevance, and can be flexibly expanded by integrating new providers. This is complemented by the EGI High Throughput Computing Solution which provides a global high-throughput data analysis infrastructure, linking a large number of independent organisations and delivering computing resources and high scalability. The EGI Federated Operations Solution provides processes and tools to federate and manage distributed ICT capabilities. The EGI Community-Driven Innovation & Support Solution provides the processes, framework and experts so that research communities can co-create the new capabilities or adapt their existing applications or platforms for compute- or data- intensive science on EGI. Access to EGIs externally provided resources is provided through three different access modes: using free grant-based allocations, pay per use, and annual membership fees. The first two modes are applicable to the high throughput computing and cloud solutions and the policies depend on the service providers of choice and can vary nationally and regionally.

The **ESFRI Landmark PRACE** offers access to world-class high-performance capability computing facilities and services. PRACE is managed by the PRACE AISBL and is governed by governmental representative organisations. PRACE systems are available to scientists and researchers from academia and industry from around the world through the process of submitting computing project proposals based on scientific peer-review and open R&D. The PRACE 2 epoch that has been launched in the beginning of 2017 welcomes a new host hence making more computing cycles available to the research community and guarantees PRACE sustainability until 2020. PRACE is only briefly presented here, further details can be found in the dedicated card in the ESFRI Landmarks section of **Part3**.

In some countries, the national representatives are the same for EGI and PRACE. Both EGI and PRACE have already established contacts with consortia that operate or prepare European large-scale Research Infrastructures to understand needs and find out how these matches with available resources and existing policies.

The amount of digital information is growing rapidly. Large-scale Research Infrastructures, such as the initiatives on the ESFRI roadmap, produce and are dependent on a rapidly increasing amount of data. The importance of data management has emerged as a key element in many large-scale Research Infrastructures projects. It is recognised that specific efforts are needed for making data discoverable and reusable, but data sharing preparedness even within disciplines still differs a lot. The data infrastructures developed by disciplinary Research Infrastructures are often, for natural reasons, customised for the concerned project or research discipline domain and not primarily aimed at use beyond the project or discipline borders. In fact, several of the existing European large-scale Research Infrastructures could be classified as disciplinary e-Infrastructures focussing on disciplinary interoperability and access to data. Several ESFRI cluster projects have been studying similarities between the data needs of sets of ESFRI Research Infrastructures, considering common data standards and formats, data storage facilities, integrated access and discovery, data curation, privacy and security, service discovery and service market places.

For research and society to take full benefit of the major investments in Research Infrastructures and research, the data needs to be made openly and easily available for researchers, over wide spans of fields, in sustainable settings. Also, the data needs to be managed, stored and preserved in a cost-efficient way and the access to the data across borders and domain boundaries must be secured. To fully exploit the underlying potential value in the rapidly increasing amount of research data, interoperability between data infrastructures at all levels is becoming crucial. Efforts have been made to attain a common understanding on the realisation of an ecosystem of data infrastructures and related services, including producing a set of joint recommendations by ESFRI and e-IRG[7]. Many disciplines work at the European and international level to define the discipline-specific aspects of their data infrastructure, which then should be interfaced with the more generic data infrastructure components to provide cross-field interoperability.

Much effort is today going into the definition and development of common or interoperable data formats and metadata, which is necessary to fulfil the general requirement to provide data following the FAIR – Findable, Accessible, Interoperable and Reusable – principles. This requires significant engagement and work from scientific communities at disciplinary level as a starting point to define standards and provide reusable data, as well as data management services to enable data interoperability and sharing, aiming at the realisation of an ecosystem with the appropriate technical and social channels for openly sharing of data at a multidisciplinary and global level. Here, an active role is played by the Research Data Alliance (RDA)[8] initiative, a bottom-up organisation with constituents in different regions – such as RDA Europe – and countries. The goal of RDA is to accelerate international data-driven innovation and discovery by facilitating research data sharing and exchange, and the work is performed in Working and Interest Groups which tackle diverse sociological and technological aspects of research data sharing. At the European level, data infrastructures are not yet as well-established as the basic networking and computing infrastructures. However, significant steps have been made in the areas of basic data services (such as storage and replication) through the EUDAT projects and access to publications and other research results through the OpenAIRE projects.

EUDAT is the largest pan-European data infrastructure initiative and has now taken the necessary steps to move towards a sustainable data infrastructure. Covering both access and deposit, from informal data sharing to long- term archiving, and addressing identification, discoverability and computability of both long-tail and big data, EUDAT services aim to address the full lifecycle of research data. The current suite of EUDAT services include a secure and trusted data exchange service, a data management and replication service, a service to ship large amounts of research data between EUDAT data nodes and workspace areas of high-performance computing systems and a metadata catalogue of research data collections stored in EUDAT data centres and other repositories allowing to find collections of scientific data quickly and easily.

OpenAIRE enables researchers to deposit research publications and data into Open Access repositories and provides support to researchers at the national, institutional and local level to guide them on how to publish in Open Access (OA) and how to manage the long tail of science data within the institution environment. If researchers have no access to an institutional or a subject repository, Zenodo[9], hosted by CERN, enables them to deposit their articles, research data and software. Zenodo exposes its contents to OpenAIRE and offers a range of access policies helping researchers to comply with the Open Access demands from the EC and the ERC. Zenodo has also been extended with important features that improve data sharing, such as the creation of persistent identifiers for articles, research data and software.

The Helix Nebula initiative is providing a public-private partnership by which innovative cloud service companies can work with major IT companies and public research organisations. The Helix Nebula Marketplace (HNX) is the first multi-vendor product coming out of the initiative and delivers easy and large-scale access to a range of commercial Cloud Services through the innovative open source broker technology. A series of cloud service procurement actions, including joint pre-commercial procurement co-funded by the EC, are using the hybrid public-private cloud model to federate e-Infrastructures with commercial cloud services into a common platform delivering services on a pay per use basis.

7. Summary of Policy Recommendations Drawn from the e-IRG Blue Paper on Data, e-IRG Blue Paper, 2013 http://e-irg.eu/documents/10920/238805/BP-summary-policy-130227.pdf

8. Research Data Alliance https://www.rd-alliance.org/

9. Zenodo https://zenodo.org/record/7636#.W0yQf9UzaUk

## GAPS, CHALLENGES AND FUTURE NEEDS

The e-IRG has identified the need for a more coherent e-Infrastructure landscape in Europe, in particular in its 2013 White Paper[10]. By now, this notion of a European e-Infrastructure *Commons* framework has been widely accepted and several steps have been taken towards its implementation, including the realisation of EOSC. The e-Infrastructure *Commons* framework has acted as the solid basis for designing the EOSC and its implementation program, already containing most of the ingredients needed for an integrated European platform for Open Science.

The e-Infrastructure *Commons* is the framework for an easy and cost-effective shared use of distributed electronic resources for research and innovation across Europe and beyond. An essential feature of the *Commons* is the provisioning of a clearly defined, comprehensive, interoperable and sustained set of services, provisioned by several e-Infrastructure providers, both public and commercial, to fulfil specific needs of the users. This set should be constantly evolving to adapt to changing user needs, complete in the sense that the needs of all relevant user communities are served and minimal in the sense that all services are explicitly motivated by user needs and that any overlap of services are thoroughly motivated. The *Commons* has three distinct elements:

- a platform for coordination of the services building the *Commons*, with a central role for European research, innovation and Research Infrastructures communities;
- provisioning of sustainable and interoperable e-Infrastructure services within the *Commons*, promoting a flexible and open approach where user communities are empowered to select the services that fulfil their requirements;
- implementation of innovation projects providing the constant evolution of e-Infrastructures needed to meet the rapidly evolving needs of user communities.

In summary, the ultimate vision of the *Commons* is to reach integration and interoperability in the area of e-Infrastructure services, within and between Member States, and at the European level and globally. It is the mission of e-IRG to support this vision through supporting a coherent, innovative and strategic European e-Infrastructure policy making and the development of convergent and sustainable e-Infrastructure services. This e-Infrastructure *Commons* is also a solid basis for building the EOSC already containing most of the ingredients needed for an integrated European platform for Open Science.

In its Roadmap 2016 document[11], the e-IRG provides the following key recommendations to attain this *Commons* or EOSC:

1) Research infrastructures and research communities should reinforce their efforts to:

- elaborate on and drive their e-Infrastructure needs;
- participate in the innovation of e-Infrastructure services;
- contribute to standards and take care of their data.

2) e-Infrastructure providers should further increase their efforts to work closely together to fulfil the often complex user needs in a seamless way.

3) National governments and funding agencies should reinforce their efforts to:

- embrace e-Infrastructure coordination at the national level and build strong national e-Infrastructure building blocks, enabling coherent and efficient participation in European efforts;
- together analyse and evaluate their national e-Infrastructure funding and governance mechanisms, identify best practices, and provide input to the development of the European e-Infrastructure landscape.

4) The European Commission should provide strong incentives for cross-platform innovations and further support the coordination and consolidation of e-Infrastructure service development and provisioning at the national and the European level.

10. e-IRG White Paper
*http://e-irg.eu/documents/10920/11274/e-irg-white-paper-2013-final.pdf*

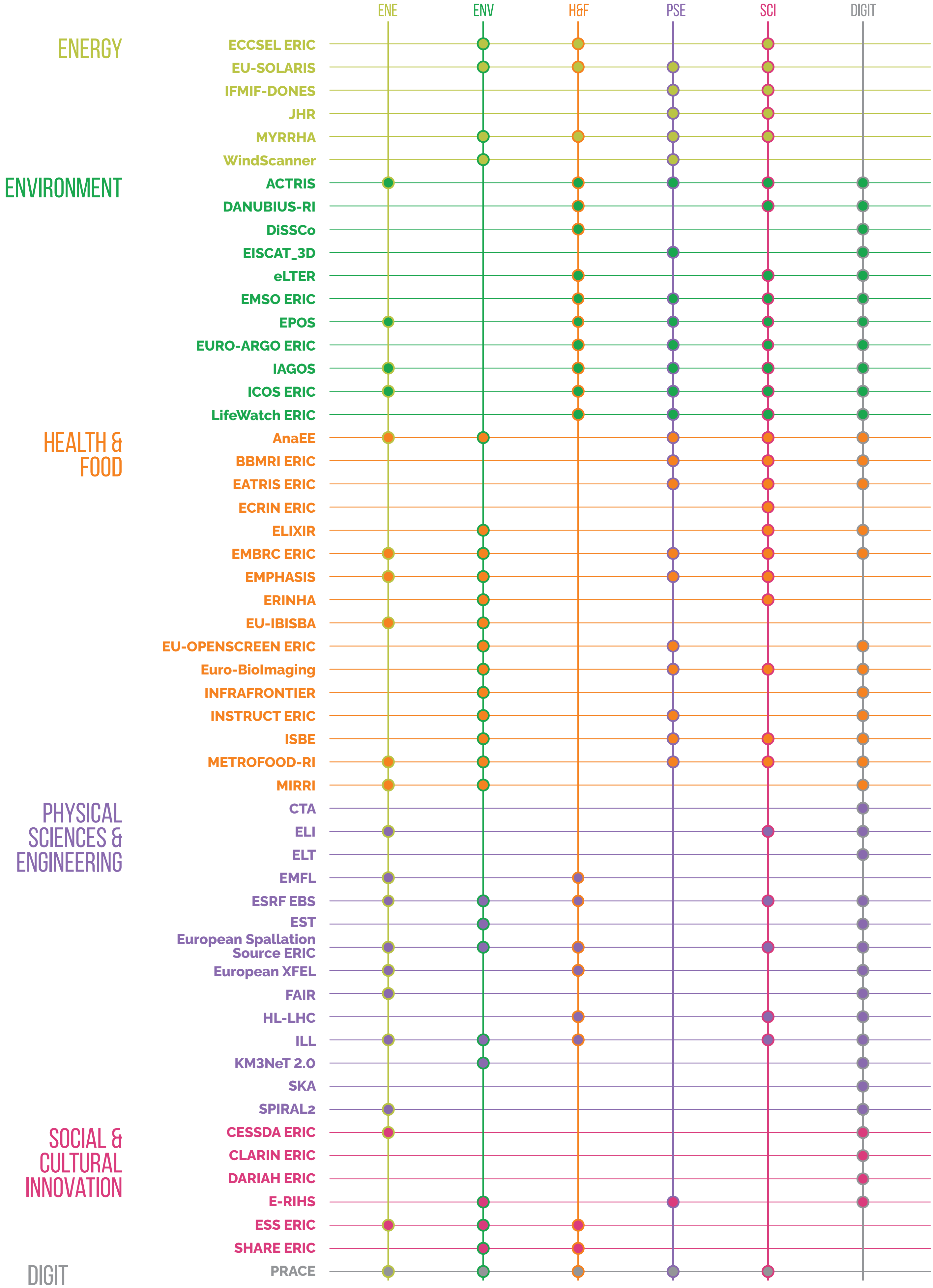
11. e-IRG Roadmap 2016 document
*http://e-irg.eu/documents/10920/12353/Roadmap+2016.pdf*

# PART2

## LANDSCAPE ANALYSIS

# SECTION2

# CONTENTS


ENE
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IFMIF-DONES
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MYRRHA
WindScanner
ENVIRONMENT
ACTRIS
DANUBIUS-RI
DiSSCo
EISCAT_3D
eLTER
EMSO ERIC
EPOS
EURO-ARGO ERIC
IAGOS
ICOS ERIC
LifeWatch ERIC
HEALTH & FOOD
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European XFEL
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DARIAH ERIC
E-RIHS
ESS ERIC
SHARE ERIC
DIGIT
PRACE

# ENERGY

| | | |
|---|---|---|
| **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) research 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 wellbeing |
| **EU-SOLARIS** European Solar Research Infrastructure for Concentrated Solar Power | ENV | **Concentrating Solar Thermal (CST) technologies for energy supply and consumption** 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 wellbeing |
| **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 |
| | PSE | **New technologies and approaches for nuclear fusion research** 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 | 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 |
| **MYRRHA** Multi-purpose hYbrid Research Reactor for High-tech Applications | ENV | **Nuclear fission research in environmental sciences** Safe disposal of radioactive waste; safe operation of nuclear installations; natural radioactivity; transmutation of long-lived nuclear waste |
| | H&F | **Nuclear fission research in health and food** Medical radiation dose optimisation; radiological measurements and analyses; studies of the impact of radiation on humans and the environment; production of advanced radioisotopes for therapeutic and diagnostic applications |
| | PSE | **New technologies and approaches for nuclear fission research** (Subcritical) fast neutron source, accelerator technology; irradiation of structural materials for nuclear fission energy |
| | PSE | **New technologies and approaches for nuclear fission research** Research on matter with radioactive ion beams |
| | PSE | **New technologies and approaches for nuclear fusion research** Irradiation of structural materials for nuclear fusion technology |
| | SCI | **Social and cultural aspects of nuclear fission research** Energy Security and social acceptance of nuclear fission; transmutation of long-lived nuclear waste |
| **WindScanner** European WindScanner Facility | ENV | **Wind energy research in environmental sciences** Land use and landscape impact of wind energy |
| | PSE | **New technologies and approaches for wind energy research** Development of technologies for turbulence and aero-dynamical phenomena |

# ENVIRONMENT

| | | |
|---|---|---|
| **ACTRIS**<br>Aerosols, Clouds and Trace gases Research Infrastructure | ENE | **Aerosol, clouds, and trace gases observations for energy supply and consumption**<br>Key atmospheric parameters and environmental assessments related to different energy production forms |
| | ENE | **Aerosol, clouds, and trace gases observations for energy supply**<br>Diagnostics development for wind and solar radiation energy applications |
| | H&F | **Aerosol, clouds, and trace gases observations for health and food**<br>Measurements of air quality parameters and impact on health<br>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**<br>Development of laser optics and detectors<br>New techniques for atmospheric corrections and aerosol physics |
| | SCI | **Social and cultural aspects about aerosol, clouds, and trace gases observations**<br>Key atmospheric parameters, climate change and impact on human wellbeing |
| | DIGIT | **Open data resources and management for aerosol, clouds, and trace gases observations**<br>Data access and curation, standardisation of data ad metadata, data and services interoperability |
| | DIGIT | **ICT tools for atmospheric research**<br>Virtual Research Environments (VRE) for data processing, trend analysis, and satellite cal/val<br>HPC for atmospheric global and regional models, data assimilation and processing of large volume of data |
| **DANUBIUS-RI**<br>International Centre for Advanced Studies on River-Sea Systems | H&F | **Advanced studies on river-sea systems for health and food**<br>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**<br>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 |
| | DIGIT | **Open data resources and management for interdisciplinary research on river-sea systems**<br>Development of DANUBIUS Commons – common set of standards, rules, methodologies supporting interdisciplinary research in freshwater, transitional and coastal marine environments |
| **DiSSCo**<br>Distributed System of Scientific Collections | H&F | **System of scientific collections for health and food**<br>Natural science collections for bio- and geo-diversity information, climate change, food security, health and bioeconomy |
| | DIGIT | **Open data resources and management for scientific collections**<br>Multi-modal access to collections for a linked open data approach |
| **EISCAT_3D**<br>Next generation European Incoherent Scatter radar system | PSE | **New technologies and approaches for monitoring of the atmosphere and ionosphere**<br>Development of new methods of radar coding, signal processing and data analysis |
| | PSE | **New technologies and approaches for monitoring of the atmosphere and ionosphere**<br>Sun-Earth interactions, radio astronomy, space security, plasma physics, magnetic field studies |
| | DIGIT | **Open data resources and management for monitoring of the atmosphere and ionosphere**<br>Collection and archive of basic data; data processing to describe the ionosphere and neutral atmosphere; selection of well-designed radar pulse schemes |

| | | |
|---|---|---|
| **eLTER**<br>Integrated European Long-Term Ecosystem, critical zone and socio-ecological system Research Infrastructure | H&F | **Long-term ecosystem research for health and food**<br>Identification of drivers of ecosystem changes for climate, food security, health and bioeconomy |
| | SCI | **Social and cultural aspects of long-term ecosystem research**<br>Understand the effects of global, regional and local changes on socio-ecological systems and their feedbacks to environment and society |
| | DIGIT | **Open data resources and management for long-term ecosystem research**<br>Access to data across multi repositories |
| **EMSO ERIC**<br>European Multidisciplinary Seafloor and water-column Observatory | H&F | **Seafloor and water column observations for health and food**<br>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**<br>Development of instrument and technologies |
| | SCI | **Social and cultural aspects of seafloor and water column observations**<br>Key hydrosphere observations, climate change and impact on human wellbeing |
| | DIGIT | **Open data resources and management for monitoring of the Seafloor and water column** |
| **EPOS**<br>European Plate Observing System | ENE | **Solid Earth science for energy supply and consumption**<br>Carbon capture and storage verification |
| | ENE | **Solid Earth science for energy supply**<br>Geo-resources; geothermal heating; anthropogenic hazards |
| | H&F | **Health impact of natural gas emissions and volcanic ashes**<br>Environmental impact of tsunamis, landslides, volcanic eruptions, lahar and gas emissions for food security |
| | PSE | **New technologies and approaches for solid Earth science**<br>Development of instrument and new technologies |
| | SCI | **Social and cultural aspects of solid Earth science**<br>Solid Earth observations for environmental changes and hazards and impact on human wellbeing<br>Hazard assessment, risk communication and emergency management<br>Increasing resilience of society to natural and anthropogenic hazards |
| | DIGIT | **High Performance Computing for solid Earth science**<br>Integration of data and services – including data products, models and facilities<br>HTC resources for data, metadata and services integration |
| | DIGIT | **Open data resources and management for solid Earth science**<br>Access to quality controlled data from diverse Earth science disciplines, tools for analysis and modelling<br>Data FAIRness in Solid Earth Science |
| **EURO-ARGO ERIC**<br>European contribution to the international Argo Programme | H&F | **Global array of oceans observing systems for health and food**<br>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**<br>Development of instrument and technologies, e.g. new sensors to be mounted on autonomous platforms |
| | SCI | **Social and cultural aspects of oceans observing systems**<br>Key ocean observations, climate change and impact on human wellbeing |
| | DIGIT | **Open data resources and management for oceans observing systems**<br>Access to quality controlled data and data products for climate and oceanography |
| **IAGOS**<br>In-service Aircraft for a Global Observing System | ENE | **Global observations of atmospheric composition for energy supply and consumption**<br>Key atmospheric parameters and environmental assessments related to different energy production forms |
| | H&F | **Global observations of atmospheric composition for health and food**<br>Measurements of air quality parameters and impact on health |
| | PSE | **New technologies and approaches for atmospheric composition observations**<br>Development of instrument and technologies |
| | SCI | **Social and cultural aspects of atmospheric composition observations**<br>Key atmospheric observations, climate change and impact on human wellbeing |
| | DIGIT | **Open data resources and management for atmospheric composition observations**<br>Near real time data on atmospheric chemical species to weather and research services |

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| **ICOS ERIC**<br>Integrated Carbon Observation System | ENE | **Integrated Carbon Observation System for energy supply and consumption**<br>Large scale monitoring of atmospheric $CO_2$ around CCS |
| | H&F | **Integrated Carbon Observation System in health and food**<br>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**<br>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**<br>Key observations on carbon cycle and greenhouse gas budget and perturbations, climate change and impact on human wellbeing, common studies on behaviour related to climate change |
| | DIGIT | **Open data resources and management for Integrated Carbon Observation System**<br>Highly standardised quality control data archived for the long term, services for GHG model integration, comparison and visualisation |
| **LIfeWatch ERIC**<br>e-Infrastructure for Biodiversity and Ecosystem Research | H&F | **Biodiversity and ecosystems in health and food**<br>Advancement of scientific and technological research on human microbiota, vectors for diseases and parasites and impacts on human health and wellbeing |
| | H&F | **Biodiversity and ecosystems in health and food**<br>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**<br>Development of ICT instruments and technologies for the control of atmospheric and hydrosphere composition |
| | SCI | **Social and cultural aspects of biodiversity and ecosystems**<br>Development of ICT instruments and technologies on socio-ecological systems, past and future ecosystem services and human wellbeing |
| | DIGIT | **High Performance Computing for biodiversity and ecosystems**<br>Integration of biodiversity and ecosystem data and services – including data products, models and facilities |
| | DIGIT | **Open data resources and management for biodiversity and ecosystems**<br>Provide Virtual Research Environments (VRE) to run scientific experiments in cooperative environments |

# HEALTH & FOOD

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| **AnaEE**<br>Infrastructure for Anlaysis and Experimentation on Ecosystems | ENE | **Managed and natural ecosystems for energy supply and consumption**<br>Bioenergy and bio-renewables – trade-offs between food supply, energy supply, biodiversity and ecosystem services |
| | ENV | **Managed and natural ecosystems in environmental sciences**<br>Land use and exploitation by agriculture change, food security and environmental sustainability |
| | ENV | **Managed and natural ecosystems in environmental sciences**<br>Bioenergy and biorenewables – trade-offs between food supply, energy supply, biodiversity and ecosystem services |
| | ENV | **Managed and natural ecosystems in environmental sciences**<br>Health, environment and air/water/food pollution |
| | ENV | **Managed and natural ecosystems in environmental sciences**<br>Climate change, weather extremes, and epidemiology of pathogenic agents, in humans, animals and plants |
| | PSE | **New technologies and approaches for managed and natural ecosystems**<br>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**<br>Land use and exploitation by agriculture change, food and non-food systems |
| | DIGIT | **Open data resources and management for managed and natural ecosystems**<br>Modelling platforms by providing the necessary hardware and software, as well as the access to expertise, datasets and modelling libraries |
| **BBMRI ERIC**<br>Biobanking and BioMolecular Resources Research Infrastructure | PSE | **New technologies and approaches for biobanks and biomolecular resources**<br>Biomedical engineering and precision medicine: imaging, diagnostics and novel therapeutic approaches |
| | SCI | **Social and cultural aspects of biobanks and biomolecular resources**<br>Use of longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing<br>Use of 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**<br>Anthropological studies using resources in biobanks, omics, metabolomics, biomedical engineering and precision medicine: ethical implication |
| | DIGIT | **Open data resources and management for biobanks and biomolecular resources**<br>Metadata and public data information service about biobanks, sample and data collections, and services |
| **EATRIS ERIC**<br>European Advanced Translational Research Infrastructure in Medicine | PSE | **New technologies and approaches for traslational medicine and drug development**<br>High-end technologies to advance new products from target validation to early clinical trials |
| | SCI | **Social and cultural aspects of traslational medicine and drug development**<br>Use of longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing<br>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**<br>Anthropological studies using resources in biomedical engineering, clinical data and precision medicine: ethical implication |
| | DIGIT | **Open data resources and management for translational medicine and drug development**<br>Open access to clinical data |

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| **ECRIN ERIC**<br>European Clinical Research Infrastructure Network | SCI | **Social and cultural aspects of multinational clinical research and trials**<br>Use of longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing<br>Use of longitudinal studies and cohorts in complex disease studies, e.g. obesity and food demand and consumption |
| | SCI | **Social and cultural aspects about of multinational clinical research and trials**<br>Trial management: ethical and cross border legal implication |
| **ELIXIR**<br>A distributed infrastructure for life-science information | ENV | **Integrated bioinformatics resources and services in environmental sciences**<br>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**<br>DNA and RNA in medical and translational research, and rare diseases: ethical implication |
| | SCI | **Social and cultural aspects of integrated bioinformatics resources and services**<br>Use of longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing<br>Use of longitudinal studies and cohorts in complex disease studies, e.g. obesity and food demand and consumption |
| | DIGIT | **High Performance Computing for integrated bioinformatics resources and services**<br>Data Resources for the life sciences and the long-term preservation of biological data; repositories for publishing open data in the life sciences |
| **EMBRC ERIC**<br>European Marine Biological Resource Centre | ENE | **Marine biological resources for energy supply and consumption**<br>Bioenergy and bio-renewables – bioenergy microbes, plants, crops, aquaculture |
| | ENE | **Marine biological resources for energy supply and consumption**<br>Bioenergy and bio-renewables – trade-offs between food supply, energy supply, biodiversity and ecosystem services |
| | ENV | **Marine biological resources in environmental sciences**<br>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**<br>Health, environment and air/water/food pollution on human health |
| | PSE | **New technologies and approaches for marine biological resources**<br>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**<br>Anthropological studies using resources in biobanks and omics |
| | SCI | **Social and cultural aspects of marine biological resources**<br>Marine and maritime education |
| | DIGIT | **Open data resources and management for marine biological resources**<br>Interoperability and standardisation of data generated by marine research and bioinformatics; processing, curation and storage of large datasets of sequences, metadata, historical time series and literature resources |
| **EMPHASIS**<br>European Infrastructure for Multi-scale Plant Phenomics and Simulation | ENE | **Multi-scale plant phenotyping and simulation for energy supply and consumption**<br>Agriculture and land-use change, food and non-food systems |
| | ENE | **Multi-scale plant phenotyping and simulation for energy supply and consumption**<br>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**<br>Bioenergy and bio-renewables – bioenergy microbes, plants, crops, biofuels |
| | ENV | **Multi-scale plant phenotyping and simulation in environmental science**<br>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**<br>Land use and exploitation by agriculture change, food and non-food systems |
| | ENV | **Multi-scale plant phenotyping and simulation in environmental science**<br>Bioenergy and biorenewables – bioenergy microbes, plants, crops, biofuels, and the environment |
| | ENV | **Multi-scale plant phenotyping and simulation in environmental science**<br>Bioenergy and biorenewables – trade-offs between food supply, energy supply, biodiversity and ecosystem services |

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| | ENV | **Multi-scale plant phenotyping and simulation in environmental science**<br>Health, environment and air/water/food pollution on human health |
| | ENV | **Multi-scale plant phenotyping and simulation in environmental science**<br>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**<br>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**<br>Land use and exploitation by agriculture change |
| **ERINHA**<br>European Research Infrastructure on Highly Pathogenic Agents | ENV | **Surveillance of highly pathogenic micro-organisms in environmental sciences**<br>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**<br>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**<br>Outbreak preparedness, surveillance and response |
| **EU-IBISBA**<br>European Industrial Biotechnology Innovation and Synthetic Biology Accelerator | ENE | **Industrial Biotechnology Innovation for energy supply and consumption**<br>Bioenergy and bio-renewables – bioenergy microbes, plants, crops, biofuels |
| | ENV | **Industrial Biotechnology Innovation in environmental sciences**<br>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**<br>European Infrastructure of Open Screening Platforms for Chemical Biology | ENV | **High-capacity screening platforms for chemical compounds in environmental sciences**<br>Development of new and safer products – e.g. drugs to treat diseases, herbicides to protect crops, food additives for livestock |
| | PSE | **New technologies and approaches for high-capacity screening platforms for chemical compounds**<br>High-end technologies to advance new products from target validation to early clinical trials<br>Imaging, diagnostics and novel therapeutic approaches |
| | DIGIT | **Open data resources and management high-capacity screening platforms for chemical compounds**<br>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, controlled datasets with great coverage of chemical space to external scientists |
| **Euro-BioImaging**<br>European Research Infrastructure for Imaging Technologies in Biological and Biomedical Sciences | ENV | **Biological and biomedical imaging in environmental sciences**<br>Studies on the bacterial response to environmental stimuli |
| | PSE | **New technologies and approaches for biological and biomedical imaging**<br>Access to range of state-of-the-art technologies in biological and biomedical imaging for life scientists; image data analysis support and training |
| | SCI | **Social and cultural aspects for biological and biomedical imaging**<br>Use of longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing |
| | SCI | **Social and cultural aspects for biological and biomedical imaging**<br>Biomedical engineering and precision medicine: ethical implication |
| | DIGIT | **Open data resources and management for biological and biomedical imaging**<br>Public data repository to store, integrate and serve image datasets from published scientific studies |
| **INFRAFRONTIER**<br>European Research Infrastructure for the generation, pheno-typing, archiving and distribution of mouse disease models | ENV | **Mouse functional genomics in environmental sciences**<br>Study of the genetic, environment and pharmacological components of human disease |
| | DIGIT | **Open data resources and management for mouse functional genomics**<br>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 |

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| **INSTRUCT ERIC**<br>Integrated Structural Biology Infrastructure | ENV | **Integrated structural biology in environmental sciences**<br>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**<br>Analytical facilities at molecular scale – i.e protein production, cryo-electron microscopy, NMR, nanobody drug discovery, protein crystallisation, X-ray approaches |
| | DIGIT | **Open data resources and management for integral structural biology**<br>Data analysis: bioinformatics, computational software, image processing |
| **ISBE**<br>Infrastructure for System Biology Europe | ENV | **System biology in environmental sciences**<br>Approached at the multiscale level to provide solutions to protect our environment; advances in bio-based products research, bioremediation, biofuels, and ecosystem health |
| | PSE | **New technologies and approaches for system biology**<br>Analytical facilities at molecular scale – i.e protein production, cryo-electron microscopy, NMR, nanobody drug discovery, protein crystallisation, X-ray approaches |
| | SCI | **Social and cultural aspects for system biology**<br>Use of longitudinal studies and cohorts in the healthy population, e.g. life course studies, ageing<br>Use of longitudinal studies and cohorts in complex disease studies, e.g. obesity and food demand and consumption |
| | DIGIT | **Open data resources and management for system biology**<br>Computational approaches and software development for data and model management, model and data analysis, and model simulation |
| **METROFOOD-RI**<br>Infrastructure for promoting metrology in food and nutrition | ENE | **Metrology in food and nutrition for energy supply and consumption**<br>Agriculture and land-use change, food and non-food systems |
| | ENE | **Metrology in food and nutrition for energy supply and consumption**<br>Bioenergy and bio-renewables – trade-offs between food supply, energy supply, biodiversity and ecosystem services |
| | ENV | **Metrology in food and nutrition in environmental sciences**<br>Agriculture and land-use change, food and non-food systems |
| | ENV | **Metrology in food and nutrition in environmental sciences**<br>Health, environment and air/water/food pollution |
| | PSE | **New technologies and approaches for metrology in food and nutrition**<br>New devices and technologies to exploit alternative sources of food; advanced digital solutions for food production and waste management |
| | SCI | **Social and cultural aspects for metrology in food and nutrition**<br>Better use of longitudinal studies and cohorts in complex disease studies, e.g obesity and food demand and consumption |
| | SCI | **Social and cultural aspects for metrology in food and nutrition**<br>Agriculture and land-use change, food and non-food systems |
| | DIGIT | **Open data resources and management for food metrology**<br>Collection, dissemination and sharing of information about principles, terminology, tools<br>Harmonization and integration of food composition databases<br>Development of new standardized tools for food quality, safety & authenticity. |
| **MIRRI**<br>Microbial Resource Research Infrastructure | ENE | **Microbial resources for energy supply and consumption**<br>Bioenergy and bio-renewables – bioenergy microbes, plants, crops, biofuels |
| | ENV | **Microbial resources for environmental sciences**<br>Bioenergy and bio-renewables – bioenergy microbes, plants, crops, biofuels environmental microbiology, food microbiology and safety, in biotechnology |
| | DIGIT | **Open data resources and management for microbial research**<br>Interoperability of data: facilitated data mining and availability of trusted data |

# PHYSICAL SCIENCES & ENGINEERING

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| **CTA**<br>Cherenkov Telescope Array | DIGIT | **Open data resources and management for ground-based observatory for gamma-ray astronomy**<br>Metadata and gamma-ray data openly available, after proprietary period.<br>On-line data analysis tools for *multi-messenger* approach |
| **ELI**<br>Extreme Light Infrastructure | ENE | **High intensity and short time light pulses impact on the research of fusion technologies**<br>Development of alternatives of fusion technologies by inertial confinement, characterization of the plasma |
| | SCI | **Intense and coherent light sources with different time structure for social and cultural sciences**<br>Spectroscopy, imaging: analysis of samples of the cultural and natural heritage |
| | DIGIT | **Open data resources and management for investigation of light-matter interactions**<br>Metadata and data on extremely powerful laser sources, atto-second pulses, nuclear spectroscopy and particle acceleration by the intense optical field |
| **ELT**<br>Extremely Large Telescope | DIGIT | **Open data resources and management for ground-based astronomy**<br>Metadata and astronomy data openly available, after proprietary period.<br>On-line data analysis tools for *multi-messenger* approach |
| **EMFL**<br>European Magnetic Field Laboratory | ENE | **High magnetic field facilities in energy materials**<br>Development and optimization of energy materials and components; experiments on materials behaviour in extreme magnetic fields |
| | H&F | **High magnetic field facilities in new and high precision imaging techniques for health and food**<br>Development and optimization of new technologies for magnetic resonance under extreme magnetic fields for medical imaging and diagnostic.<br>NMR high field-high frequency for protein crystallography and structural biology |
| **ESRF EBS**<br>European Synchrotron Radiation Facility Extremely Brilliant Source | ENE | **Synchrotron radiation facility in energy materials**<br>Development and optimization of energy materials and components: analysis of materials in extreme conditions and *in operando* conditions |
| | ENV | **Synchrotron radiation facility in spectroscopy and analysis of contaminant components**<br>Reflectometry on the interactions on contaminants in the atmosphere and liquid systems. Analytical tools |
| | H&F | **Synchrotron radiation facility in heath and food**<br>Protein crystallography and spectroscopy; high resolution structural biology, X-ray imaging, mammography |
| | SCI | **Synchrotron radiation facility in social and cultural sciences**<br>Materials structure, spectroscopy, imaging: analysis of samples of the cultural and natural heritage |
| | DIGIT | **Open data resources and management for synchrotron radiation facility**<br>Large sets of metadata and data on physics, chemistry, material science, life sciences, heritage science, palaeontology, nanotechnology, engineering; data analysis tools |
| **EST**<br>European Solar Telescope | ENE | **Large-aperture solar telescope observations in environmental sciences**<br>Sun observations for the understanding of auroras and other reflections of magnetic phenomena on Earth |
| | DIGIT | **Open data resources and management for large-aperture solar telescope observations**<br>Metadata and astronomy data openly available, after proprietary period |
| **European Spallation Source ERIC**<br>European Spallation Source | ENE | **Spallation neutron source for energy materials**<br>Development and optimization of energy materials and components: analysis of materials in extreme conditions and *in operando* conditions |
| | ENV | **High flux neutron beams facility in spectroscopy and analysis of contaminant components**<br>Reflectometry on the interactions on contaminants in the atmosphere and liquid systems. Analytical tools |

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| | H&F | **Spallation neutron source in heath and food**<br>Protein crystallography and spectroscopy: high resolution structural biology, microscopy, spectroscopy |
| | SCI | **Spallation neutron source in social and cultural sciences**<br>Materials structure, spectroscopy, imaging: analysis of samples of the cultural and natural heritage |
| | DIGIT | **Open data resources and management for neutron science and technology**<br>Large sets of metadata of physics, chemistry, material science, life sciences, heritage science, palaeontology, nanotechnology, engineering; data analysis tools |
| **European XFEL**<br>European X-Ray Free-Electron Laser Facility | ENE | **X-ray Free Electron Laser facility in energy processes and materials**<br>Development and Optimization of Energy Materials and Components: analysis of materials in extreme conditions and *in operando* conditions, time resolved methods |
| | H&F | **X-ray Free Electron Laser facility in heath and food**<br>Protein crystallography and spectroscopy: single-protein X-ray diffraction, time resolved spectroscopy |
| | DIGIT | **Open data resources and management for X-ray Free Electron Laser radiation facility**<br>Large sets of metadata and data on physics, chemistry, material science, life sciences, heritage science, palaeontology, nanotechnology, engineering; data analysis tools |
| **FAIR**<br>Facility for Antiproton and Ion Research | ENE | **Nuclear physics in energy materials**<br>Development and Optimization of Energy Materials and Components |
| | DIGIT | **Big data management and high through computing analysis for exotic nuclear reactions**<br>Large sets of metadata and data on nuclear physics, instable isotopes, nuclear spectroscopy and particle acceleration; data analysis tools |
| **HL-LHC**<br>High-Luminosity Large Hadron Collider | H&F | **Large hadron collider in health and food**<br>Developing accelerators and radio-isotope for medical treatments |
| | SCI | **Large hadron collider in social and cultural sciences**<br>Global collaboration: example of world laboratory |
| | DIGIT | **Big data management and high through computing analysis for large hadron collider**<br>GRID and cloud management of data analysis and storage |
| **ILL**<br>Institut Max von Laue-Paul Langevin | ENE | **Neutron science and technology in energy materials**<br>Development and optimization of energy materials and components: analysis of materials in extreme conditions and *in operando* conditions |
| | ENV | **High flux neutron beams facility in spectroscopy and analysis of contaminant components**<br>Reflectometry on the interactions on contaminants in the atmosphere and liquid systems. Analytical tools |
| | H&F | **Neutron science and technology in health and food**<br>Protein crystallography and spectroscopy: high resolution structural biology, microscopy, spectroscopy |
| | SCI | **Neutron science and technology in social and cultural sciences**<br>Materials structure, spectroscopy, imaging: analysis of samples of the cultural and natural heritag |
| | DIGIT | **Open data resources and management for neutron science and technology**<br>Large sets of metadata of physics, chemistry, material science, life sciences, heritage science, palaeontology, nanotechnology, engineering; data analysis tools |
| **KM3NeT 2.0**<br>KM3 Neutrino Telescope 2.0 | ENV | **Neutrino telescope in environmental sciences**<br>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 |
| | DIGIT | **Open data resources and management for under water observatory for neutrino and high energy particle detection**<br>Metadata and neutrino detection data openly available, after proprietary period. On-line data analysis tools for *multi-messenger* approach |
| **SKA**<br>Square Kilometre Array | DIGIT | **Big data management and high through computing analysis for radio-astronomy telescope**<br>Vey large data sets, curation, storage and access. On-line data analysis tools for *multi-messenger* approach |
| **SPIRAL2**<br>Système de Production d'Ions Radioactifs en Ligne de 2e génération | ENE | **Nuclear physics in energy materials**<br>Development and Optimization of Energy Materials and Components |
| | DIGIT | **Big data management and high through computing analysis for exotic nuclear reactions**<br>Large sets of metadata and data on nuclear physics, instable isotopes, nuclear spectroscopy and particle acceleration; data analysis tools |

# SOCIAL & CULTURAL INNOVATION

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| **CESSDA ERIC** Consortium of European Social Science Data Archives | ENE | **European social science data archives in energy** Data sets providing detailed evidence about behaviour with respect to energy issues and policies |
| | DIGIT | **Open data resources and management for data archives and digital preservation** Data catalogue for software tools and services to provide trustworthy, sustainable, and efficient preservation of data; metadata harvesting from Service Providers and other sources |
| **CLARIN ERIC** Common Language Resources and Technology Infrastructure | DIGIT | **Open data resources and management for common language resources** User-friendly overview of the available resources from digital humanities, social sciences and human language technologies – e.g. corpora, lexica, audio and video recordings, annotations, grammars, etc. Archives for language resources and depositing services |
| **DARIAH ERIC** Digital Research Infrastructure for the Arts and Humanities | DIGIT | **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 |
| **E-RIHS** European Research Infrastructure for Heritage Science | 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 |
| | DIGIT | **Open data resources and management 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 |
| **ESS ERIC** European Social Survey | ENE | **Cross national survey data in energy issues and policies** Data sets providing detailed evidence about behaviour with respect to energy issues and policies |
| | ENV | **Environmental sciences for social and cultural innovation** Climate change impact on human wellbeing, common studies on behaviour related to climate change<br>Citizens' perception of environment and air/water/food pollution |
| | H&F | **Cross national survey data in 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 |
| **SHARE ERIC** Survey of Health, Ageing and Retirement in Europe | ENV | **Environmental sciences for social and cultural innovation** Climate change, pollution and extreme events impact on human life |
| | H&F | **Connecting surveys to 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 |

# DATA, COMPUTING AND DIGITAL RESEARCH INFRASTRUCTURES

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| **PRACE** Partnership for Advanced Computing in Europe | ENE | **High Performance Computing for energy**<br>Modelling of Energy Systems (high-resolution, real time)<br>Modelling of Energy Materials and Components<br>Modelling of the interaction between Energy and Environment |
| | ENV | **High Performance Computing for environmental sciences**<br>Modelling of complex dynamical systems (oceans, atmosphere, climate, weather forecast)<br>Modelling of earth and ocean dynamics |
| | H&F | **High Performance Computing for health and food**<br>Modelling and simulation of biological processes |
| | PSE | **High Performance Computing for physical sciences and engineering**<br>Modelling and simulation of condensed matter behaviour<br>Modelling and simulation of out of equilibrium phenomena<br>Computing theoretical models in HEP, hydrodynamics etc. |
| | SCI | **Social and cultural aspects of advanced computing**<br>High-impact scientific discovery and engineering research and development across all disciplines to enhance European competitiveness for the benefit of society |

# PART2
## LANDSCAPE ANALYSIS
# SECTION3

# CONTENTS

# EDUCATION AND TRAINING

RIs are key elements in the higher education and training for European researchers in all domains as well as for technology developers and innovators. RIs from all scientific domains invest important resources in Education & Training integrating the academic disciplinary culture with multi-disciplinary research methodologies, advanced data technologies and skills to perform research on complex problems.

## EDUCATION

In the framework of the study on Long-Term Sustainability of RIs it has been pointed out the need to optimize the role of RIs in higher education by establishing structured collaborations – e.g. credits – and mobility exchange programmes between universities and RIs.

RIs can provide education services and advanced education at master or doctoral level that are complements to the advanced academic education. In the **PSE** domain, one example is the Hercules European School[1] that concentrates on synchrotron and neutron radiation methods of research in a broad range of disciplines, from the life sciences including health, materials science, nanoscience, physical chemistry, archeometry and palaeontology to physics. Hercules is in fact a well established complement of PhD and post-doctoral level education for young researchers in these sciences.

In the **DIGIT** domain, digital infrastructures are expected to boost research, growth, innovation and job creation, and it is clear that education of digital scientists and practitioners is a priority for Europe as this can effectively give people the knowledge, skills and competences to critically use and benefit from scientific data, to contribute creating the European identity, building on common values and cultures. Education on newly emerging technologies for data collection, compression, preservation, and analysis can be realized in collaboration with Digital Infrastructures. The e-learning programs complement and enhance traditional learning, support existing teaching methods and provide a valuable reference point, which can be accessed anytime, anywhere. These programs cover computer science, data and statistics, engineering, life sciences, social sciences and humanities and more, providing proper platforms and, which is extremely important, sharing the knowledge and data stored by all RIs connected via networks.

In the **SCI** domain, the **ESFRI Landmarks CLARIN ERIC** and **DARIAH ERIC** are Digital Humanities RIs that jointly maintain a registry of about 150 courses on Humanities and Computer Science. A more formal integration of educational initiatives between RIs and universities could shape attractive options for advanced-level student to identify possible research and career paths.

## TRAINING

Training initiatives are practiced at all operational levels of RIs, from management to maintenance, from in-house research to technology upgrade, as well as specific training of the users. RIs managerial skills need to address the complexity of international undertakings characterized by challenging technical and organizational structures and to create advanced services for both the very demanding scientific community and trust by the institutional stakeholders and supporting governments – e.g. RITrain Research Infrastructure Training Programme *Executive Masters in Management of Research Infrastructures* hosted by the University of Milano-Bicocca[2]. Training of users cover laboratory safety and research good practices as well as technical skills to operate the RI facilities or the scientific data services.

RIs may represent prototypes for new solutions adapted to changing boundary conditions that have general technological and societal perception implications: specific training needs concern also the optimization of the mix of energy sources that may contribute to sustainability – economic, environmental and social. The integration in the electricity grid of renewables and novel nuclear plants – IV-G or fusion – with currently operational sources requires a high level of knowledge of all technologies and their complementarity. Examples in the **ENE** domain are: the **ESFRI Landmark ECCSEL ERIC** which runs a programme for the development of a capacity building and provides training to the prospective users by webinars and conferences; the **ESFRI Landmark JHR** which relies on a dedicated simulator to train future operators.

In the **ENV** domain, education and training activities focus on the cross-fertilisation and knowledge transfer of new technologies, best practices, approaches and policies of the involved RIs via specific training courses and staff exchange programs for RIs personnel. In addition, an e-training platform developed by the **ESFRI Landmark LifeWatch** ERIC supports the training activities, giving sustainability and re-use to the course materials and offers specific e-training tools for RIs users.

In the **H&F** domain examples are: the **ESFRI Landmark ECRIN ERIC** with a course on *Clinical evaluation of medical devices: from the restrictions and obligations to the means and levers*, focused on requirements

1. Hercules European School
http://hercules-school.eu

2. Executive Masters in Management of Research Infrastructures
http://www.emmri.unimib.it/en/

for clinical investigations, clinical data, decision analytic modelling and financial instruments; the **ESFRI Landmark BBMRI ERIC** course on *How to build a biobank*; the **ESFRI Landmark EATRIS ERIC** online course *The Landscape of Translational Medicine* covering target validation, predictive models, biomarkers, personalized medicine, and regulatory environments; the **ESFRI Landmark ELIXIR** provides training to life science professionals to deal with the exponential growth of bioinformatics tools and data, and filling the training gap left by transformative data technologies in medicine and the life sciences, including how *Big Data* are generated, analysed and interpreted.

In the domain of **SCI** training activities by RIs help scholars to find the appropriate data and access norms to personal datasets. An example is given by the **ESFRI Landmark DARIAH ERIC** which provides supporting platforms to the researchers for the access and the use of the data-sets generated by RIs. A remarkable initiative is the training programme organized by the Synergies for Europe's Research Infrastructures in the Social Sciences (SERISS)[3], which aggregates the six major European RIs for Social Sciences. The reference organization in information technology and data services that supports research, training and teaching in the social sciences at international level is the International Association for Social Science Information Service and Technology (IASSIST)[4].

EU-funded RIs consortia in the **PSE** subdomain of Analytical Physics like CALIPSO[5] (Synchrotrons), SINE2020[6] (Neutrons), ESTEEM[7] (Electron Microscopy), and more in the PSE domain, organize workshops and advanced training.

The training in data sharing, on how to make data FAIR – Findable, Accessible, Interoperable, Reusable – and on the broad implications of Open Science should be substantially supported jointly by Digital and Research Infrastructures. The users of data intensive infrastructures – as the **ESFRI Projects ACTRIS**, **DANUBIUS-RI**, **EMPHASIS**, **ISBE**, and the **ESFRI Landmarks CTA** and **SKA** – need specifically tailored education and training programs for data acquisition, usage and interoperability.

# OUTREACH

Outreach activities are important in several aspects: to communicate with other fields of science that can benefit from the services offered by a given RI, to communicate correctly with Government administrations and stakeholders, to reach industry and civil service operators, to diffuse scientific culture to the students at all levels – from primary education on – and to the general public.

Outreach initiatives by RIs in all domains are aimed at reducing barriers between science and citizens providing evidence of the direct benefits to society in many aspects of life, from health to communication, from environment and energy to cultural heritage and to economic competitiveness. All RIs practice outreach initiatives in form of public events often conducted by well-known journalists, site visits – open door days, general media hard and software products including interactive virtual experiences.

3. Synergies for Europe's Research Infrastructures in the Social Sciences (SERISS)
*https://seriss.eu*

4. International Association for Social Science Information Service and Technology (IASSIST)
*http://www.iassistdata.org*

5. CALIPSOplus
*http://www.calipsoplus.eu/*

6. SINE2020
*https://www.sine2020.eu*

7. ESTEEM 2
*http://esteem2.eu/*

# INNOVATION

RIs are important innovation drivers for the development of a competitive knowledge-based economy providing competences and data to – for example – society and industry. They are mission-driven open innovation centres – knowledge hubs – where advanced technologies are created for serving the RI's specific mission and for maintaining the RI's scientific excellence by involving industry and services in public/private partnerships, spin-offs or start-ups therefore realizing an effective knowledge-transfer to industries that raises their standards. Conversely, RIs are test beds of innovative equipment and instrumentation.

Among the solutions developed at RIs and successfully transferred to industrial or civil applications one can quote, within the **PSE** domain, detectors of electromagnetic fields from terahertz to X-rays, neutrons, electrons, high energy particles, and the associated signal electronics; adaptive optics and advanced integration of mechanics and nanomechanics from telescopes; extremely stable power lasers and ultra-short laser pulses; stable hadron beams; imaging; irradiation; high throughput signal processing, data reduction and distribution; visual or textual pattern recognition; efficient archiving and more. All the above yielded innovation in medical, environmental, information, production monitoring, security, computing applications.

Industrial Liaison Offices and Industry Advisory Boards of RIs are the typical interfaces to industry as user-supplier-partner. On the market side a central European portal should inform thoroughly on calls for tenders, RI needs and Technology Transfer (TT) opportunities, upcoming procurements concerning all major RIs.

Research data represents significant financial assets and business opportunities: RIs manage the full chain of data from production and provision of metadata, data curation, long-term preservation to open data services for research and, when appropriate, pay-services for commercial re-use of data. Ensuring research data availability across disciplinary borders, and data handling and portability of results are increasingly important in many industrial and service sectors.

Distributed RIs in the **H&F**, **ENV**, and **SCI** areas are seeds for research and innovation hubs of excellence throughout Europe, also offering services to SMEs, from quality control to new product development and training. Overall IPR issues for cooperation with industry for the development of new devices, the commercial use of scientific data, and ethical considerations are sensitive issues across the fields.

Innovation along the whole value-chain for electrical energy production, from structural materials to components and devices and their integration into the energy system, is supported in the **ENE** domain by the ESFRI RIs that address cutting edge research in this field within a governance scheme that includes industrial advisors.

**ENV** RIs foster innovation for new measurement concepts and technologies for environmental monitoring in all compartments of the Earth system. The transfer of cutting edge solutions to industry is often realized by spin-off companies and start-ups linked to the RIs.

**SCI** RIs contribute to innovation articulating aspects as Innovation in service industries, creating new services based on Natural Language Processing, machine learning and semantic technologies based on knowledge graphs, design, game development and social media. Societal and cultural innovation detects spontaneous, emerging changes in society – e.g. co-housing practices among seniors or evolution of ideas and aspirations among citizens and helps innovative policies with evidence-based guidelines about appropriateness and acceptability of rules and norms.

The European Open Science Cloud (EOSC)[8] is an emerging Digital Infrastructure with structuring impact on European science and beyond, setting up a European Data Infrastructure, underpinning high-capacity cloud solutions with super-computing capacity, federating its services to RIs and community produced ones and widening the user base to the public sector and industry. As such, the EOSC will be a fundamental enabler of the digital transformation of science, offering access and reuse of research data in Europe, across disciplines and borders. EOSC has the potential to leverage past investment in research data infrastructures to add value in terms of scale, interdisciplinary, and faster innovation. ESFRI recognised the Research Infrastructures and their users will enable a successful start of the EOSC providing high quality controlled data and data analytics. A suitable organization of work should be designed to optimize the roadmap towards the realization of the EOSC goals by fully exploiting the ESFRI contribution, as recommended by the European Council in May 2018.

By covering different aspects of key future digital technologies, innovation is driven forward by ESFRI data-intensive RIs. Given the service-oriented nature of the field, innovation support to the industry and business is inherent for the ESFRI RIs, which are data-intensive.

8. The European Open Science Cloud (EOSC) *https://ec.europa.eu/research/openscience/index.cfm?pg=open-science-cloud*

# SOCIO-ECONOMIC IMPACT

RIs contribute to accelerate the transition to a knowledge based economy. Capacity building, high-level training, provision of innovative technologies, and implementation of know-how, methods and standards to national and international stakeholders, training and education, and advising on policies do impact the European society and economy. Socio-economic impact (SEI) is an element of the ESFRI Roadmap assessment procedures and it is central in the networking activities of the ESFRI RIs. It remains challenging to elaborate a robust model and metrology to quantitatively estimate the SEI.

The contemporary results of *Big Science* from space-missions like Cassini or the detection of gravitational waves demonstrating the genesis of heavy elements in the collapse of binary systems, contribute to broadening attraction to science and rational scientific research efforts, as well as the results of genomics and related medical research addressing common and rare diseases. High-quality research, as generated by RIs, develops a large SEI, and a baseline for pursuing a truly knowledge-inspired societal policy.

The assessment of SEI stemming from RIs' activities is a standardized way to evaluate the effective use of public resources, to inform future decision and policy-making and to secure funding for the continuous operation of RIs. The SEI assessment is relevant along the whole lifecycle of RIs, from design to termination, and may require *ex ante* as well as *ex post* assessments. Dedicated studies of SEI of large single-site facilities in the ENE and PSE areas were published, but we lack proven models for SEI in the case of distributed RIs typical of the **ENV**, **H&F** or **SCI** domains. Here we list some elements that contribute to SEI for all ESFRI RIs areas.

The geographical coverage, complementary resources and concerted approach of **H&F** RIs represent unique assets for accelerating drug discovery and production, testing of new diagnostics and therapies, supporting the development of personalised or stratified medicine, identifying new models of human rare diseases, and facilitate the emergence of new biomedical applications. These concerted actions accelerate socio-economic competitiveness and foster an equitable healthcare in Europe. **H&F** RIs will provide data in strategic areas for Europe such as marine bio-resources, good environmental status, circular economy, therefore supporting the efforts to address challenges as the increasing demand for food connected to population growth, the increasing use of biomass for non-food purposes and the competition for arable land. Research in the **H&F** domain has direct impact on society and helps strengthening public awareness and support to science, including attraction for the youths towards science and technology careers.

The SEI of **ENV** RIs is based on the knowledge contribution to society for educating and preparing people to environmental hazards therefore increasing the resilience to natural and anthropogenic risks – e.g. the **ESFRI Landmarks EPOS** and **EMSO ERIC**. Moreover, long-term observation data on the changing Earth system help triggering new technology development and innovation in the field of mitigation and adaption to climate change – e.g. the role of the **ESFRI Landmarks ICOS ERIC**, **IAGOS**, **EURO-ARGO ERIC** and the **ESFRI Project ACTRIS** in Copernicus.

The SEI of the Analytical Research Infrastructres (ARIs) in the **PSE** domain – synchrotrons, FELs and neutrons facilities – include the multi-disciplinarity generating societal benefits from technology to heritage preservation. Competitive research hubs do qualify the host territory by attracting highly skilled human resources and generating jobs of higher knowledge content in the local economy.

The SEI of RIS in **SCI** is easily perceived as these infrastructures provide information that relates to our cultural heritage, preserves art, uncovers our past, informs political thinking and decision making and supports our social and economic well-being. An important SEI indicator is the effect of **SCI** RI-supported research on evidence-based public policy. The data from the **ESFRI Landmark SHARE ERIC**, for example, revealed a strong correlation between early retirement and the loss of cognitive abilities with strong policy implications both at European and national level. The EU Commission as the single largest user of **SHARE ERIC** data, uses the data for economic and social benchmarking exercises. The social and longitudinal surveys deal with values, representations, beliefs and subjective conditions such as well-being that drive human behaviour, proved their SEI with a better common understanding across Europe. RIs on common language and cultural heritage, its richness and diversity, strengthening cultural citizenship and linking with the most advanced technologies producing a high SEI for Europe. Working with complex questions as contemporary societal challenges requires a system that is capable of giving access to and handle large amounts of data from a wide variety of sources covering many scientific areas.

**DIGIT** RIs create a safe and seamless environment for sharing research data, accessing to new platforms and software tools do contribute to increase the scientists' productivity and enable data reuse with the aim of generating new science and science services, ultimately generating major economic benefits. The net effect is a more efficient usage of the existing infrastructures and attracting new resources to the European science sector, creating a circle that fuels investment in innovative businesses, new public services, higher quality scientific information.

# BIG DATA AND e-INFRASTRUCTURE NEEDS

Science and Technology of Information and Communication (STIC) and RIs must develop the maximum synergy to produce, communicate and diffuse the culture of high quality data in all areas of science. Frontier research generates high-quality data and extracts knowledge from them. Raw data are generally unstructured flows that are effectively usable only by the scientists who generated them, or by a specialized scientific community. Open Data science requires large cohorts of structured and well documented data: only a special effort pushing ahead the state-of-the-art of e-Infrastructures can enable this goal by realizing advanced standards of accessibility, quality control of data and analysis tools.

The multi-disciplinarily character of data-intensive themes imposes the scalability of the digital infrastructures with increasing e-needs, calling for a coordinated effort of all RIs. ESFRI foster adoption of FAIR – Findable, Accessible, Interoperable and Reusable – data principles plus data Reproducibility and Openness by all RIs of the Roadmap. ESFRI RIs generate massive data and have often developed own standards and metadata formats, developed data analysis and computational resources available to users, as well as data repositories for storage facilitating data sharing and re-use optimized for their reference scientific communities. High throughput (HTC) and high performance computing (HPC) are key services for the RIs activities. RIs in different domains face similar data management challenges – e.g. validation and access – and this gives high evidence of the urge of concerted actions towards innovative data policies as well as for the training of data scientists.

The European Open Science Cloud can realize a framework of *Commons* – good practices and instruments of interdisciplinary value – to organize a consistent system of RIs and e-Infrastructures, assuring data preservation and protection, Virtual Research Environments (VREs) data interoperability, and suitable data analytics and computational resources across all disciplines, with proper solutions for ethical and IPR issues. EOSC will federate the most advanced data and service infrastructures, often directly built and supported by the RIs. ESFRI RIs – among other European, national and international – represent a major investment in data infrastructure. In contributing to the EOSC the RIs should retain control over the quality of their data, its persistence in time, and over the quality of the data services that might eventually be also provisioned by others to the general scientific users and for innovation purposes.

Important efforts are being developed for coordinating a harmonized contribution to all e-Infrastructure European initiatives – e.g. EOSC, EDI and HPC, in tune with the most recent recommendation of the European Council. Notably HPC applications for data analysis are expected to have a multiscale integrating character and contribute filling gaps with regard to databases and research platforms.  Distributed RI platforms and a rising number of national hubs have the potential to advance the digital RIs in the ecosystem.

RIs producing *Big Data* need, for example, pre-exascale computing technology – e.g. green computing, data and streaming, nano-photonics, etc. – that requires an important R&D effort. Green computing will radically reduce the power needed to do computationally intensive work on large amounts of data. Data & streaming technologies are needed to process data on-the-fly and to efficiently archive data – e.g time series that need perpetual conservation. Nano-photonics research addresses technologies to drastically reduce the energy cost of data transport over long distances as well as inside computing devices.

In the **PSE** domain, astronomy has pioneered a global framework for FAIR data sharing, which is operational and intensively used by the international community: ground and space-based observatories provide access to their data, which can be reused for scientific aims different from the initial motivation of the research; a Virtual Observatory (VO) defines the relevant data standards as well state-of-the-art data analysis tools. The VO shows the power of interoperability *within a discipline* to enable data and *Commons* to become an integrated Research Infrastructure. The International VO Alliance (IVOA)[9] is expanding with the inclusion of Astroparticle Physics needs through the Astronomy ESFRI & Research Infrastructures cluster (ASTERICS)[10] and planetary physics by the Virtual Atomic and Molecular Data Centre (VAMDC)[11]. The rate at which data-handling is required at analytical facilities exceeds Moore's Law and will further accelerate as new-generation detectors and brighter sources come online – ARIs' instruments produce PBs of data a year, e.g. in imaging and tomography. Advanced ARIs need to process data in near-real-time to enable the users to steer their

9. International VO Alliance (IVOA)
http://www.ivoa.net

10. Astronomy ESFRI & Research Infrastruttures cluster (ASTERICS)
https://www.asterics.eu

11. Virtual Atomic and Molecular Data Centre (VAMDC)
http://www.vamdc.org

experiments and optimize the costly and scarce beam time availability. An example are Free Electron Laser facilities requiring large computing power and advanced analytics at hand during the experiment sessions. The RDA is developing reference criteria and methods and a broader concept of virtual observatory/laboratory enabling remote access to RIs spanning over the **PSE** domain.

**ENV** RIs are distributed with nodes/sites acquiring data with a range of spatial and time coordinates so that data standardization and quality control are built-in activities to provide exploitable information and data services for research and society. The **ENV** RIs involve *Big Data* as collections of many different kinds of environmental data and share common challenges such as data capture from distributed sensors, management of high volume data, data visualization and web-casting of data nearly in real time.

Europe is the most environmentally monitored continent, there is however an urgent need to develop a more advanced approach to environmental observation capable of integration across diverse science domains, temporal and spatial scales, space-based observations and *in situ* measurements, data and analysis performed by researchers, industry and governments. A priority and a key driver for **ENV** RIs is to implement a federated approach to IT resources for greater integration and interoperability building on the examples of earth observation – e.g. the role of the **ESFRI Landmarks EPOS** and **Lifewatch ERIC** in the Global Earth Observation System of Systems (GEOSS)[12]– and meteorology – e.g. the role of the **ESFRI Projects ACTRIS** and the **ESFRI Landmark IAGOS** in the World Meteorological Organization (WMO)[13].

**H&F** RIs data and knowledge output, as well as the technologies to manage and integrate with other research data in this field, will extend the frontiers of research and generate opportunities to respond to the health and food challenges. **H&F** RIs have a long track record on generating the conditions to share data. In the Health domain, there are special requirements in the Data management, concerning protection, anonymization, identification, storage and data analytics to keep data public and confidential. This expertise can be translated into other fields in order to align and to extract knowledge from **H&F** data in combination with data from other domains, including the development and application of AI and machine learning.

The multi-disciplinarity intrinsic to **ENE** domain requires developing and applying scale-bridging approaches to the design of new materials and to study energy related processes. The study of energy networks and systems from local to macroscopic scales needs handling large volumes of data and intensive model-based processing. New initiatives as the Energy oriented Centre of Excellence for computing applications (EoCoE)[14] are expected to have a multiscale integrating character and to contribute filling gaps between databases and research platforms. Distributed RI platforms such as the European Distributed Energy Resources Laboratories (DERlab)[15] and European Real-time Integrated Co-simulation laboratory (ERIC-Lab)[16] and a rising number of national living laboratories collecting and processing data of real energy systems have the potential to advance the digital real-time integration of distributed and volatile energy resources into advanced and sustainable energy systems.

An important element that needs special mention in e-needs is Human Resources (HR). HR are at the core of all aspects of the overall e-infrastructure and *Big Data* ecosystem at institutional, national, European (EOSC, EDI, EU-HPC etc.) and global level. Sustainability of the RIs and e-Infrastructures must be approached simultaneously with an unprecedented effort in training of data scientists as a specialised profession and of broad data literacy to enable more and more users of the data system.

Finally, it is important to say that there is a clear need to bring together data from multiple platforms to solve increasingly complex problems, and this requires more open access and transferability of data, but the ethical issues and those related to industrial confidentiality need to be properly addresses by all the concerned RIs aiming at developing well based rules.

12. Global Earth Observation System of Systems (GEOSS)
https://www.earthobservations.org/geoss.php

13. World Meteorological Organization (WMO)
https://public.wmo.int/en

14. Energy oriented Centre of Excellence for computing applications (EoCoE)
https://www.eocoe.eu

15. European Distributed Energy Resources Laboratories (DERlab)
http://der-lab.net/about/

16. European Real-time Integrated Co-simulation laboratory (ERIC-Lab)
http://www.eric-lab.eu

# REGIONAL IMPACT

RIs strongly characterize the territory that host them as drivers for regional development in terms of scientific production and culture, higher education services, innovation in procurement and services and the promotion of supplying industries including SMEs and start-ups oriented to innovation. Enforcing the cooperation between the research sector and economic activities through RIs is central to driving innovation, which typically emerges at local and regional level before spreading globally.

RIs impact the local and regional development: they attract highly internationally qualified staff, the best researcher users from all over the world, students and trainees, and reflect excellence on the local educational system, on the job market and overall regional economy. The role of the regional and local authorities is, thus, fundamental from the preliminary stage of declaring their smart specializations as background for the RI and for the possibility of benefiting of EU structural and investment funds or other financial support facilities at national or European level. Further stimulus role should foster collaboration of RIs with universities and local research institutions.

**ENV** RIs have a prominent role for addressing the global scientific challenges related to environmental and climate change which impact our society on all levels up from the local, regional, national, to the continental and global scale. The majority of these are of distributed nature, and constitute pan-European hubs of scientific excellence that are, by definition, regional - Think regionally, but work together internationally. The sustainability of **ENV** RIs involves regional investment among others. Various showcases particularly in Southern and Eastern Europe have demonstrated the beneficial effect and proper use of European Structural and Investment Funds and of collaboration with regional governments to improve our environment – i.e. the **ESFRI Landmark LifeWatch ERIC** and the **ESFRI Project DANUBIUS-RI**.

The distributed **H&F** RIs provide opportunities for regional development of the entire EU-28. The objective is to increase active participation of all Member States in RIs, to support regional research output, to offer new capacities and expertise, prevent brain drain and regional unbalance and ensure coherence and synergy of resources throughout Europe, overall reinforcing cooperation and the formation of EU-wide centres of expertise.

Electron Microscopy laboratories are ubiquitous at universities and research laboratories, but the few that operate as users' facilities have been developed at regional scale, or in conjunction with large ARIs. CEITEC in the Czech Republic is an example of the strategic use of EU Structural Funds for infrastructure development in science, with a strong cryo-EM component. Another example of regional funding is the support from Regione Toscana for the Italian node of the **ESFRI Landmark INSTRUCT ERIC**, the Centre CERM/CIRMMP.

**ENE** RIs are drivers for regional development in terms of scientific knowledge, innovation and the promotion of supplying industries including SMEs and start-ups with their often special competences in innovative technologies. For Energy RIs, this is especially true for innovative materials, components and devices as well as for high-level characterization technologies, engineering equipment and technical plant construction.

**PSE** RIs substantially contribute to the Regional economy as they represent large investments and create conditions for collaboration and partnership schemes. Regional facilities are increasingly networked thanks to strategic initiatives like ASTRONET or APPEC. New schemes and initiatives with impact at regional level emerge: the LEAPS initiative – league of electron acceleration driven photon sources – brings together 12 national facilities with the **ESFRI Landmarks ESRF EBS** and the **European XFEL** – aiming to strengthen the network of the analytical facilities and support the free open access to all national resources. Medium power nationally-funded neutron sources and the pulsed sources ISIS (UK) and SINQ at PSI (CH) are open to international users and develop collaboration/funding schemes. The high flux sources – the **ESFRI Landmarks ILL** and the **European Spallation Source ERIC** – are governed under international ownership schemes. The regional dimension of an international source is measured by the impact of the large investment in construction and long-term operation on local economy, society, University and broader educational system, as demonstrated by the competition for hosting large RIs.

The EU FP measure *Integrating Activities* contributes to the Regional impact supporting the networking of national/regional facilities for common research and infrastructure service including transnational access.

RIs and Digital Infrastructures create regional opportunities to compete for Structural and Cohesion Funds in RI investments which in turn can be seeds for the development of innovation nodes within distributed RI. The increasing synergy and complementarity of ESFRI and national roadmaps will create a facilitator for a coherent development of RIs and e-Is in Europe from the pan-European to the regional scale.

# PAN-EUROPEAN DIMENSION

Pan-European relevance is the rationale of ESFRI RIs in terms of the resources involved – competences, financial, human resources, services – and of the EU-wide research users' community needing such unique facility. The entire ESFRI assessment, coaching and monitoring activity has as a reference the criteria for effective pan-European relevance. The e-Infrastructure aspects are assessed against indicators adopted in cooperation with e-IRG[17].

**H&F** RIs and their services are crucial to offer solutions to the provision of sustainable food options for Europe and the world in the context of a changing climate and limited land availability. Extreme climatic events observed in several European countries have led to a marked decrease in the growth trends of major crop yields – such as wheat – over the past two decades, thus also affecting health, welfare and quality of life of Europeans. The well integrated and synergetic **H&F** RIs landscape is key to understand the best strategy towards sustainable and safe food development, i.e. producing goods and services while minimising the consumption and waste of raw materials, water and energy sources. The **ESFRI Projects AnaEE**, **EMPHASIS** and **METROFOOD-RI** are important RIs in the context of these challenges. **H&F** RIs are also very relevant to state-of-the-art healthcare in Europe for the implementation of personalised medicine and for tackling global infectious diseases. The implementation of personalised medicine requires *Big Data* and data sharing. Omics data – the **ESFRI Landmark ELIXIR**; biobanking – the **ESFRI Landmark BBMRI ERIC**; translational medicine – the **ESFRI Landmark EATRIS ERIC**; and clinical trial platforms – the **ESFRI Landmark ECRIN ERIC** – are key RIs to achieve this. It is also necessary to foster collaborations with the International Consortium on Personalized Medicine (IC PerMed) and ERAPerMed, and with the European ecosystem of supercomputing facilities. The Multi-disciplinary HPC-BD infrastructure for Personalized Medicine data analysis and clinical diagnosis in Europe, a part of IPCEI HPC initiative, is an example. Research and clinical infrastructures in the hadron oncologic therapies, like the CNAO and HIT facilities are coordinated by the ENLIGHT network, and new initiatives are emerging in the Balkans. The ageing population in Europe has led to a rising demand for advanced healthcare, especially in the context of the current shift towards complex multi-morbidity patterns and chronic illnesses, monitoring by longitudinal studies – the **ESFRI Landmark SHARE ERIC** – is very important. The Human Brain Project FET Flagship is also relevant in this context. Climate change is projected to greatly affect public health in Europe, particularly in the elderly and chronic disease patients, as well as by shifting the pattern of spread of some mosquito borne diseases – e.g. Zika virus vector has reached central European countries such as Switzerland. Again similar collaborations, including the **ESFRI Landmark ERINHA** with GloPID-R (International Consortium for Global Infectious Diseases Preparedness) are important. The developing RI landscape offers a unique opportunity to exploit inter- and cross- disciplinary research models and the latest technological advances to foster the development of safe and effective approaches for the screening, prevention, early diagnosis and therapies and therapy monitoring, thus bridging scientific research with tangible benefits for the European society.

17. Evaluation of e-Infrastructures and the development of related Key Performance Indicators, ISBN 978-90-823661-4-3].

Within Europe the **ENV** RIs already operate and collaborate across borders for a long time being the RIs thematic areas of global interest by nature. So the collaboration at global scale is already in their DNA. This makes also easier for European initiatives to extend their collaborations outside Europe. Moreover, the pan-European dimension of **ENV** RIs is necessary to ensure peer and balanced collaborations both with other developed and emerging world areas. ESFRI helped consolidating integration of **ENV** RIs with the further effect of advancing technological developments to provide users services, making possible to bring **ENV** RI's to the next level of service provision. The **ENV** RIs were able to learn from their own problems/issues/efforts, and they have today a leading position for global collaborations. Better awareness of the EU RIs outside EU can attract more scientific talent.

All **ENE** RIs aim at providing solutions for the transformation of the energy system as one of the major scientific, economic and societal challenges of Europe. To this purpose, they either gather a number of distributed RIs and expertise in different EU countries in order to combine and accelerate efforts in form of platform-building decentralized RIs – the **ESFRI Landmark ECCSEL ERIC**, and the **ESFRI Projects EU-SOLARIS** and **Windscanner**– or they provide technology-related R&I services to the European and worldwide community – e.g. the **ESFRI Project MYRRHA** and the **ESFRI Landmark JHR**.

**PSE** RIs are pan-European with relevance expanding to the global scale as emphasized by the Membership and Usage indicators. Astronomy and astroparticle physics are well organised at European level, with world-leading ESFRI RIs, and other major facilities of global interest such as the EGO/VIRGO gravitational telescope part of the LIGO-VIRGO GW-Detector global network. The strategic vision of ASTRONET and APPEC provides a pan-European and international vision and strategy for the field. Transnational Access programmes in EC-funded networks such as OPTICON and RADIONET give a pan-European dimension to national and multilateral facilities. The open access to astronomical data allows researchers from all European countries to access and use the best data-sets and data-analysis tools, contributing powerfully to a better integration in the European Research Area.

About 30.000 scientists in Europe perform their research using some 15 synchrotron radiation facilities and Free Electron Lasers either at national facilities or at ESFRI RIs, and about 5.000 scientists in Europe are users of neutron beams at the 10 European sources (see the Neutron Landscape) that are presently operational. An overall number as high as 10.000 researchers needing neutron spectroscopy, mainly from academia, have been estimated by the network of European neutron facilities, SINE2020. The **ESFRI Landmark European Spallation Source ERIC** has adopted the ERIC framework and explores options for international collaborations at global scale. Supporting user programmes and excellence-based access, especially for researchers from countries without neutron sources, is a very critical point at the present level of development of the neutron landscape and a necessary investment to manage properly the evolving neutron scenario[18].

Estimates arising from ESTEEM, ESTEEM 2 projects, the **ESFRI Landmark INSTRUCT ERIC** and the European Microscopy Society indicate a user base of more than 5.000 scientists skilled in TEM and a broader base of scientists who will benefit from access at advanced TEM RIs indicating the need of further investment, integration-standardisation and inter-operability in this field.

In the case of the **SCI** RIs the complete European coverage is a key strategy goal for the efficient construction of instruments and services enabling research on cultural, linguistic, social, political and economic life in Europe in its variety and complexity. The large membership of **SCI** RIs proves their importance for research community as well as confidence of decision makers in the efficiency of established services, but the remaining gaps in European coverage limit their pan-European impact. Some areas of Europe, e.g. eastern and southern parts, are less represented in ESFRI **SCI** RIs than others. This may have negative implications: the creation of biases in understanding of Europe, the undermining of European comparative research, less comprehensive standards, reduced possibilities because of missing languages and language families, persistent inequality in scientific research among European countries.

18. Neutron scattering facilities in Europe: Present status and future perspectives, ESFRI Scripta Vol.1, September 2016 *http://www.esfri.eu/sites/default/files/u4/NGL_CombinedReport_230816_Complete%20document_0209-1.pdf*

The aim of all ESFRI RIs is the transformation of their data intensive feature to address one of the major scientific and societal challenges of Europe – digitalization of science and industry to introduce the open science and open access paradigm. To achieve the goal, RIs collect expertise in different EU countries in order to combine and accelerate the efforts.

# GLOBAL DIMENSION

European competitiveness in research is strengthened by RIs with prominent role in the global landscape. The long tradition of Physics RIs sees Europe as a global player in the High Energy Particle (HEP) and ion/nuclear research with colliders, in the detection of all the cosmic messengers – Electro Magnetic radiation, High Energy Astroparticles, Neutrinos, Gravitational Waves – and in the Analytical RIs and extreme optical pulse sources. But globalization is a need and an opportunity in all other fields of research, from solid Earth, ocean and atmosphere observation to H&F, SCI, ENE and DIGIT domains.

Promotion of global consortia of advanced facilities and novel Global Research Infrastructures (GRIs) are needed to enhance the role of European RIs and science in the global context. The Group of Group of Senior Officials (GSO)[19] has defined a framework for GRIs and the considered case studies have already involved ESFRI RIs and other leading European research facilities.

19. Group of Senior Officials (GSO) on global Research Infrastructures *https://ec.europa.eu/research/infrastructures/index.cfm?pg=gso*

Global cooperation on RIs is strategic to Europe for maintaining leadership in standardization of data protocols and the sharing of best practices all over the world. The role of electronic infrastructures is central on this playground. The electronic infrastructures providing services to global RIs like the **ESFRI Landmarks SKA**, **HL-LHC**, **EURO-ARGO ERIC**, and **ELIXIR** ensure the opening of these infrastructures to the world fostering cooperation between European RI and other international world class RIs. Developing a staff exchange programme at the global level, including the organisation of thematic courses and workshops for staff managing and operating Research Infrastructures, is largely facilitated by the electronic platforms available via electronic infrastructures.

In the **SCI** domain the context of globalisation implies that public authorities and companies have a vital need to better know and understand cultural diversity. It is essential to analyse factors of social cohesion, economic development and well-being, by looking at the roles and forms that risk acceptance or risk avoidance take. Of particular importance will be those RIs that support the understanding of the driving forces that can enable our society to offer a better framework for integration, to fight inequality and to promote social and economic development. It is important to *go beyond Europe* because much can be learned from sharing data, best practices and know-how, in addition to ensuring harmonization and interoperability. All of the existing ESFRI Landmarks in the **SCI** domain have a policy for international collaboration and partnership.

The **ESFRI Landmark CESSDA ERIC** has a close cooperation with the Inter University Consortium for Political and Social Research in the US and with relevant institutions in India, Japan and Australia and South Africa among others. The **ESFRI Landmark ESS ERIC** has informal collaborative links with a number of global research programs such as the International Social Survey Program (ISSP)[20], Eurobarometer[21], AfroBarometer[22], Comparative Survey of Electoral Systems (CSES)[23], East Asian Social Survey (EASS)[24], Gallup World Poll[25], EU-SILC[26], Latinobarómetro[27], World Values Survey (WVS)[28] and the EU Household Budget Surveys (HBS)[29]. The **ESFRI Landmark SHARE ERIC** has a long-standing cooperation with the United States sister survey Health and Retirement Study sponsored by the National Institute of Ageing which is also providing funding to SHARE. Further sister surveys exist in China, Korea, Japan, India, Mexico and Brazil. In terms of users the US is ranked second – after Germany – in the user statistics of the SHARE data, which is also a strong proof of the international impact. The **ESFRI Landmark CLARIN ERIC** is actively becoming more global. Across the world, there is an obvious need for access to data for cross-lingual and cross-cultural research, and collaborative research can only be fruitful if researchers have access to the same data and tools and are prepared to share them. At present CLARIN is actively discussing partnership with South Africa, it is exploring possibilities with other African languages, and Arabic speaking countries. In the US, Carnegie Mellon University has a recognised CLARIN centre, and they are now beginning to create a US consortium for CLARIN relations. There are links to other networks and actors in North and South America and Japan. CLARIN collaborates with the RDA. The **ESFRI Landmark DARIAH ERIC** participates to the creation of sustainable platforms for Digital Humanities, from the US Bamboo project (2008-2012) to the Australian Humanities Network Infrastructure HuNi. DARIAH ERIC together with CLARIN ERIC and Bamboo established in 2009 the international CHAIN initiative (Coalition of Humanities and Arts Infrastructures and Networks). The DARIAH node in Italy, co-organised in 2014 events and meetings around the theme of Fostering Transatlantic Dialogue on Digital Heritage and EU Research Infrastructures which were held at the Library of Congress in Washington DC. There have been expressions of interest from Israel, Canada and Australia, regarding the possibility of DARIAH Membership. Data and resources of other current and former projects should be interlinked for open access and interoperability, as in the case of the *Digital Preservation of Cultural Heritage*, funded under FP7 or projects of the Societal Challenge 6.

The **ENV** domain is of global dimension by nature and close collaborations on Earth system research are already established worldwide. Few **ENV** RIs – the **ESFRI Landmarks EPOS** and **IAGOS** – are already listed as candidate Global Research Infrastructures by the GSO. Global cooperation on RIs is strategic to Europe for maintaining leadership in environmental research on UN Sustainable Development Goals[30]– i.e. the **ESFRI Landmarks EURO-ARGO ERIC** and **ICOS ERIC** – as well as standardization of data protocols and the sharing of best practices all over the world. **ENV** RIs play also a crucial role in developing areas in the world, as ICOS ERIC which is supporting the development of a climate and greenhouse gas observation system in Africa.

The cluster of **ENV** RIs (ENVRI) is working on positioning the **ENV** RIs in the global playing field through its presence in GEO, various international fora, participating in projects to enhance global collaboration (COOP+, GLOBIS-B) and the AGU conference for instance.

In fields like **H&F**, the opportunities generated by global RIs for the worldwide scientific communities are crucial to address the global challenges of the area. Global impact of the ERA emphasises the role of **H&F** RIs in providing a sustainable world-class quality infrastructure environment and services to serve the **H&F** research community and to assist in attracting top scientists and collaborations worldwide from public research as well as industry. RIs like the **ESFRI Landmark ELIXIR** and the **ESFRI Landmark BBMRI ERIC** have been proposed to the GSO list of potential GRIs that indicates those RIs who seek interest by other RIs to coordinate with or other Countries to participate. The **ESFRI Landmark INFRAFRONTIER** is an important partner of the International Mouse Phenotyping Consortium (IMPC), which aims at creating a comprehensive catalogue of mammalian gene functions, this was a Case Study of GSO, considered to be in an advanced status of development. **H&F** RIs have established numerous connections internationally, e.g. the **ESFRI Landmark EATRIS ERIC** established links with NIH, USA; the **ESFRI Landmark INSTRUCT ERIC** continues developing relationships with China, Brazil, Argentina and India. The European Virus Archive (EVA), including the **ESFRI Landmark ERINHA** partners, has been very visible at international level on the occasion of the Ebola outbreak. The **ESFRI Landmark Euro-BioImaging** is part of the Global BioImaging Project, which will follow-up on the existing collaboration agreements with Australia and India and reach out to new international partners in North and South America, Africa and Asia to develop a sustainable network

20. International Social Survey Program (ISSP) *http://w.issp.org/menu-top/home/*

21. EUROBAROMETER *http://ec.europa.eu/commfrontoffice/publicopinion/index.cfm*

22. AFROBAROMETER *http://afrobarometer.org*

23. Comparative Survey of Electoral Systems (CSES) *http://www.cses.org*

24. East Asian Social Survey (EASS) *http://www.eassda.org/modules/doc/index.php?doc=intro*

25. Gallup World Poll *http://www.gallup.com/home.aspx*

26. EU-SILC *http://ec.europa.eu/eurostat/web/microdata/european-union-statistics-on-income-and-living-conditions*

27. LATINOBAREMETRO *http://www.latinobarometro.org/lat.jsp*

28. World Values Survey (WVS) *http://www.worldvaluessurvey.org/wvs.jsp*

29. Household Budget Surveys (HBS) *http://ec.europa.eu/eurostat/web/household-budget-surveys*

30. Sustainable Development Goals *https://sustainabledevelopment.un.org/sdgs*

of collaborating imaging infrastructures. The **ESFRI Landmark ECRIN ERIC** has collaborations with Japan, Brazil and USA. EMPHASIS is part of the International Plant Phenotyping Network. IPPN supports the development of concepts and technologies in plant phenotyping through interactions between major phenotyping centres in 17 countries.

Opening the global dimension in the **ENE** domain is – implicitly or explicitly – integral part of the Energy RI's mission and work plans. **ENE** RIs generally provide R&I services to the international community to address the global challenges of energy supply. Examples of initiatives in this regard are the **ESFRI Landmark ECCSEL ERIC** transnational access programmes or the **ESFRI Project MYRRHA**, which includes four third countries partners within the consortium. The realization of IFMIF as well will have to rely on a broad international collaboration.

**PSE** is a domain of very high globalization including High Energy Physics, GW interferometer detectors, underground and under-water laboratories and neutrino detectors, as well as large analytical RIs. Among the ESFRI RIs those for astronomy and astroparticle physics are global in their design, construction and operation: the **ESFRI Landmarks SKA**, **CTA** and **ELT** have observation sites distributed around the globe both in the north and south hemispheres. The ESS-neutron source has been analysed as a Case Study of the GSO regarding the good practices of in-kind contribution management. Accelerator based facilities for nuclear physics and ion physics also involve informal or formal international collaborations e.g. with Russia. Synchrotron radiation sources are ubiquitous in research-intense countries: Europe hosts what is arguably the world leading high-energy synchrotron facility, the **ESFRI Landmark ESRF EBS**, and several national facilities are also leaders in their own specialization, as for example the high-brillance MAXLAb IV. Petra-III was proposed as GRI to the GSO concerning good practices of global-excellence-based access. FELs are a newer kind of source of X-rays with competitive facilities in the USA (LCLS), Japan (SACLA) and the **ESFRI Landmark European XFEL**. At lower energies FERMI@Elettra is the unique seeded source in the world, and a class of intermediate energy FELs are being completed and coming on-line in Switzerland, Korea and China.

The global situation for neutron facilities shows an overall growing trend lead by US, Japan, Russia and China, while the European neutron capacity is expected to face an overall decrease despite the **ESFRI Landmark European Spallation Source ERIC** starting operation in coming years. Therefore, the globalization of neutron sources is a serious step to be considered for the benefit of European scientists.

In general, collaborations and exchanges exist between individual facilities within and outside Europe and there is also a healthy flow of scientists between facilities as a natural part of career development as well as the provision of access to European facilities to scientists outside Europe and vice versa, particularly where a facility offers capability not available elsewhere. Some European facilities may also play a role in helping develop facilities and user communities elsewhere, for example supporting the development of the SESAME project in Jordan, or the user community in South Africa. Exchange and collaboration for neutron technologies, knowledge and software are a well established tradition between the European neutron community and the US and Japan, with support recently offered for the development of the Chinese facilities and setting up collaboration projects with Russia.

As to EM RIs, the TEAM project initiated in US in 2004 is a collaborative research project between four US laboratories and two companies. In Japan, National facilities exist at the National Institute of Advanced Industrial Science and Technology and at the Nagoya High Voltage EM Laboratory. Looking further ahead, the Digital Infrastructures in Europe can play an important role in fostering global agreements on the standardisation, sharing and harmonisation of data collection and re-use.