CONTENTS

PART2

LANDSCAPE ANALYSIS - SECTION1

ENERGY

ENERGY

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

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

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

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

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

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

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

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

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

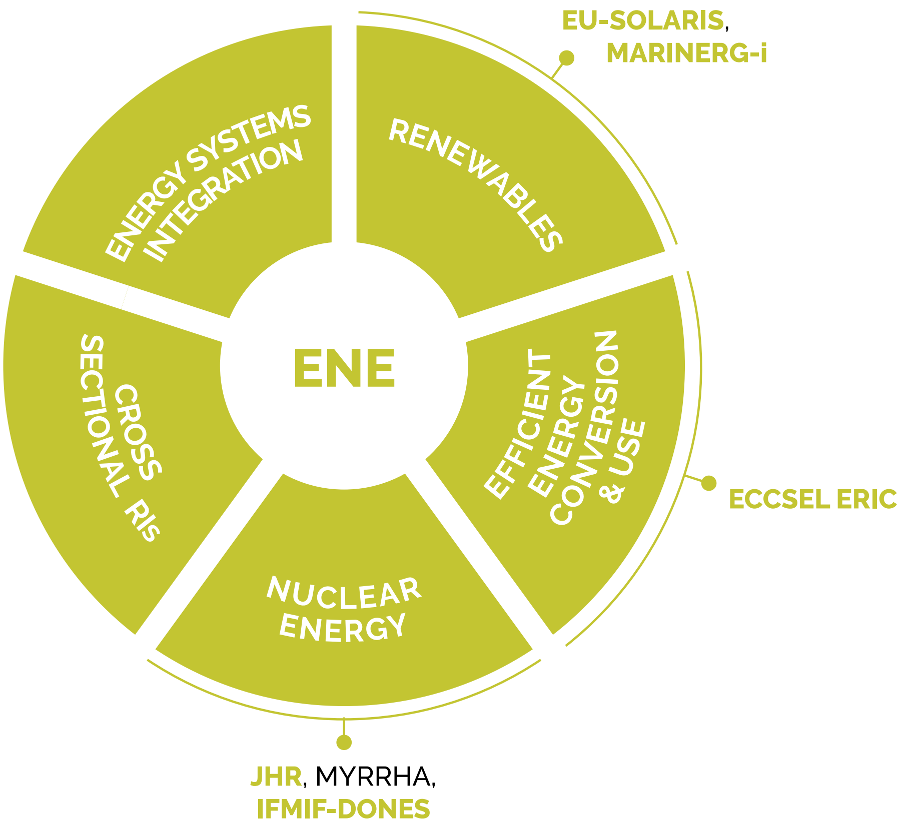

FIGURE 1.
The Landscape of the Energy domain.

ENERGY SYSTEMS INTEGRATION

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

II CURRENT STATUS

ENERGY NETWORKS

The future European energy system, with an envisaged much higher penetration of renewables given the Member States increased ambitions and requirements under their National Energy and Climate Plans (NECP's), needs an extremely strong interplay between different energy carriers such as electricity, heating and cooling – e.g. gas and other chemical fuels. Such a system demands control of intermittent production from renewable energy and variable consumption of all carriers as well as energy storage which is an important technology to stabilize the power fluctuations and to define economically and environmentally sustainable options. *Smart Grid* refers to a progressive evolution of the electricity network towards "a network that can intelligently integrate the actions of all users connected to it – generators, energy storage facilities

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

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

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

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

and consumers in order to efficiently deliver sustainable, economic and secure electricity supply and safety". It is a combination of the grid control technology, information technology and intelligence management of generation, transmission, distribution and storage. Energy Management Systems (EMSs) are vital tools to optimally manage the interplay across the variety of systems components, system grids and networks. In fact, the need for new EMSs to minimize emissions, costs, improve security at different spatial and temporal scales is the basis of the RIs in this field that implement the interaction among equipment, communication protocols, simulation and control. Over 450 demonstration projects with different RIs have been launched in Europe exploring system operation, consumer behaviour and new innovative technologies. As these systems evolve it will become an ever-increasing requirement to also research the supply chain demands of materials required for the network infrastructures.

ENERGY STORAGE

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

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

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

EFFICIENT LOW EMISSION TRANSPORT

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

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

SMART CITIES, COMMUNITIES AND LIVING LABORATORIES

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

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

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

GAPS, CHALLENGES AND FUTURE NEEDS

ENERGY SYSTEM INTEGRATION

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

ENERGY NETWORKS AND STORAGE

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

EFFICENT LOW EMISSION TRANSPORT

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

SMART CITIES AND COMMUNITIES

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

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

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

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

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

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

RENEWABLE ENERGY

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

CURRENT STATUS

PHOTOVOLTAIC SOLAR ENERGY

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

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

RENEWABLE FUELS

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

CONCENTRATED SOLAR POWER

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

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

WIND ENERGY

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

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

GEOTHERMAL ENERGY

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

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

OCEAN ENERGY

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

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

GAPS, CHALLENGES AND FUTURE NEEDS

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

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

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

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

The development of new **GEOTHERMAL ENERGY** technologies can be expensive and projects may be high-risk in the sense that commercial success is not guaranteed. Therefore, society cannot rely only on commercial initiatives, and public R&D support is often necessary. A coordinated trans-European initiative to co-exploit existing and

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

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

new geothermal test sites would appear to be strongly motivated. Such an initiative would naturally link to and significantly enhance existing ESFRI initiatives such as the **ESFRI Landmark EPOS ERIC** (ENV).

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

EFFICIENT ENERGY CONVERSION AND USE

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

CURRENT STATUS

ENERGY EFFICIENCY IN BUILDINGS

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

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

ENERGY EFFICIENCY AND USE IN INDUSTRY

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

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

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

POWER-TO-X (P2X) AND HYDROGEN TECHNOLOGIES

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

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

CARBON CAPTURE STORAGE AND UTILIZATION

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

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

GAPS, CHALLENGES AND FUTURE NEEDS

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

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

It remains unclear if large-scale **CARBON DIOXIDE CAPTURE, STORAGE AND UTILISATION** will become an important part of the energy system, but there is a

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

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

possibility that this is the case. Therefore, further major investments in relevant Research Infrastructure should be considered among the topics mentioned above.

NUCLEAR ENERGY

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

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

CURRENT STATUS

NUCLEAR FISSION

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

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

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

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

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

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

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

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

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

NUCLEAR FUSION

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

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

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

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

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

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

CROSS-CUTTING ISSUES BETWEEN FISSION AND FUSION

Materials research is the most prominent common topic to fission

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

GAPS, CHALLENGES AND FUTURE NEEDS

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

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

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

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

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

CROSS-SECTIONAL ENERGY RIs

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

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

CURRENT STATUS

SPECIAL MATERIAL FOR ENERGY SYSTEM

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

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

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

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

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

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

ENVIRONMENT

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

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

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

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

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

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