# CONTENTS



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**.

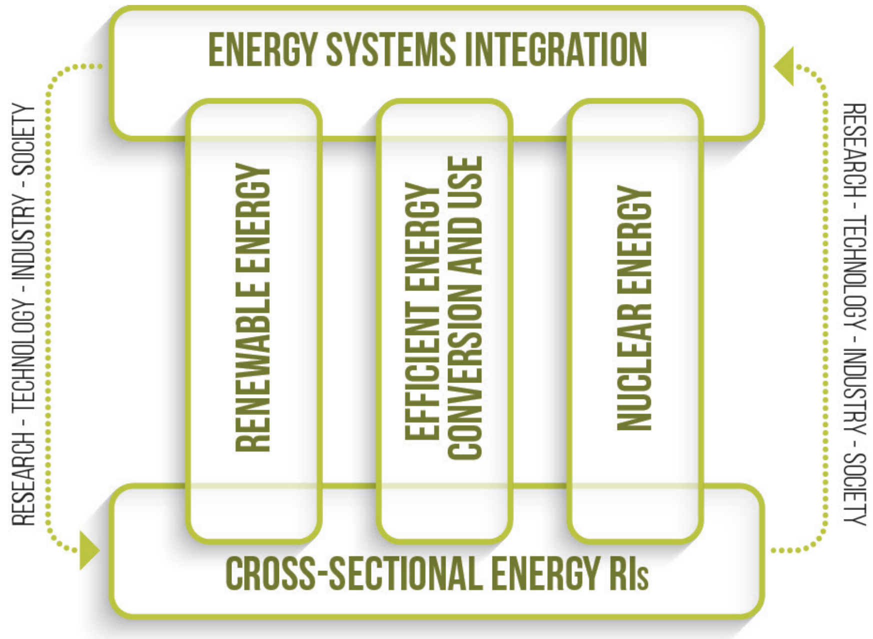


FIGURE 1.
Energy RIs Interplay.

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 CO2 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 CO2 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 CO2 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 CO2 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 CO2 capture using two units each approximately 12 MWe in size, able to capturing 100.000 tonnes CO2/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 CO2 in geological reservoirs have been achieved. The Sleipner CO2 Storage facility was the first in the world to inject CO2 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 CO2 Storage facilities has captured more than 4 million tonnes of CO2 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 CO2 from industrial processes has some advantages like lower capture cost, excess energy that can be used for CO2 capture and stable CO2 source. The concentration of CO2 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 CO2 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 CO2 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 CO2 utilisation (CCU). Specifically, a number of facilities that use CO2 in products, or to support operations have been constructed or announced in the last decade. It is important to note that not all CO2 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 CO2 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 CO2 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 CO2 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 21st 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.