Chapter 5
Sustainable Nuclear Energy Helps Europe to Meet Its Energy Challenges

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Abstract The European Sustainable Nuclear Energy Technology Platform (SNETP) now gathers more than 100 organizations (research organizations, utilities, vendors, technology providers, technical safety organizations, universities, consulting companies, and nongovernmental organizations). Its first Strategic Research Agenda (SRA) was edited by a specific Task Group drawing on contributions from more than 160 scientists and engineers from more than 60 member organizations of SNETP and taking into account the feedback obtained from an open public consultation: the SRA provides the foundation for the establishment of joint research priorities that will enable European stakeholders, with the support of the European Commission, to transform a shared vision into reality, thus contributing to European energy policy and in particular, via the European Sustainable Nuclear Industrial Initiative (ESNII), to the objectives of the European Strategic Energy Technology Plan (SET Plan).

This chapter summarizes the contents of the agenda and presents the prospects for the need for hot labs and their application to the different generations of reactors. The implications of the Fukushima accident for SNETP is discussed and the imperative necessity of increased research, education, and training, to reinforce nuclear energy sustainability is also emphasized.

Keywords Nuclear energy • Fission • Reactor safety • Gen IV • ADS

List of Acronyms

ADS	Accelerator-driven systems
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
CCS	Carbon capture and storage

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CEA	Commissariat à l'énergie atomique et aux énergies alternatives (Alternative Energies and Atomic Energy Commission).
dpa	Displacement per atom (irradiation exposure unit)
ENEF	European Nuclear Energy Forum
ENEN	European Nuclear Education Network
EPR	European pressurised water reactor
ESNII	European Sustainable Nuclear Industrial Initiative
ETKM	Education, training, and knowledge management
ETPP	Experimental Technological Pilot Plant
EU	European Union
FNR	Fast neutron reactor
FP6	Framework Program 6
Gen III	Third generation reactors
Gen IV	Fourth generation reactors
GFR	Gas fast reactor
GIF	Generation IV International Forum
JRC EU's	Joint Research Centre
LFR	Lead fast reactor
LWR	Light water reactor
MOX	Mixed oxide fuel (uranium and plutonium) involving spent fuel treatment
MFSR	Molten salt fast reactor
MYRRHA	Multi-purpose hybrid research reactor for high-tech applications
P&T	Partitioning and transmutation
PSA	Probabilistic safety assessment
PWR	Pressurized water reactors
SCK·CEN	StudieCentrum voor Kernenergie – Centre d'Etude de l'énergie Nucléaire – Belgian Nuclear Research Centre
SCWR	Supercritical water reactor
SET Plan	Strategic Energy Technology Plan
SFR	Sodium fast reactor
SNETP	Sustainable Nuclear Energy Technology Platform
SRA	Strategic Research Agenda
VHTR	Very High Temperature reactor
WETO	World Energy Technology and Climate Policy Outlook

5.1 Introduction

The Sustainable Nuclear Energy Technology Platform (SNETP 2007) was officially launched in September 2007, and at this event, the vision of the technology platform was presented. It highlighted the role nuclear energy plays in Europe's energy mix as the main provider of low carbon electricity (providing 31 % of EU's electricity and representing a nonemission of almost 900 million tonnes of CO_2 per year), and identified future research, development, and demonstration (RD&D) tracks that the nuclear fission sector must follow in order to address three objectives:

1. Maintain the safety and competitiveness of today's technologies.
2. Develop a new generation of more sustainable reactor technologies, the so-called Generation IV (Gen IV) fast neutron reactors with closed fuel cycles.
3. Develop new applications of nuclear power such as the industrial-scale production of hydrogen, desalination, or other heat applications in industrial processes.

The SNETP aims to support fully through RD&D programs the role of nuclear energy in Europe's energy mix, its contributions to the security and competitiveness of the energy supply, as well as to the reduction of greenhouse gas emissions. To achieve this objective, SNETP has elaborated a Strategic Research Agenda (SRA 2009), that identifies and prioritizes research topics which are presented here.

We first emphasize the role of nuclear fission in Europe's low carbon energy policy, then present the 2020 objectives (maintain the competitiveness of nuclear energy with long term waste management solutions), and the 2050 vision (Gen IV fast neutron reactors with closed fuel cycle for increased sustainability). The case of high-temperature heat processes and developing other applications of nuclear energy are discussed, and we identify the needs in terms of research infrastructures and competences, to ensure the success of all these new developments. Before concluding, we also examine the implications of the Fukushima accident for SNETP.

5.2 The Role of Nuclear Fission in Europe's Low Carbon Energy Policy

In January 2007 the European Commission published a seminal communication, EPE (2007), that underlined for the first time the benefits of nuclear energy: low carbon emissions, competitiveness, and stable prices. In the context of an anticipated increase in the use of nuclear energy in the world, the Commission also recognised that "There are therefore economic benefits in maintaining and developing the technological lead of the EU in this field." This communication was endorsed by the Council in March 2007, and also committed the European Union to meet ambitious objectives by 2020 of a 20 % reduction in greenhouse gas emissions (compared to 1990), 20 % renewable energies in the energy mix, and 20 % reduction in energy consumption through better energy savings and management.

In order to achieve these goals and realize the longer-term vision of a low carbon society by 2050, the Commission identified RD&D prospects of key low carbon energy technologies in a follow-up communication, SET Plan (2007), published in November 2007. "Europe needs to act now, together, to deliver sustainable, secure and competitive energy. The inter-related challenges of climate change, security of energy

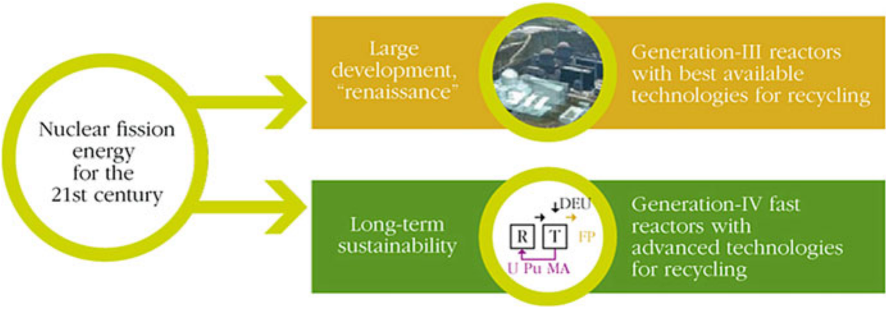

Fig. 5.1 Two main roads for nuclear of future: improvement of the Gen III (Sect. 5.3) and development of the new Gen IV technologies (Sect. 5.4)

supply and competitiveness are multifaceted and require a coordinated response … [We] need a dedicated policy to accelerate the development and deployment of cost-effective low carbon technologies."

Nuclear fission is cited together with other low carbon technologies, such as renewables and carbon capture and storage (CCS) technology, as one of the contributors to meet the 2020 challenges. By maintaining "competitiveness in fission technologies, together with long- term waste management solutions," fission energy will continue to lead low carbon energy technology in Europe. Projections published in the WETO (World Energy Technology and Climate Policy Outlook) report (WETO 2003) indicate that by 2030, nuclear energy will continue to produce more than half of the electricity produced by nonfossil fuel-based technologies.

Beyond the 2020 objectives, the SET Plan also identifies fission energy as a contributor to the 2050 objectives of a low carbon energy mix, relying on a new generation of reactors and associated fuel cycles. This objective is to be achieved by acting now to "Complete the preparations for the demonstration of a new generation (Gen IV) of fission reactors for increased sustainability."

From 2040 onwards, it is envisaged that this new generation of fast neutron reactors will be operating in parallel to the advanced Generation III (Gen III) light water reactors (LWRs) now being built in Europe and China, thereby maintaining the current one third share of nuclear electricity in Europe (Fig. 5.1).

5.3 The 2020 Objectives: Maintain the Competitiveness of Nuclear Energy with Long-Term Waste Management Solutions

Maintaining competitiveness should necessarily assure safe, secure, and economical operation of existing and future light water reactors but at the same time, the problems of waste minimization and resource optimization should also be considered as high priorities.

5.3.1 How to Assure Safe, Secure, and Economical Operation of Existing and Future Light Water Reactors (LWRs)?

Given the present share of low carbon electricity produced by nuclear reactors, it is essential that the European energy policy support the long-term operation of current plants, among which, about 75 % are pressurized water reactors (PWR). To achieve this objective, priority actions must be undertaken:

- Enhance knowledge to understand, prevent, and mitigate the effects of ageing.
- Harmonize long-term operation justification methodologies at the European level.

In addition to the operation of existing plants, it is essential to facilitate the construction of new Gen III light water reactors, among which are the European pressurized water reactors (EPR). Design certification should be harmonized so that requirements necessary for licensing should be the same throughout Europe aiming at European harmonized plant design and justification methodology.

Gen III reactors will contribute significantly to Europe's low carbon electricity production. Future units shall benefit from experience feedback from the first ones and from integration of RD&D results addressing:

- Improvement of system, structure, and component design
- Upgraded human–system interface, simplified reactor systems
- Advanced fuel and power performance

The impact of external issues, such as industrial obsolescence, impact of the environment on power generation, or evolution of regulatory requirements are also taken into account.

5.3.2 How to Develop Advanced Fuel Cycles for Waste Minimization and Resource Optimization

Nuclear waste is often perceived by the general public as a problem without a solution. However, the technical feasibility and safety of geological disposal sites are now undeniable, and within a decade the first geological repositories for conditioned high-level nuclear waste are expected to be in operation in the European Union.

However, to increase the sustainability of nuclear energy, more efforts should be dedicated to the development of advanced fuel cycles. This will further improve the competitiveness of nuclear energy, for instance, through use of more efficient cores and fuels for an optimal exploitation of the energy content of uranium fuel (improve uranium and plutonium usage in LWRs).

To minimize the high-level long-lived waste, research on partitioning and transmutation (P&T) must be continued, with the view to separate ("partition") from the spent fuel the *trans*-uranic elements (plutonium and minor actinides) that are responsible for the highest heat loads and radiotoxicity inventory in the long term. The next step is to burn or "transmute" these minor actinides, something that can only be envisaged in fast neutron spectrum systems. We need for this to continue the research on partitioning

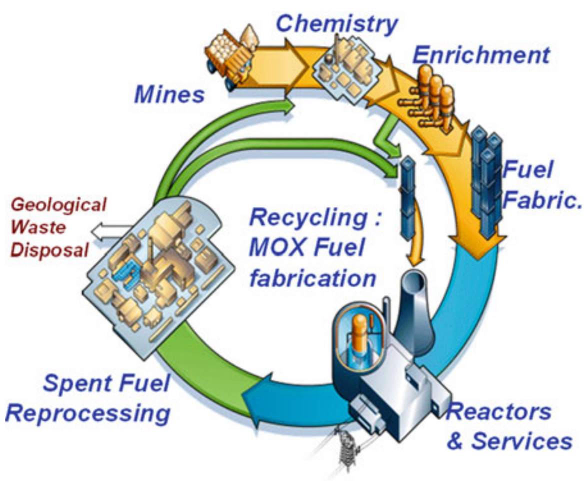

Fig. 5.2 The nuclear fuel cycle

technologies and fast neutron systems (reactors and accelerator-driven systems, ADS) well adapted to transmutation. The objective of this research is to assess the industrial feasibility of the minor actinide reprocessing and burning option (Fig. 5.2).

Generation IV International Forum (GIF 2001)

The GIF, founded in 2001, now has 13 members: Argentina, Brazil, Canada, China, France, Japan, Russia, South Korea, South Africa, Switzerland, United Kingdom, United States, and Euratom.

The goals adopted by the GIF provided the basis for identifying and selecting six nuclear energy systems for further development. The six selected systems employ a variety of reactor, energy conversion, and fuel cycle technologies. Their design may involve thermal or fast neutron spectra, closed or open fuel cycles, and a wide range of reactor sizes from very small to very large. They plan to improve economy and safety, but also the minimization of both fuel consumption and waste production, and finally to enhance the resistance to proliferation. Depending on their respective degrees of technical maturity, the Generation IV systems are expected to become available for commercial introduction in the period between 2020 and 2030 or beyond (CEA Clefs 2007; ADS 2011).

Fast neutron[1] reactors (FNR).

The Gas Fast Reactor (GFR) cooled with helium, has an outlet temperature of 850 °C and can deliver electricity, hydrogen, or process heat with high efficiency.

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[1] *Fast neutrons* are those neutrons generated by nuclear reaction, moving at a very high velocity (~20,000 km/s) corresponding to a kinetic energy of ~2 MeV.

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The sodium fast reactor (SFR) is sodium cooled and is designed for management of high-level wastes and, in particular, management of plutonium and other actinides.

The lead fast reactor (LFR) cooled with lead allows an optimal use of uranium and burning plutonium and minor actinides.

The molten salt fast reactor (MSFR) uses molten salt fluorides both as fluid fuel and coolant (favorable thermal-hydraulic properties, high boiling temperature, optical transparency, online separation of poisoning fission products)

Thermal neutrons[2] reactors.
The very-high temperature reactor (VHTR) is cooled with helium and operates at a high temperature (outlet up to 1,000 °C). It is a high-efficiency system, and can supply electricity and heat to a broad spectrum of high-temperature and energy-intensive processes.

The supercritical water reactor (SCWR) cooled with supercritical water has a thermal efficiency about one third higher than current light water reactors (outlet up to 550 °C).

5.4 The 2050 Vision: Gen IV Fast Neutron Reactors with Closed Fuel Cycle for Increased Sustainability

To address the issue of sustainability of nuclear energy, in particular, the use of natural resources, fast neutron reactors (FNRs) must be developed, inasmuch as they can typically multiply by over a factor of 50 the energy production from a given amount of uranium fuel compared to current reactors. FNRs, just as today's fleet, will be primarily dedicated to the generation of low carbon base-load electricity. Demand for electricity is likely to increase significantly in the future, as current fossil fuel uses are being substituted by processes using electricity. For example, the transport sector is likely to rely increasingly on electricity, whether in the form of fully electric or hybrid vehicles, either using battery power or synthetic hydrocarbon fuels. Here, nuclear power can also contribute, via generation of either electricity or process heat for the production of hydrogen or other fuels.

FNRs have been operated in the past (especially in Europe), but today's safety, operational, and competitiveness standards require the design of a new generation of fast reactors. Important R&D is currently being coordinated at the international level through initiatives such as GIF. Europe, through SNETP, has defined its own strategy and priorities for FNRs: The sodium-cooled fast reactor (SFR) as a proven concept, as

[2] *Thermal neutrons* are also called slow or thermalized neutrons (in equilibrium with the atoms of the matter) and move at a low velocity (#2–3 km/s) corresponding to a kinetic energy of ~1 eV.

well as the lead-cooled fast reactor (LFR) and the gas-cooled fast reactor (GFR) as alternative technologies. The French Commissariat à l'Energie Atomique (CEA) has chosen the development of the SFR and GFR technologies. Other countries including Italy, Belgium, Sweden, and Romania are focusing their R&D efforts on the LFR.

R&D topics for all three FNR designs include:

- Primary system design simplification
- Improved materials
- Innovative heat exchangers and power conversion systems
- Advanced instrumentation, in-service inspection systems
- Enhanced safety

Those for fuel cycle issues pertain to:

- Partitioning and transmutation
- Innovative fuels (including minor actinide-bearing) and core performance

Beyond the R&D, demonstration projects are planned in the frame of the SET Plan ESNII (European Sustainable Nuclear Industrial Initiative, ESNII 2010) for sustainable fission.

These demonstration projects include the SFR prototype ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) whose construction is planned to be finished in France in 2020 and the construction of a demonstrator of an alternative technology—either LFR or GFR—to be decided around 2012. The MYRRHA project proposed in Belgium by SCK·CEN can play the role of an Experimental Technological Pilot Plant (ETPP) for the LFR technology. In addition, supporting research infrastructures, irradiation facilities, experimental loops, and fuel fabrication facilities, will need to be constructed.

Regarding transmutation purposes, the ADS technology must be compared to FNR technology from the point of view of feasibility. It is the objective of the MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) project in Belgium to be an experimental demonstrator of ADS technology. From the economical point of view, the ADS industrial solution should be assessed in terms of its contribution to closing the fuel cycle.

ADS Technology

The concept of an accelerator-driven system combines a particle accelerator (protons) with a subcritical core reactor that produces fission without achieving criticality. Instead of a sustaining chain reaction, a subcritical reactor uses additional neutrons from an outside source that can be a particle accelerator producing neutrons by spallation: a high energy proton (~1 GeV[3]) impinges upon a

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[3] 1 eV is 1 electron volt. Its value is defined as the kinetic energy of an electron accelerated from rest through a potential difference of one volt. So 1 eV = 1.6 10^{-19} J, 1 keV = 10^{3} eV, 1 Mev = 10^{6} eV, 1 Gev = 10^{9} eV.

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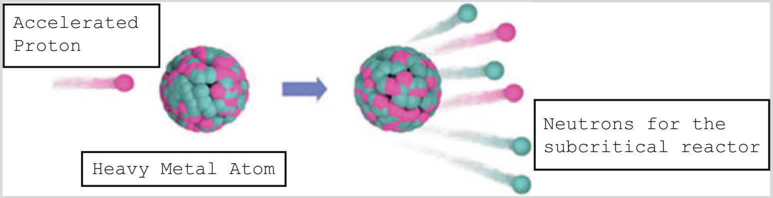

Fig. 5.3 Schematic of the spallation process

heavy metal atom and initiates the spallation process[4] during which neutrons and protons are set free (Fig. 5.3).

The spallation neutron flux can be used to cause a fission process (chain: neutron and energy emission/fission/neutron and energy emission, etc.) of thorium or uranium atoms mixed with minor actinides to be burned, but the chain reaction can be controlled by controlling the beam intensity of incident protons and there is no longer the risk of a runaway or criticality accident. Such a device with a reactor coupled to an accelerator is called an *accelerator-driven system* (ADS), or a hybrid system. It can be used, of course, as a generator to produce energy.

But the neutron flux can also be used for nuclear waste burning (leading to the reduction of the radioactive decay period of the high-level waste): it can thus help to destroy, or "burn," plutonium or waste even more troublesome than the actinides that are currently generated in the power generation reactors.

These properties make hybrid reactors particularly attractive and therefore SNETP in its SRA recommends foreseeing a demonstration program at a reasonable power scale (~100 MWth) that would allow realistic projection towards an industrial scale. Ambitious research programs have been undertaken to validate the principles. A first demonstrator, before a prototype on an industrial scale, could emerge by 2020: the MYRRHA project, supported by the European Community and developed in the laboratory of SCK·CEN at Mol, Belgium

MYRRHA: Multi-purpose hYbrid Research Reactor for High-tech Applications

MYRRHA is a Belgium project developed in Mol (SCK•CEN, StudieCentrum voor Kernenergie – Centre d'Etude de l'énergie Nucléaire), including a flexible fast spectrum research reactor (50–100 MWth) conceived as an accelerator-driven system (ADS) able to operate in subcritical and critical modes. It contains a proton accelerator of 600 MeV, a spallation target, and a multiplying core with MOX fuel, cooled by liquid lead–bismuth (Pb–Bi; Fig. 5.4).

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[4] *Spallation* is a process in which fragments of material (spall) are ejected from a body due to impact or stress. In the present case, a high-energy proton coming from an accelerator impinges on a heavy metal atom (the spallation target: lead, bismuth, etc.), producing in particular a flux of neutrons.

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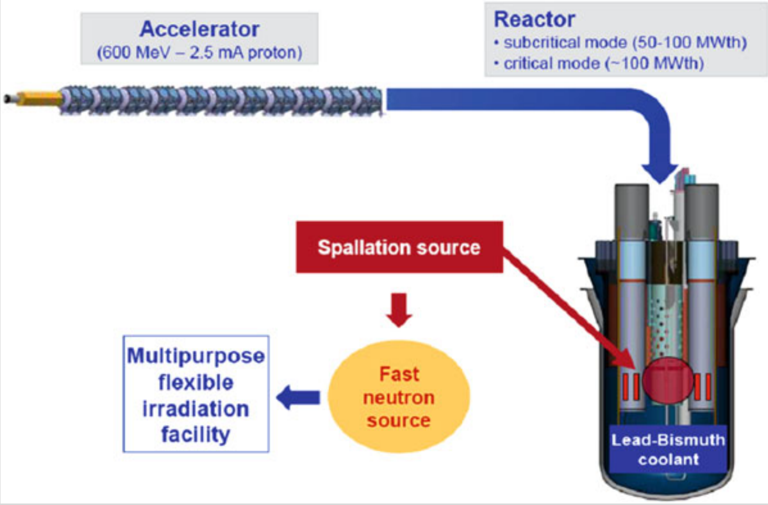

Fig. 5.4 The principle of MYRRHA (Aït Abderrahim 2011)

5.5 High-Temperature Heat Processes, Developing Other Applications of Nuclear Energy

Increasingly, fossil fuel-based industrial processes will be substituted by processes that use low carbon energy supplies. These processes typically require large and continuous amounts of energy in the form of heat, electricity, and hydrogen, all of which can be supplied by a nuclear reactor. Examples of such processes include the large-scale production of hydrogen for synthesizing fertilizers, for refining heavy crude oil, for optimizing the production of synthetic hydrocarbon fuels from coal or biomass, or for other industrial processes.

High-temperature gas-cooled reactors have long been identified as the most appropriate supplier of nuclear heat, and a first prototype of such a reactor coupled to the process heat application could be built around 2020. Other types of advanced reactors may also be suitable. The main R&D challenges lie with the technology of the coupling of the reactor to the industrial processes, and with the licensing issues:

- Technology developments: heat exchangers, heat transport systems, adaptation of industrial processes to specific aspects of nuclear heat supply
- Material and fuel improvement for very high temperature and qualification
- Tools and methodologies for licensing of nuclear reactor coupled to industrial process
- Management of waste (especially graphite)

5.6 A Need for Research Infrastructures and Competences

In order to carry successfully out the above R&D programs and demonstration projects, the nuclear sector must address the need to reinforce and further develop its competence pool, manage existing knowledge, and organize a network of research infrastructure.

5.6.1 Basic Research Needs for Cross-Cutting Topics

- *Material research*
  Material research is one of the most important topics for energy research, in particular for nuclear fission, where ageing, performance, and safety issues all need to be addressed. New materials as well as fabrication and welding processes need to be developed to achieve higher performance levels and longer lifetimes, as well as to withstand more extreme conditions such as higher temperatures (beyond 500 °C) and higher irradiation exposure (up to 100 dpa). Challenges remain in the area of multiscale modeling of material behavior under irradiation, which together with irradiation experiments will be the key techniques in the development of new materials.
- *Prenormative research*
  For the development of European codes and standards to be used for the future construction of Gen IV reactors, prenormative research must also be performed. R&D performed under quality assurance will contribute to this objective.
- *Modeling, simulation, and methods*
  The development of more advanced physical models and computational approaches benefiting from the increase of computational power allows for very detailed simulation of reactor behavior over a range of scenarios from normal to accident conditions and provide best estimate safety evaluations.
  A further area of application of best estimate methods with statistical analysis is the mechanical analysis of components. To exploit fully the potential of these tools, new basic data and specific separate and integral effect validation experiments using advanced measurement techniques will be required (Fig. 5.5).

5.6.2 Fuel Research

Basic research is needed to develop and improve modeling tools for innovative fuels (including minor actinide-bearing fuels) for Gen IV reactors. This research aims at establishing fuel properties and behavior under representative nominal operating, incidental, and accidental conditions, as well as addressing fabrication processes. Experimental programs aiming at qualifying the fuel must also be carried out.

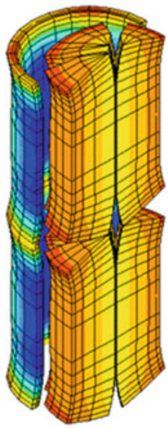

Fig. 5.5 Advanced modeling and simulation methods. This can be achieved by coupling neutronics, thermal-hydraulics, and fuel performance codes, at various physical and time scales. Particular efforts shall be directed at the development of CFD (computational fluid dynamics) methods for reactor design and safety analysis, and at the development of uncertainty and sensitivity analyses

5.6.3 Nuclear Safety

Nuclear reactor research in Europe has always had a strong focus on safety, and this will continue so as to ensure that European reactors continue to operate at the highest level of safety. In addition to further research to increase knowledge in the basic nuclear sciences, research on human and organizational factors and plant-relevant issues such as instrumentation and control (I&C) and electrical equipment, or external hazards, will be addressed. Research must also be carried out specifically to:

- Support long-term operation of nuclear power plants.
- Contribute to the design of intrinsically safe Gen IV FNRs.

5.6.4 Building a European Research Area of Nuclear R&D Infrastructures

Fission research has always relied on experimental programs for validating models, qualifying materials, and, more generally, for developing knowledge. Because the cost of maintaining research infrastructures is high, and following a more integrated approach to carrying out research programs, a network of complementary facilities must be established in support of the Strategic Research Agenda. Some facilities will need to be upgraded to support the R&D programs. New facilities will also need to be constructed to replace old ones.

Let us mention, among the new facilities:

- *Very large scale nuclear research infrastructures*
  They provide irradiation capabilities that are essential for material and fuel development, and safety experiments. Three major facilities are being planned in Europe, the Jules Horowitz Material Testing Reactor (whose construction started in Cadarache, France, in March 2007), the MYRRHA fast spectrum irradiation facility (planned in Mol with a 40 % support from the Belgian government with a provisional date for start of construction in 2015), and the Pallas reactor that will replace the JRC (EU's Joint Research Centre) High Flux Reactor of Petten as Europe's leading provider of radioisotopes (RI) for medical applications and a back-up material test reactor. In addition to these facilities, the fast spectrum Gen IV demonstrators will also provide supplementary experimental irradiation and minor actinide transmutation capabilities.
- *Fuel cycle facilities*
  Gen IV demonstration reactors and associated irradiation facilities also call for the construction of pilot manufacturing facilities for their driver (MOX fuel) and experimental fuels (minor actinides bearing fuels).

5.6.5 Education and Training

Education and training of young researchers and engineers is necessary to maintain existing knowledge and to carry out the research and development programs described above. SNE-TP has set up a specific Working Group dedicated to education, training, and knowledge management (ETKM 2010) issues with essential support in this area being provided by the European Nuclear Education Network (ENEN) Association, through its activities in FP6 (ENEN-II) and FP7 (ENEN-III) programs. This trained workforce will in part also provide qualified staff to Europe's nuclear industrial sector to accompany the development of the sector in the next decades, although this need will primarily be addressed by specific industry-led initiatives discussed in the European Nuclear Energy Forum (ENEF). More detailed information on ETKM activities can be found on the platform's website.

5.7 The Implications of the Fukushima Accident for SNETP

The accident that occurred at the Fukushima Dai-Ichi nuclear power plant on March 11, 2011, has raised public concern on nuclear energy and drawn new attention to the safety of nuclear power plants, in particular in the case of extremely severe external hazards.

A number of initiatives have been undertaken in many countries and at an international level in order to take into account the very first lessons learned from this accident for the improvement of nuclear reactor design and for the organization to manage an accidental situation. SNETP decided to empower a Task Group to investigate how the first lessons learned from the Fukushima accident could affect safety-related R&D orientations and priorities. The Task Group has concentrated on the developments, updating and validating of methods and tools for areas that are not considered well-enough understood. The report (IFA 2011) issued by the Task Group gives high-level orientations on the main challenges revealed by the accident, on the identification of relevant research areas, and finally provides a vision on post-Fukushima nuclear energy.

5.7.1 What Are the Main Challenges Revealed by the Fukushima Accident?

The Fukushima accident was triggered by the combination of two main initiating events:

- An exceptional magnitude earthquake which caused the sudden total loss of almost all the off-site power supply
- The associated tsunami caused flooding of the site under a wave of about twice the size considered previously in the evaluation of risk. It led to both the loss of all emergency power supply systems and of the cold sink.

The immediate challenge for the emergency response team was to recover cooling capabilities, in a situation where the off-site power supply has required about 11 days to be effective.

More generally, the challenges identified from the first lessons learned from the accident are the following.

- To extend even more in depth the safety approach to any type of initiating event, especially severe natural hazards and any combination of them. It shall be done to current reactors, Gen III reactors, and the development of GEN IV reactors.
- To include more systematically, at the design stage, the beyond-design basis accidents to ensure robustness of the defense in depth and to avoid cliff-edge effects. The approach shall include situations where all units on the same site are affected by a beyond-design event.
- To develop wider and more robust lines of defense with respect to the design basis aggressions and beyond-design basis events to define additional measures to consider in the design.

A specific emphasis has to be put on emergency management which has been very challenged during the accident due to:

- The concomitance of many events, the severe environmental conditions, and the mutual interaction between the affected units on site
- The complexity and the difficulty of the decision-making process which has altered the effectiveness and the promptness of the actions and has generated both confusion and delay.
- The practical impossibility to recover a suitable and stable electrical supply source during several days

The improvement of the emergency preparedness and response shall include the consideration of several items:

- The availability of more sophisticated tools to provide to the operators more reliable and quick indications/measurements on the reactor status to help in the implementation of an appropriate recovery strategy
- The availability of redundant intervention means in the vicinity of the site
- Better international cooperation/expertise which could provide help on the plant status diagnostic for the situation evolution and on the mitigation strategy

A careful investigation of the Fukushima accident outcomes will generate a new scale of priorities with a specific focus on extreme external events and their combinations, on common mode failure and human behavior, and with the assessment of their impact on the robustness of the defense in depth.

5.7.2 Identification of Relevant Research Areas

The Fukushima event especially reveals the importance of enhancing the analysis of human and organizational factors under high stress and harmful conditions in order to identify operational ways to improve emergency preparedness and the response to a severe nuclear accident.

Following a review of the available information on the Fukushima accident, nine main areas of research have been identified focused on siting, design, and operation of nuclear power plants:

- Systematic assessment of vulnerability in the defense in depth
- Advanced method for the assessment of external hazards
- Probabilistic safety assessment (PSA) application to external hazards
- Advanced method for the analysis of severe accidents
- Enhanced methods for accident management
- Improved modeling of fuel degradation in the spent fuel pool
- Radiological impact of serious reactor accident
- Advanced safety systems
- Advanced materials for nuclear reactors

Special attention shall be paid as to how the research outcomes will be implemented and so transferred into normal industrial practice.

5.7.3 A Vision of Post-Fukushima Nuclear Energy

Despite the Fukushima accident, nuclear energy remains an important component for today and for the future. But it is the prime responsibility of the nuclear energy stakeholders—and SNETP is an appropriate forum—to take benefit from all the lessons learned from the accident.

Research and development are essential tools for a better understanding of the phenomena and thus to enhance the prevention and the mitigation of severe accidents. No really new phenomena were revealed from the Fukushima accident and the basic orientations of the Strategic Research Agenda are still valid. However, the specific research areas, as identified above, shall be considered with the appropriate priority in the update of the SRA to be developed by the end of 2012. In particular, the issues related to extreme severe and rare accidents shall be considered in a more global approach to safety in order to better understand the design margins and the behavior of nuclear reactors under beyond-design scenarios.

With the perspective of the worldwide development of nuclear energy, the implementation of Generation III reactors should be accelerated and, with a longer perspective, the development of Generation IV reactors remains an important goal keeping a high safety level as an uppermost priority.

5.8 Conclusion

Let us start with a very simple exercise: the current global energy consumption is about 500 EJ[5] annually, which is equivalent to an instantaneous yearly average consumption of 16 TW. Projected population and economic growth will more than double this global energy consumption by the mid-twenty-first century, asking probably for a prospective new resource of more than 15 TW. This would require, for instance, the construction of a new 1 GW nuclear fission plant somewhere in the world every day for the next 40 years (BESW 2005). This is, of course, unrealistic, but it is just helpful to give an idea of our energy challenge! Yet, when faced with the problem of CO_2 mitigation, combined with the diminishing resources of fossil fuels, and with a slow development of renewable energy now, nuclear power cannot be swept aside with the back of a hand. To enlighten the reader, we have first emphasized the role of nuclear fission in Europe's low carbon energy policy, and its place in the future Europe's energy mix.

Nuclear electricity is already providing 31 % of the EU's electricity, representing a nonemission of 900 million tons CO_2 per year. Projections indicate that by 2030, nuclear energy will continue to produce more than half of the electricity produced by nonfossil fuel-based technologies. Beyond the 2020 objectives, the SET Plan also identifies fission energy as a contributor to the 2050 objectives of a low carbon energy mix, relying on a new generation of reactors and associated fuel cycles.

The 2020 objectives are oriented towards maintaining competitiveness that should necessarily assure safe, secure, and economic operation of existing and future light water reactors (Gen III). But at the same time, the problems of waste minimization and resource optimization will also be considered as high priorities.

[5] 1 EJ = 1 ExaJoule = 10^{18} J.

The 2050 vision considers the Gen IV fast neutron reactors with closed fuel cycle for increased sustainability. Fast neutron reactors must be developed, because they can typically multiply by over a factor of 50 the energy production from a given amount of uranium fuel compared to current reactors. This is particularly compatible with the transport demand for electricity which is likely to increase significantly in this future (fully electric or hybrid vehicles, either using battery power or synthetic hydrocarbon fuels) and nuclear power can also contribute, via the generation of electricity or of the accompanying heat, to the production of hydrogen or other fuels.

Despite the Fukushima accident, the nuclear energy remains an important component for today and for the future European energy mix and also a very significant contribution to fulfill the worldwide energy needs. But it is the prime responsibility of the nuclear energy stakeholders—and SNETP is an appropriate forum—to take benefit from all the lessons learned from the Fukushima accident.

In a more general sense, and it has been reinforced by the recent events in Fukushima, there is a permanent need for increased research, education, and training in nuclear R&D, with a strong cooperation between European and world experts.

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