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Michelangelo Network

Competitiveness and sustainability of nuclear energy in the European Union

(MICANET)

A European vision for nuclear energy and main lines of recommended R&D support

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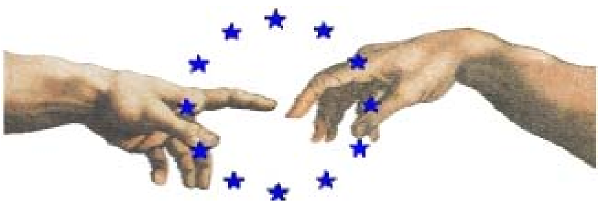

Abstract

The need to establish a long-term sustainable and cost-effective energy system in Europe leads us to the conclusion that nuclear energy will play an important role in the future, the trend being to increase its contribution to the electricity generation mix and with a high potential to participate in the promotion of other energy vectors, such as hydrogen, in Europe. A consistent and increased effort on innovative nuclear systems is of particular importance: to address societal issues relating to nuclear power, including economic competitiveness, safety, sustainability, proliferation resistance, and radioactive waste management; to maintain and advance nuclear skills at the highest possible level in order to ensure the efficient and safe operation of existing facilities; and to provide a favourable environment for the development of the nuclear industry's next generation of skilled personnel.

Related R&D efforts are highly beneficial to Europe's high-tech industry and will help preserve common understanding of nuclear issues among European countries. They will keep the nuclear option open in Europe as a means of alleviating fossil fuel dependence and securing the supply of low-cost energy.

Taking into account the potential of different systems to meet the main goals, the Michelangelo Network proposes that the development of gas technology be made a high priority, first with the thermal-spectra very-high-temperature reactor, which is selected not only for electricity generation but also for its potential use in alternative applications. For the longer term, fast reactors – with their fast-neutron spectrum – appear to be a good way to save resources and solve waste management issues. The gas-cooled fast reactor is on the same technological path as gas-cooled reactors; the sodium-cooled fast reactor has reached technological maturity; the supercritical water-cooled reactor represents the evolution of water-cooled reactors; the technology of lead-cooled fast reactors is of particular interest for transmutation; while only exploratory research and survey strategies are suggested for non-conventional systems such as the molten salt reactor.

The transition from the present nuclear fleet status to the deployment of fourth-generation systems is addressed. Innovative fuels and fuel-cycle processes for light-water reactors and high-temperature reactors are recognised as an important subject for European R&D in the short and medium term to alleviate the waste issue. The partitioning and transmutation technologies for current or future light-water reactor (LWR) wastes remain an option for minimising the waste burden and should remain fully consistent with the deployment of fast-spectra systems. R&D on this topic, widened to the fuels of fourth-generation systems, would be useful to validate the solutions proposed for waste management.

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1 The need to keep the nuclear option open

Over the next 50 years, world energy demand is expected to increase rapidly: Global energy use will at least double, electricity demand is projected to grow even faster, and new energy carriers may enter the market (e.g. hydrogen). Studies have been conducted by several organisations to assess a variety of strategies for using energy resources to face this growing energy demand.

New abundant and economically viable energy sources (thermonuclear fusion, advanced solar technologies) will not be available within this timescale. A projected increase in fossil-fuel consumption is largely responsible for the expected fast-paced growth in global carbon-dioxide emissions.

Preservation measures and renewable sources can play a significant but largely insufficient role in satisfying world energy demand, meaning that no energy-supply technology currently in existence or development, including nuclear technology, can be abandoned without risking a severe impact on society, the economy, and the environment.

With the rising concern over global warming and the scarcity of natural resources, nuclear energy has been recognised as being an important domain, with very stringent safety requirements that result in effective environmental protection. It should therefore be expected to play an important role in meeting increasing world energy demand in different market sectors, with particular focus on cost-effectiveness and supply independence, and in meeting international commitments on the greenhouse effect.

2 Nuclear energy in the world and in Europe

2.1 Current status

Nuclear power plants operating worldwide supply around 16 % of generated electricity and around one third in the European Union. Nuclear power is recognised as a mature industrial technology, with very high safety standards and remarkable availability. However, in spite of the excellent operating feedback from existing commercial nuclear power plants (except the specific situation of RBMK plants) and fuel-cycle facilities, development has slowed down in most of the world and public opinion is divided about the extended use of nuclear energy.

Japan and Korea remain very active in the nuclear field, and developing countries “hungry” for energy and with intensive economic development such as China and India have ambitious nuclear deployment programmes. Canada and the USA operate a large fleet of nuclear power plants but there has been no growth in nuclear capacity for more than a decade.

There is a considerable amount of nuclear know-how in many European countries, but despite the significant overall involvement of Europe in nuclear power generation and nuclear technology, the present energy policies of individual countries vary considerably with regard to the future use of nuclear energy. A few are keeping their nuclear programme alive and have already chosen nuclear as the most adequate option to cover the country’s increased electricity needs and reduce dependency on imports. For instance, Finland has ordered its fifth nuclear power plant after a long and thorough evaluation process involving all stakeholders.

2.2 Initiatives to restart nuclear programmes

It is generally recognised that new investments in nuclear power facilities will require improvements to be made to currently available technologies to overcome constraints in key – and interrelated – areas, i.e. economic performance, environmental impact, and societal acceptability.

Nuclear energy cannot be developed without the consensus of public and private stakeholders on issues such as economic competitiveness, the safety of nuclear installations, the long-term availability of fuel, waste production and disposal, and the proliferation risk. Therefore many initiatives, either national or international, have been or will be launched to address these issues, both by providing information on the technical solutions that can be adopted to resolve them and by carrying out the R&D actions needed to make these innovative solutions available in future generations of nuclear systems.

Despite the diverse positions that European states presently adopt with regard to the nuclear option for the future, many European countries recognise the need to participate in the development of nuclear energy. The European Commission’s Green Paper *Towards a European strategy for the security of energy supply* recommends research into future types of reactors, to manage used fuel and waste, and to make the nuclear safety standards of new Member States compatible with those of existing states. This attitude has been confirmed by Euratom, which has been an effective member of the Generation IV Forum since September 2003.

In the USA, the Report on National Energy Policy published in 2001 “…recommends (…) to support the expansion of nuclear energy in the United States as a major component of the national energy policy” and a series of R&D initiatives to prepare the future of nuclear energy has been launched, such as the Nuclear Energy Research Initiative (NERI) and the Advanced Fuel Cycle Initiative.

The USA also initiated what is currently the most comprehensive initiative: the Generation IV International Forum (GIF), comprising international government entities. The GIF Charter expresses a profound belief in the nuclear option for the future. The GIF emphasises its willingness to facilitate bilateral and multilateral cooperation in developing the most promising nuclear energy systems, in order to share expertise, resources, and test facilities, thereby gaining efficiency and avoiding duplication.

Many concepts of innovative nuclear systems (reactors and their fuel cycles) have been assessed by large international groups of experts, including European specialists. The goals that steered the selection of generation-IV nuclear systems were sustainability, economics, safety and reliability, proliferation resistance, and physical protection. Further aspects were also taken into consideration for the final selection of the six systems, such as plant size, actinide management capability, and the potential for generating other forms of energy beyond electricity (e.g. process heat, hydrogen production, etc.).

The technology road map describes the R&D required for developing each of the six generation-IV systems selected. Cross-cutting R&D in areas of common interest such as the fuel cycle, fuels and materials, energy products, risk and safety, economics, and proliferation resistance and physical protection is also defined. Organisation of the relevant R&D programmes is currently underway.

The IAEA has initiated an international project on innovative nuclear reactors and fuel cycles (INPRO) aimed at ensuring that nuclear energy is available to help meet the energy needs of the 21st century in a sustainable manner.

3 What kind of nuclear technologies for Europe? The MICANET approach

The approach proposed by MICANET represents the views of several major European organisations involved in nuclear energy regarding how to overcome the obstacles that limit the extended use of nuclear energy and how to enhance the competitiveness of products and services offered by the European nuclear industry. Although similar to those expressed by other initiatives, they are more specifically tailored to the European situation.

Three main steps have been identified:

(1) determine the main goals characterising the breakthrough in terms of economic performance, environmental impact, and societal acceptability that can be expected of innovative nuclear technology and which are, in principle, likely to obtain the consensus of the stakeholders

(2) select those systems that are expected to achieve these goals, taking into account the experience already existing in Europe as well as the technology gaps to be closed in order to demonstrate the feasibility of the proposed innovative solutions

(3) establish the R&D programme for dealing with the technology issues and to identify the necessary structural support; this programme is expected to develop over 20 or 30 years, but intermediate milestones will make it possible to assess whether the final results can be achieved.

The MICANET criteria have been kept very consistent with those established during the generation-IV exercise, whilst ensuring that the criteria fully reflect a European perspective.

In order to determine what kind of nuclear technologies seem appropriate for Europe, the following criteria were addressed in the selection process.

3.1 Economic competitiveness

Nuclear fission is already one of the cheapest electricity sources in some EU Member States, and its low fuel-cycle costs keeps the energy quite unaffected by fluctuations on the uranium market, thus guaranteeing true independence of supply and stability against fossil fuel price escalations.

However, current nuclear technology is objectively complex, and building a nuclear power plant requires high initial investments (EUR 1500-2000 per kW_e) and relatively long construction times. Consequently, nuclear energy must be developed according to a relevant strategy to maintain and moreover to continuously improve its economic attractiveness with regard to the other energy sources.

The nuclear industry is now looking for new design solutions to reduce investment costs and construction time. In parallel, plant owners are expecting a licensing process with few, clearly identified steps for granting the final start-of-operation permit to a new plant within a proper time schedule.

New markets may open up for nuclear energy in the area of transport fuel (hydrogen) production and process-heat demands. Competitiveness within these markets is likely to be enhanced with the increasing cost of fossil energy and levies on CO_2-emitting techniques (CO_2 taxes) or compared to other still more expensive CO_2-free alternatives.

3.2 Saving resources and managing waste

Saving resources and managing waste are key issues for ensuring sustainable development. Current thermal neutron-spectrum reactors (LWRs, AGRs) are able to burn only a small fraction of the mined uranium and only a small fraction of the plutonium produced can be recycled in light-water reactors (LWRs) as MOX fuel. Other strategies, e.g. symbioses between LWRs and high-temperature reactors (HTRs) allowing for high burn-up, are being examined. Fast-neutron spectra, through the conversion of fertile to fissile isotopes, makes it possible to burn almost all the fuel, thereby greatly increasing the amount of available resources. Thorium is also available in vast amounts and may be burnt efficiently, even in a thermal spectrum.

The underground repository in geologically stable soil structures and with specifically designed containers has been adopted as the most appropriate solution for disposing of waste and/or used fuels by many countries owning nuclear plants. To reduce the amount of waste, recycling plutonium in advanced fuel for LWRs (e.g. inert matrix fuels, Pu/Th-MOX) can help to improve Pu-burning capabilities and increase leach resistance in final repository conditions. However, using fast-neutron spectra on critical or hybrid systems may make it possible to achieve a closed fuel cycle by transmutation of the most toxic radioactive waste. The size and the constraints for the design of final repositories will be strongly affected by the chosen partitioning and transmutation strategy, as well as a conditioning approach that provides reliable radiotoxicity retention from the biosphere.

3.3 Safety and reliability

The generation-III reactors currently available already incorporate many features to avoid the propagation of severe-accident consequences outside the physical boundaries of the plant and to exclude the need for a stringent emergency plan.

With the need to improve the sustainability of power generation, the future potential of next-generation reactor developments hinge on the development of relevant innovative safety approaches that strengthen the principles of defence in depth, to prevent and further limit the consequences of accidents, taking into account the specific reactor characteristics.

R&D programmes may help to identify and assess design solutions with high levels of reliability and operating safety, incorporating inherent and passive safety characteristics as well as prevention, protection, and mitigation systems.

3.4 Proliferation resistance and physical protection

The development of new nuclear systems must allow for measures to limit the proliferation risk. Intrinsic and extrinsic features are designed to address these concerns, e.g. introducing new fuels and new fuel cycles that discourage the diversion of fissile material for military use.

Physical protection issues are also addressed through the implementation of inherent and extrinsic features that impede malevolent hazards.

4 Recommended European strategy for nuclear R&D

Nuclear energy systems aim to satisfy the energy needs of people and countries in a sustainable manner. They must be competitive, safe and reliable, and must ensure a high level of protection with regard to proliferation and physical aggression. Otherwise they are not deployable. Current operating systems meet these targets; future systems will have to do at least as well, but in addition, these new systems will aim to:

- expand the amount of available resources through efficient conversion from fertile to fissile materials,
- control nuclear waste issues,
- expand the use of nuclear energy (hydrogen production, combined heat and power (CHP) generation, process-heat applications), thus helping to further reduce CO_2 emissions.

Different stakeholders can give their own relative weights to these goals and criteria, which are expected to vary with time. The appeal of a system may thus change between now and the end of the century.

- Economy and safety will remain a high priority because without cheap energy output and safe production systems, nuclear energy will not be considered.
- Managing the back-end of the nuclear fuel cycle is an ongoing target and will remain so as the waste issue may hinder the future development of nuclear power; but different options are still open for individual national policies.
- The CO_2 issue may gradually increase in importance, due to commitments to cut emissions; this may lead to the deployment of a cost-competitive hydrogen industry.
- The need to rely on fertile materials will increase when it becomes apparent that inexpensive uranium resources are almost exhausted.

The nuclear systems will have to address all of the above topics. This can lead to simultaneously deploying:

- reactors with a high temperature output that offer high efficiency and versatility in the use of the energy produced,
- reactors with cores that allow sustainability targets to be reached: breeding capability to make the best use of natural uranium, waste minimisation, closed fuel cycle allowing the plutonium produced by the current fleet of reactors to be burned, and, if needed, the ability to recycle minor actinides. The fast-neutron-spectrum option is preferred but it might be challenged by the use of thorium in a thermal neutron core.

The transition between the current reactor fleet, the systems to be built, and those selected for the long term must be planned and optimised, allowing for changes in the relative weighting of the different requirements to be fulfilled and taking into account the fact that the technologies for such reactor systems are not currently available. The degree of consistency between reactors of different generations and/or technologies must also be addressed.

When identifying the potential best choices for the future, one has to consider the available expertise, the size of the technology gap to be filled, and the possibility of meeting set goals through a step-by-step approach in line with changes in their weighting by different stakeholders.

Furthermore, it will be necessary to attract young specialists to the nuclear field and to safeguard the accumulated expertise in nuclear fission energy (including experience in decommissioning) in the EU to ensure the ability to develop reactor concepts and implement strategies for the back-end of the fuel cycle.

4.1 The nuclear energy system envisioned for the long term

The fourth-generation systems considered to be best suited to meet European criteria are described below. It should be kept in mind that several types of systems might be needed for the future deployment of nuclear energy, because different needs have to be addressed. Different missions cannot be carried out by a single system but by different types of systems coupled in a symbiotic way.

In the following, the different systems are described briefly in decreasing order of anticipated and recommended R&D effort at European level.

Gas-cooled reactor systems

The high-temperature reactor (HTR) uses particle fuel able to withstand high temperatures, allowing for very high burn-up and graphite as a moderator. Helium is used as a coolant, allowing an output temperature of more than 850 °C. European industry has been involved in gas reactor technology since its early days, and a considerable part of HTR technology relies on past European experience. The HTR has a high potential for improving competitiveness and safety. It could be built in modular units and be deployable in the medium term for heat, hydrogen, and power applications.

The very-high-temperature reactor (VHTR), with an output temperature of about 1000 °C, offers additional efficiency benefits when the reactor is used for hydrogen production and other heat applications. However, the technical challenges, especially those associated with fuel behaviour and material issues, are far greater than for the HTR. For both, the specific waste issues relating to the treatment and reuse or disposal of large quantities of contaminated graphite have to be resolved. The development of hydrogen production still needs considerable R&D efforts.

The gas-cooled fast reactor (GFR) should, in the longer term, make it possible to address sustainability targets through breeding capability and the minimisation of long-lived radioactive wastes, while preserving the main capability of the HTR/VHTR with regard to high efficiency and hydrogen production.

A significant part of the technology challenges, mostly in the scope of the primary systems and balance of plant, are shared by the HTR/VHTR and the GFR. However, some main features are fully specific and there are still some major unresolved key issues such as fuel and core design, reactor safety and fuel reprocessing technology.

These gas technologies (HTR, VHTR and GFR) are being given top priority, and a phased development path may be drawn from the thermal to the fast-spectrum gas-cooled systems.

Supercritical water-cooled reactor (SCWR) concept

As long as the main criteria are economy and safety, the light water reactors currently available (i.e. generation-III reactors) are well suited. This technology is expected to evolve in order to achieve both a significant increase in thermal efficiency and a major reduction in investment cost with the development of the high-performance light-water reactor (HPLWR), also referred to as the supercritical light-water reactor (SCLWR). This is an evolutionary concept based on many existing technologies used in LWRs for the nuclear island and in supercritical fossil-fired plants for the conventional island. The important HPLWR technology gaps are to be found in the areas of materials and structures, safety, and plant design.

The ultimate step in the progress made with HPLWRs would be the development of fast-neutron cores with a tight fuel lattice enabling a high conversion ratio and a fair sustainability ranking, but the viability of this option is yet unknown.

It is proposed that R&D actions be focused on the key technologies and feasibility issues. This will also help to maintain the necessary European expertise in both nuclear and fossil power plant technologies.

Sodium-cooled fast reactor (SFR) systems

These are technologically the most highly developed of the generation-IV systems. However, existing designs do not offer cost-competitive energy generation. The fast spectrum core may provide a high conversion factor, thereby increasing the use of fuel resources, and efficient transuranic consumption, leading to a reduced actinide load in high-level waste. Some technology gaps remain in the areas of severe accident management, capital cost reduction (the chemical reactivity of sodium has a significant impact on the cost of the systems) and in-service inspection and repairs (ISIR).

Considering the experience already available in Europe, the main objective of the European strategy is to maintain its expertise of this technology and to enhance previous expertise in the next generation of SFRs through international cooperation.

Lead-cooled fast reactor (LFR) systems

These share numerous design features with SFR systems; they should be capable of converting fertile uranium and reducing the actinide inventory; and they present similar unresolved technology issues on ISIR and less experience is available. They are not affected by chemical-reactivity issues but they do need materials capable of withstanding the corrosive molten-lead environment. As regards competitiveness, the envisaged elimination of the secondary system would compensate for the larger mass of the primary coolant.

The important LFR technology gaps are in the areas of system fuels and materials, system design, balance of plant, and fuel-cycle technology. These are addressed in ADS programmes.

Molten salt reactor (MSR) systems

This concept is particularly well suited to the use of thorium. It could offer a high level of breeding performance using a thermal neutron spectrum core, allowing it to operate with a small fissile core inventory and thus scoring highly in both sustainability and safety. The economics are difficult to anticipate because of the large number of sub-systems for fuel and coolant maintenance and because the entire fuel-cycle technology must be changed.

The MSR has a number of technical viability issues that need to be resolved, such as molten salt chemistry and structural material behaviour, tritium control technology, and graphite technology.

4.2 The transition phase

Major uncertainties exist as to when the systems of the fourth generation will be available for deployment and when such a deployment will be needed. This is why the strategy for the transition phase remains generic, in an attempt to cover the plausible requirements in a broad and flexible manner.

Consideration has to be given to existing light-water reactors and their evolutionary successors. The majority of the nuclear power plants currently operating in Europe will remain in operation for the next two decades at least and relevant skills will need to be maintained for their safe and efficient operation and for related fuel-cycle/waste issues.

To cover the plausible future of nuclear energy in Europe, scenarios maintaining the nuclear option available to all European countries must be considered, thus allowing every country the freedom to change its national policy at will.

This goal is achievable through the generation-III reactors already commercially available. If deployed in just a few countries, these would keep the relevant technology alive and potentially available for all, and may remain in operation far into the second half of this century. For such a long period, research programmes on system and component technology and material improvement, ageing, improved fuels and fuel-cycle processes are essential for enhancing competitiveness and robustness performance.

For both present and future LWRs, a co-operative R&D effort should focus on advanced fuel cycles for reducing plutonium stockpiles and on research into final disposal, for instance leach-resistant fuel/waste matrices, in order to qualify the strategy based on waste management in geological repositories. Some countries are exploring waste-minimisation strategies through advanced systems offering areas of synergy with fourth-generation systems, thus anticipating R&D advances in the latter.

As regards sustainable development, plutonium must be recycled to gain valuable material and to reduce the long-term radiotoxicity of the waste. The physical characteristics of systems with fast neutrons also give them a certain flexibility for subsequently recycling plutonium and minor actinides, keeping in mind that the deployment of fast-neutron spectrum reactors will require sufficient plutonium resources.

With regard to hydrogen generation, nuclear energy may also be used on today's large and expanding hydrogen market (e.g. refineries, petrochemicals and ammonia). This could offer firm support as hydrogen-based technologies are introduced during the transition to a broader hydrogen economy.

5 Implementation of the recommended strategy

Europe has precious assets such as unique research facilities and unique expertise in specific nuclear technologies (e.g. gas-cooled reactor technology, reprocessing, recycling, nuclear process heat applications, etc.), which must be preserved and further developed for the benefit of future generations.

The right balance should be found between the research activities intended for the transition phase, with possible short- or medium-term industrial applications, and developments needed for the long-term systems envisioned for industrial applications.

Within this balance it should be considered that some of the innovative systems could be deployed relatively earlier than others. For those envisioned for early industrial deployment, the research shall focus on design and licensing technologies. For longer-term systems and/or uncertain applications, R&D should focus on the key feasibility issues; the application options should not be decided too early. There is a need to focus R&D support on addressing certain topics effectively. It is not necessary to support every programme if there is a lack of resources.

Significant R&D programmes, design efforts, and training programmes on the gas-cooled reactor system will be useful for addressing HTR, VHTR and GFR issues. Involvement in the construction of a demonstrator model will also help to establish a durable European R&D and industrial infrastructure in these fields. This is consistent with the EU’s overall policy on sustainable development and complements its ambitious strategy on hydrogen and fuel cells.

Used-fuel reprocessing is a key technology for the long-term sustainability of nuclear power. Incentives exist to make further improvements in current technology to decrease costs, reduce waste, and increase proliferation resistance. These are being explored in the thematic area “partitioning and transmutation”.

European R&D on nuclear fission must focus not only on health and environmental issues, but also on competitiveness issues, which are a prerequisite for maintaining the nuclear option and expanding its market sectors beyond electricity generation. It should therefore re-balance nuclear R&D effort by considering both the development of technologies for future competitive nuclear energy sources and waste issues and by harnessing any possible synergies.

An active European R&D policy will encourage young scientists to study nuclear engineering and safeguard the expertise in nuclear fission energy in the EU. Existing and planned instruments to maintain nuclear know-how and expertise in Europe, including education and training and heavy R&D infrastructures, should be maintained. In particular, the educational framework (ENEN, Marie Curie fellowships) should be strengthened.

A broadly based co-operation among industry and research institutions is seen as an efficient way to drive the development of nuclear systems for the mid and long term, in addition to helping investigation into specific R&D topics and sub-systems. It is therefore recommended to set up the right resources to deal with the long-term commitments of the whole of R&D projects, networks, and heavy R&D infrastructure in Europe on scientific issues and key technologies needed for both transition-phase challenges and future nuclear energy systems. This would also help to take advantage of similar international initiatives (generation IV and others) to strengthen co-operation.

5.1 Costs and funding

Overall R&D efforts on nuclear fission should be increased to a level in proportion to the issue: more than 900 TWh of nuclear electricity is generated in the EU per year, for a value greater than EUR 7 billion.

The cost of R&D for a new energy system is in the range of USD 1 trillion, an evaluation not seen as particularly excessive seen in light of the GIF road map. A technology demonstrator reactor and at least one pilot plant are also likely to be built (for perhaps USD 1 trillion) before any commercial deployment of the system may start. At least 20-25 years and considerable resources will be needed between the development launch of a new system and the time when this is ready for deployment.

The development time span and cost of new systems are too large to be fully supported by industry. This is why public-sponsored R&D programmes are needed, as is the case for other energy sources. The involvement of public money in this field is also practised outside Europe. This is justified, as the global economy benefits from the return on investment from locally-produced and cost-competitive energy.

Increased collaboration on research programmes around the world, such as those undertaken within the framework of the GIF, makes it possible to share efforts between European and non-European entities. European contributions to these actions and internal R&D programmes must be at a level that enables Europe to stay as one of a major player in the field.

European involvement in nuclear energy research includes both programmes individually financed by national (either public or private) sources and programmes fully or partly supported by the European Union. At present, European funding is well below par, thereby impeding Europe’s ability to be a global driving force behind R&D programmes today, and a leader tomorrow. A better balance between national and European efforts, with a significant increase of the EC’s contribution, is therefore expected.

In other countries, for example the USA, public funding has already been ploughed into the industry to support short/medium-term actions such as the restart of a LWR erection programme, thus promoting a positive attitude with regard to nuclear energy and a good incentive to deploy nuclear systems. Programmes addressing the short-term deployment of evolutionary systems must be considered as important goals, before ambitious projects can go ahead to deploy more advanced and innovative systems.