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The Sustainable Nuclear Energy Technology Platform | A vision report

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Background

Nuclear fission energy can deliver safe, sustainable, competitive and practically carbon-free energy to Europe's citizens and industries. Within the framework of the Strategic Energy Technology Plan (SET Plan)[1], the European Commission's stakeholders in this field have formulated a collective vision of the contributions this energy could make towards Europe's transition to a low-carbon energy mix by 2050, with the aim of integrating and expanding R&D capabilities in order to further this objective. The groundwork has been prepared by the stakeholders listed in Annex II, within the framework of two Euratom FP6 (Sixth Framework Programme) Coordination Actions, namely SNF-TP (Sustainable Nuclear Fission Technology Platform) and PATEROS (Partitioning and Transmutation European Roadmap for Sustainable Nuclear Energy), with contributions from Europe's technical safety organisations.

The high-level reprensentatives listed in Annex I have endorsed this vision report.

Executive summary

This vision report prepares the launch of the European Technology Platform on Sustainable Nuclear Energy (SNE-TP). It proposes a vision for the short-, medium- and long-term development of nuclear fission energy technologies, with the aim of achieving a sustainable production of nuclear energy, a significant progress in economic performance, and a continuous improvement of safety levels as well as resistance to proliferation. In particular, this document proposes roadmaps for the development and deployment of potentially sustainable nuclear technologies, as well as actions to harmonise Europe's training and education, whilst renewing its research infrastructures.

Public acceptance is also an important issue for the development of nuclear energy. Therefore, research in the fields of nuclear installation safety, protection of workers and populations against radiation, management of all types of waste, and governance methodologies with public participation will be promoted.

The proposed roadmaps provide the backbone for a strategic research agenda (SRA) to maintain Europe's leadership in the nuclear energy sector, in both research and industry. By emphasising the key role of nuclear energy within Europe's energy mix, this document also contributes to the European Commission's Strategic Energy Technology Plan, by calling on Europe to mobilise the resources needed to fulfil the vision of sustainable nuclear energy.

Foreword

Technology has a key role to play in solving our energy problems. However, no single option can address all outstanding issues. A broad portfolio of low-carbon energy sources and carriers needs to be investigated and developed as part of a general strategy to confront the growing problems faced not only here in Europe, but by the whole world. Nuclear energy, as the largest single source of carbon-free and base-load electricity in Europe, certainly has a place in this strategy. At the same time, a realistic assessment of its potential cannot ignore the essential question of public acceptance. Long-term sustainability, safety of operation and safe management of waste all influence the general public's perception of nuclear as a viable energy source. This underlines the importance of new nuclear technology that promises vastly improved efficiency in the utilisation of natural resources, cogeneration of electricity and process heat, achieving even higher levels of safety, minimisation of waste and increased resistance to weapons proliferation. These objectives are at the core of the Sustainable Nuclear Energy Technology Platform's shared vision, and its strategic research agenda will enable this vision to be realised.

In its recent energy package, the European Commission has clearly recognised the role played by nuclear energy in limiting greenhouse-gas emissions and in contributing to Europe's security of energy supply. At EU level, this requires those Member States that choose nuclear power to maintain very high standards of safety, waste management, security and non-proliferation, both now and in the future. Priority areas of research of common interest in these areas are clearly identified in the Seventh Euratom Framework Programme, adopted unanimously by the Member States in December last year. This Community research effort is fully consistent with the objectives of the new platform.

To rise to the challenges associated with future carbon-constrained scenarios, a reinforced and increasingly integrated research effort is needed in all energy technologies; this is the basis of the Strategic Energy Technology Plan currently in preparation. The initiative to launch a European technology platform (ETP) in nuclear energy is fully in line with this strategy and is therefore both timely and welcome. It will ensure enhanced coordination between national and industrial programmes while guaranteeing the most effective use of framework programme funding. It also underlines the important research dimension of the nuclear sector, the need to maintain high levels of safety, the importance of retaining competences and know-how and the increasingly competitive nature of this global industry.

I would like to thank the broad range of R&D stakeholders that have come together over recent weeks and months in the preparation of this ETP, its vision report and the launch conference taking place on 21 September 2007. As with other ETPs, success will depend on a strong and bottom-up stakeholder involvement supported through a transparent and inclusive approach to membership of the platform itself. This should also extend to interested civil society organisations wishing to enter into constructive debate.

In conclusion, I would like to wish all present and future stakeholders involved in this new endeavour the greatest possible success and am confident that this initiative will benefit Europe, its industry and its citizens.

Janez Potočnik
Commissioner for Science and Research

Introduction

Current forecasts indicate that the primary energy consumption worldwide by 2050 will probably be doubled in comparison with the year 2000. Energy security is becoming a major global concern. Fossil fuel reserves, particularly for crude oil, are confined to a few areas of the world. Political, economical, and ecological factors often force volatile and high fuel prices. Simultaneously, to combat climate change, a global environmental policy which includes a major reduction in greenhouse-gas emissions is required. Thus, availability of an affordable, secure and sustainable energy is necessary to preserve the living standards of Europe's population. The nature and scale of this challenge has been recognised by the European Union and its Member States.

At its March 2007 summit, the European Council defined an integrated policy for energy and climate, which had three objectives: increased security of supply; competitiveness of European economies and availability of affordable energy; environmental sustainability whilst combating climate change. The Heads of States and Governments committed the European Union to a reduction of greenhouse-gas emissions of at least 20% by 2020 as compared to the level of 1990. The European Council also adopted an action plan, Energy Policy for Europe [2], whose fifth chapter, dedicated to energy technologies, covers nuclear technologies and supports research in order to "further improve nuclear safety and the management of radioactive waste". Additionally, results from a recent European project [3] indicate that "a policy which combines emission control strategies with the present technology policy measures is not projected to be the least cost strategy for the European electricity market" and that "support schemes for renewable energy sources and phasing-out policy for nuclear generation in some European countries induce higher cost without reducing the import dependence of fossil fuel significantly". Nowadays, with its 31% share of electricity production, the nuclear sector represents a 'non-emission' of nearly 900 million tonnes of CO_2 per year in the EU. This represents almost the quantity of carbon dioxide produced annually by the transport sector*. Given these facts, it is very unlikely that the goal of a 20% CO_2-emission reduction by 2020 can be achieved if the EU energy mix does not include a share of nuclear energy at least as large as it is today.

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This statement, from the Brundtland report [5], meets economic, environmental, and standard-of-living criteria.

- In a context of high fossil hydrocarbon prices, limitations and taxing of CO_2 emissions, nuclear energy offers economically competitive solutions. One main advantage of nuclear energy is that the price of electricity would remain stable even if the price of natural uranium increased substantially.
- Nuclear electricity production emits practically no greenhouse gases.
- Energy and in particular electricity is needed worldwide (1.6 billion people have no access to electricity [12]).
- In Europe, where citizens of all Member States aspire to a high standard of living, sustainable nuclear energy would ensure security of supply of electricity at predictable prices over reasonable periods, which is a key issue for the well-being of all sectors of socio-economic life (both public and private).
- A better public acceptance of nuclear energy in Europe would favour its development and thus improve its competitiveness over other energy technologies. Open and two-way dialogues on key issues such as management of waste, safety and protection of the populations against radiological hazards are necessary to inform the public at large that these issues are being appropriately addressed.

Nuclear fission energy is one of the highly technological sectors in which Europe has undisputedly acquired a world leadership. The renewal of a worldwide interest for nuclear fission technologies demonstrates a general recognition of the merits of this energy source. The construction of a new EPR-type reactor is underway in Olkiluoto, Finland, and France has decided to build another EPR in Flamanville. Initiatives for building new nuclear power plants are also taking place in Bulgaria, Romania, Lithuania (associated to the other Baltic States and Poland), and Slovakia. However, Europe's leadership in the world competition is now challenged by large-scale initiatives from the United States [6], Russia [7], China, and

** According to [4], in 2004 in EU-25, the power-generation sector and the transport sector emitted 1512 Mt CO_2 and 1021 Mt CO_2 respectively.*
Out of the 3179 TWh gross electricity production, 1723 TWh are produced by conventional thermal power plants (emitting CO_2) and 986 TWh are produced from nuclear power plants. Thus, on average the amount of CO_2 emitted by EU-25 thermal power plants is 1512/1723 Mt CO_2/TWh. Replacing the nuclear production by the equivalent thermal production would lead to the additional annual emission of 865 Mt CO_2.

India. Europe, which has the largest nuclear industry in the world, has continuously enforced a high safety level, while promoting fuel and system innovation thanks to its research programmes. In order to preserve this unique asset, it is imperative to strengthen the structure of EU research and development forces, and its industrial community.

This document proposes a vision for the short-, medium- and long-term development of nuclear energy technologies, with the aim of achieving a sustainable production of nuclear energy, significant progress in economic performance, technological breakthroughs, and a high safety level. Roadmaps are proposed for the development and deployment of several potentially sustainable nuclear technologies as well as for actions to harmonise Europe's training and education and renew its research infrastructures. The main elements of the vision discussed in this document are:

- nuclear energy as a key element in Europe's future low-carbon energy system, to address simultaneously the three challenges formulated in [1]:
  1. security of supply and lesser dependence on foreign hydrocarbon fuel imports for primary energy,
  2. reduction of greenhouse-gas emissions,
  3. increase of the competitiveness of European industry;
- the perspective of an important development of nuclear energy in the world (nuclear market renaissance) relying on generation-III light-water reactors, in which it is Europe's interest to maintain its present industrial leadership. Nowadays, the primary energy production worldwide is approximately 10 Gtoe. A sober energy-growth scenario for the worldwide primary energy supply requires at least 14 Gtoe by 2050 (for example, the "modest growth" scenario of WEC IIASA B [8] forecasts a yearly consumption of 19.7 Gtoe).
  Assuming that:
  1. energy efficiency measures would amount to a saving of 5 Gtoe compared to 'business as usual',
  2. renewable energy could reach a share as large as 5 Gtoe,
  3. the share of fossil fuel would amount to 4 Gtoe (without CO_2 sequestration) plus 2.5 Gtoe (with CO_2 sequestration),

  it follows that by 2050 nuclear energy would have to produce at least 2.5 Gtoe (corresponding to 1300 GWe), i.e. about three and a half times more than today;
- the development of generation-IV fast-neutron reactors with closed fuel cycle which require technological breakthroughs. Such reactors could be deployed by the middle of the 21st century, to enhance significantly the sustainability of nuclear energy. Through recycling, such nuclear systems will maximise the use of the energetic potential of recycled fuel, thereby making fission a sustainable source of energy for thousands of years. Thus, nuclear energy will contribute even more to Europe's energy independence. This provisional calendar could be accelerated depending in particular on conditions affecting Europe's security of energy supply;
- generation-IV systems with closed fuel cycles to substantially minimise the volume, the radiotoxic content and thermal load of the residual high-level waste requiring geological disposal. As a consequence, the isolation time and repository volume can be reduced [9]. Significant progress towards practical implementation of geological disposal for high-level wastes has been achieved in Finland, Sweden and France. Notably, a technology platform for geological disposal is being considered by the stakeholders in the CARD project [10];
- the development of new applications of nuclear energy in Europe, focusing on the production of alternative fuels for transport (hydrogen and bio-fuels, which are less carbon-intensive than oil) and the delivery of process heat to high-temperature energy-consuming industrial processes;
- the preliminary roadmaps for nuclear energy related technologies, which will form the basis of the future strategic research agenda (SRA) and deployment strategies (DS), and which identify the required resources.

Through the use of the instruments of the Sixth Framework Programme (FP6) – e.g. the Networks of Excellence SARNET, ACTINET, and NULIFE and the Integrated Projects NURESIM, PERFECT, RAPHAEL, EUROPART, and EUROTRANS – the nuclear RD&D community and industry have demonstrated their ability to coordinate their efforts, collaborate and deliver results [11]. Much more can be attained by fostering coordination with the national and private programmes, leading to the creation of the European Research Area (ERA) for nuclear research. This would foster the best use of the funding means, including public-private partnerships. Further progress can be achieved through the harmonisation of Europe's education and training system, and renewal and integration of its research infrastructure and facilities. The Sustainable Nuclear Energy Technology Platform (SNE-TP) proposed in this document is an instrument for attaining the above goals, leading to the long-term establishment of sustainable nuclear energy production in Europe.

1. The energy challenge: the role of nuclear energy

Current forecasts (World Energy Outlook [12], WEC IIASA [8], WETO [13]) indicate that primary energy consumption will increase significantly by 2030, despite potential improvements in energy efficiency (Fig. 1). The share of electricity in the energy mix will increase more rapidly than the share of other energies, even more when low-carbon technologies are implemented. Security of energy supply is a major concern for the world and for Europe in particular. Today Europe imports 50 % of its energy and with current energy and transport policies, this dependence would increase up to 65 % by 2030 (Fig. 2); reliance on imports of gas would increase from 57 to 84 %; and reliance on imports of oil would increase from 82 to 93 % [15].

In addition to the foreseen growth of Europe's dependence on fossil fuels, there is an increasing risk of supply failure. Fossil fuel reserves, particularly those of crude oil, are localised in a few areas of the world. Political, economical, and environmental factors often induce volatile and high fuel prices.

Simultaneously, environmental policies are demanding a significant reduction of greenhouse-gas emissions. Today, energy consumption accounts for 80 % of Europe's greenhouse-gas emissions. If present energy and transport policies are maintained, the carbon-dioxide emissions in the EU would continue to increase and, by 2030, exceed 1990 levels by 5 % [15]. The present energy trends within the EU are thus not sustainable.

In summary, the European energy market faces three challenges:

- increase the security of energy supply;
- reduce greenhouse-gas emissions. The majority of the scientific community [14] currently considers that the sustainable threshold for global annual anthropogenic greenhouse-gas emissions should be below 3 Gt carbon equivalent per year, which would mean reducing current emissions by a factor of 3;
- maintain and even increase competitiveness of the electricity production. For the citizens and for the companies located in Europe, it is important to prevent delocalisation of the electricity-dependent industry sector to regions where it is cheaper.

Developing sustainable nuclear energy is of paramount importance to meet these three objectives.

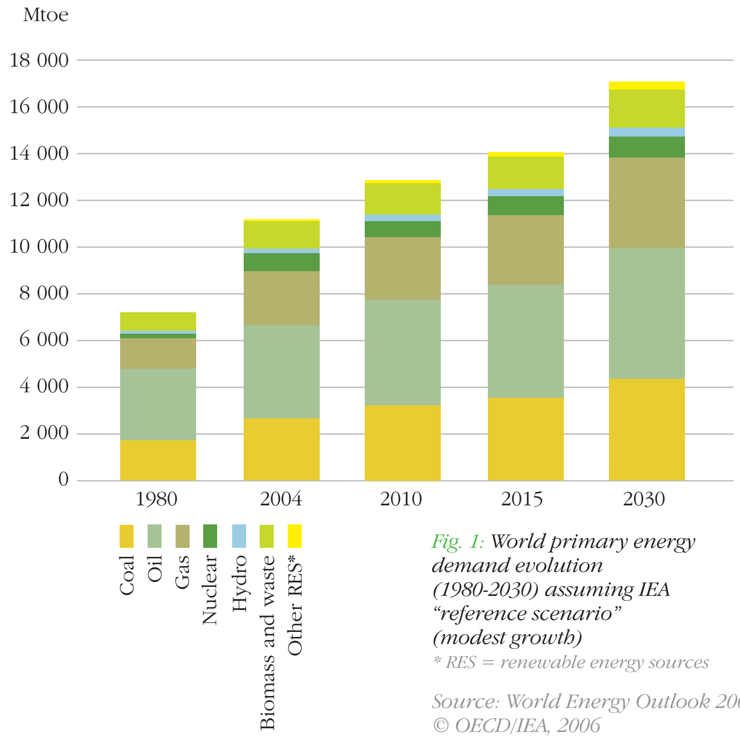


Fig. 1: World primary energy demand evolution (1980-2030) assuming IEA "reference scenario" (modest growth)

** RES = renewable energy sources*

Source: World Energy Outlook 2006 © OECD/IEA, 2006

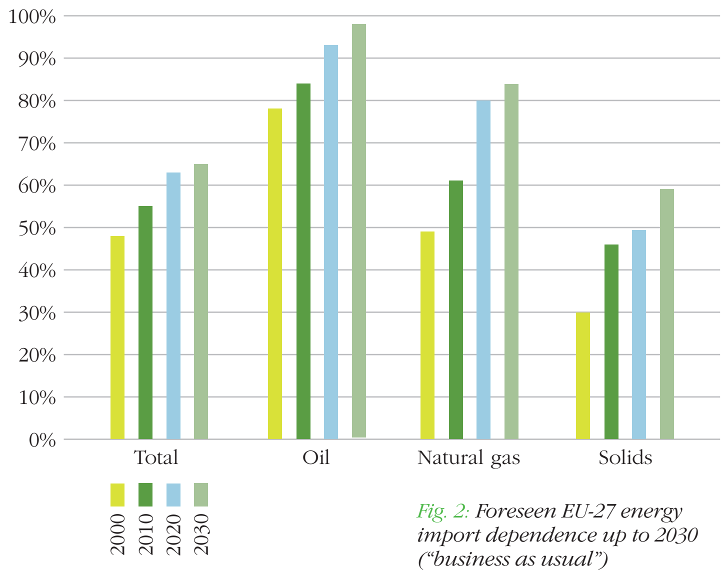


Fig. 2: Foreseen EU-27 energy import dependence up to 2030 ("business as usual")

Source: European Commission, DG TREN, PRIMES

Reduction of greenhouse-gas emissions

In 2004 in EU-25, nuclear energy represented 31 % of the electricity produced in the European Union (Fig. 3) and 15 % of the total energy consumed (Fig. 4).

Nuclear energy is one of the energies with the lowest emissions of carbon dioxide per GWh (Fig. 5). On the basis of the IEA (International Energy Agency) World Energy Outlook 2006 data [12], a comparison can be made between three scenarios of CO_2 emissions from electricity production for the EU by 2030:

- Scenario 1: phase-out of nuclear power;
- Scenario 2: reference scenario with 22 % nuclear production of electricity;
- Scenario 3: the same share of nuclear electricity as today, i.e. 31 %.

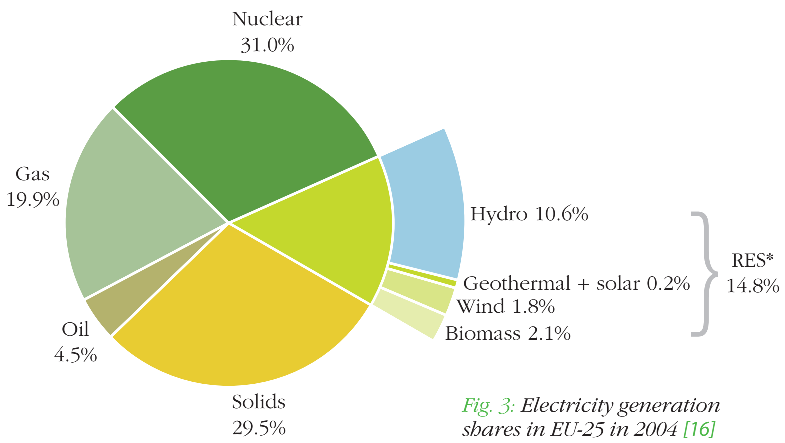


Fig. 3: Electricity generation shares in EU-25 in 2004 [16]
** RES = renewable energy sources*

Source: Eurostat

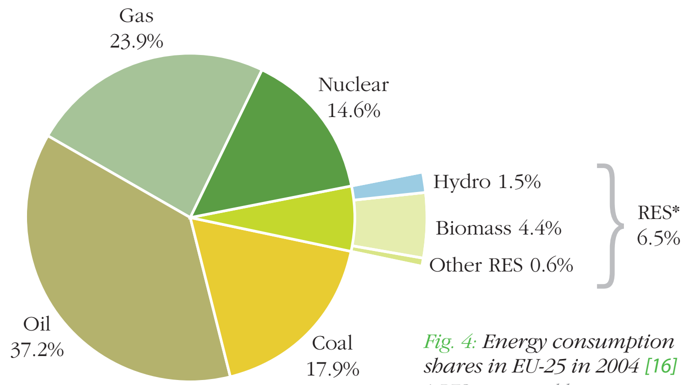


Fig. 4: Energy consumption shares in EU-25 in 2004 [16]
** RES = renewable energy sources*

Source: Eurostat

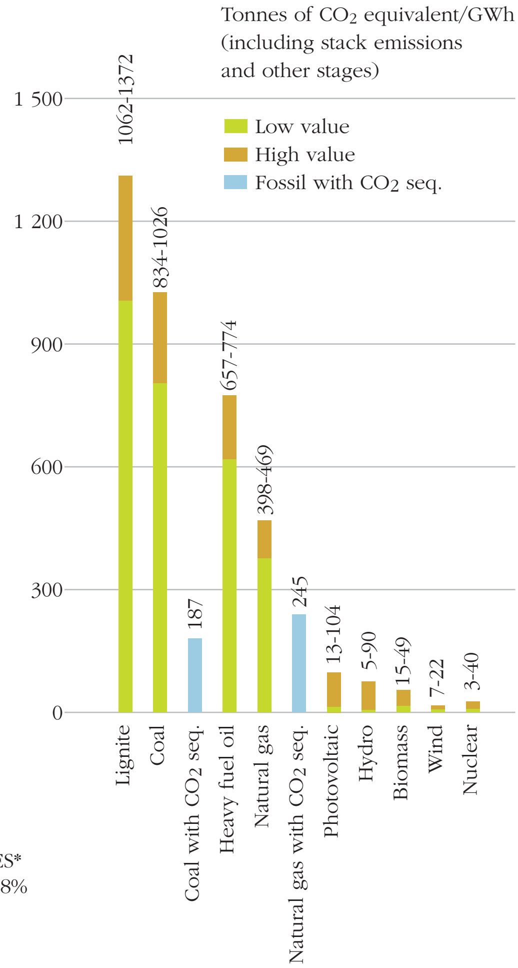


Fig. 5: Greenhouse-gas emissions (in tonnes of CO_2-equivalent) per GWh for different electricity production means

From data in [42]

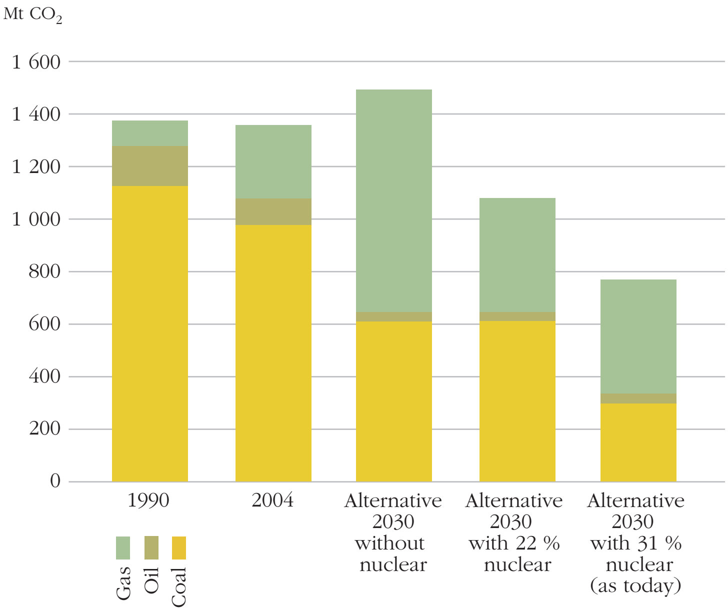


Fig. 6: CO_2 emissions by electricity production in the EU (in million tonnes)

From data in [12]

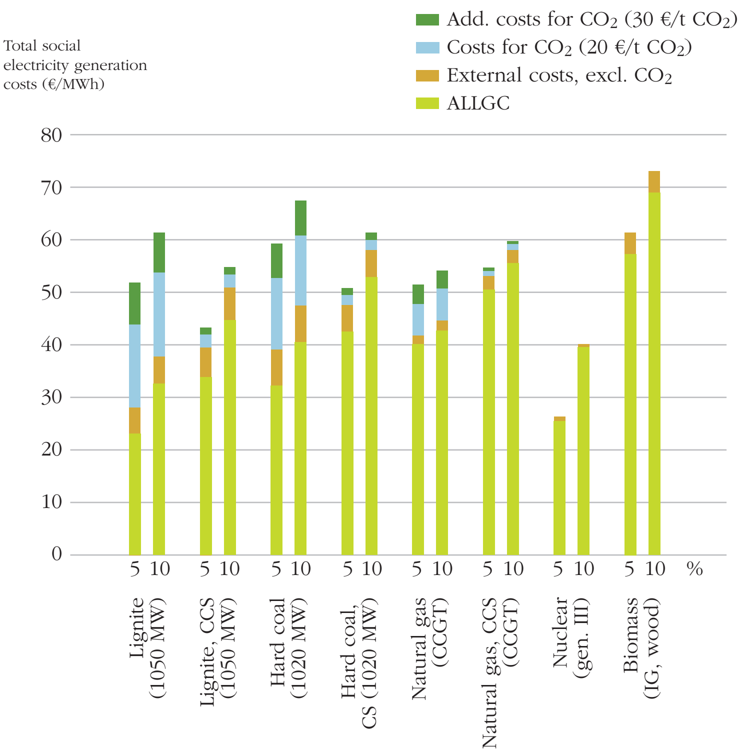


Fig. 6 shows that if one replaces the nuclear electricity by combined-cycle gas turbine (CCGT)-produced electricity, even in the case of strong energy management and a renewables policy, CO_2 emissions would remain the same or even slightly increase compared to 2004 levels. Thus, nuclear energy is essential if Europe wants to reduce its greenhouse-gas emissions.

Competitiveness and security of supply

The recent European Commission Communication about the new energy policy for Europe [15] outlines the fact that nuclear energy "is one of the largest sources of carbon-dioxide-free energy in Europe". It also states that "nuclear power is less vulnerable to fuel-price changes than coal- or gas-fired generation, as uranium represents a limited part of the total cost of generating nuclear electricity and is based on sources which are sufficient for many decades and widely distributed around the globe".

As can be seen from Table 1 [17], which outlines the advantages and disadvantages of different sources of energy, nuclear energy is one of the cheapest sources of low-carbon energy that is presently produced in the EU and has relatively stable costs. According to [12], "new nuclear power plants could produce electricity at a cost of less than USD 5 cents per kWh [EUR 3.7 cents at mid-April 2007 exchange rates] if construction and operating risks are appropriately managed by plant vendors and power companies" and also "at USD 10 [EUR 7.40 at mid-April 2007 rates] per tonne of CO_2 emitted makes nuclear competitive with coal-fired power stations. The next generation of nuclear reactors should reduce these costs further."

Table 1 calls for two further remarks:

1. For intermittent renewable energy sources such as wind, the capacity factor, defined as the ratio of actual power produced over power that could have been produced if turbines operated at maximum output 100 % of the time, is the main driving factor for cost calculations. For wind power, it ranges between 25 and 40 %.

Fig. 7: Estimated total social costs for different electricity generation technologies in 2030.

From the EUSUSTEL project [3]

ALLGC: average lifetime levelised generation costs. Calculations based on an 85 % capacity factor. Discount rate: 5 or 10 %

Table 1: Energy sources for electricity generation [17]

Energy source	Technology considered for the cost estimate	Cost in 2005 (€/MWh)	Projected cost in 2030 (€/MWh with 20-30 €/t/ CO_2)	Green-house-gas emissions (kg CO_2 eq./MWh)	EU-27 import dependency		Efficiency	Fuel-price sensitivity	Proven reserves at annual production
		Source: IEA			2005	2030			
Natural gas	Open-cycle gas turbine	45-70	55-85	440	57 %	84 %	40 %	Very high	64 years
	CCGT (combined-cycle gas turbine)	35-45	40-55	400			50 %	Very high	
Oil	Diesel engine	70-80	80-95	550	82 %	93 %	30 %	Very high	42 years
Coal	PF (pulverised fuel with flue gas desulphurisation)	30-40	45-60	800	39 %	59 %	40-45 %	Medium	155 years
	CFBC (circulating fluidised bed combustion)	35-45	50-65	800			40-45 %	Medium	
	IGCC (integrated gasification combined cycle)	40-50	55-70	750			48 %	Medium	
Nuclear	Light-water reactor	40-45	40-45	15	Almost 100 % for uranium ore		33 %	Low	Reasonable reserves: 85 years
Biomass	Biomass-generation plant	25-85	25-75	30	Nil		30-60 %	Medium	Renewable
Wind	Onshore	35-175	28-170	30			95-98 %	Nil	
		35-110	28-80						
	Offshore	50-170	50-150	10					
		60-150	40-120						
Hydro	Large	25-95	25-90	20			95-98 %		
	Small (< 10 MW)	45-90	40-80	5					
Solar	Photovoltaic	140-430	55-260	100			/		

2. The EU imports almost all its uranium ore. However, uranium is available throughout the world, and contrary to oil or gas, the main suppliers of uranium to the EU are politically stable countries, Canada (25 %) and Australia (16 %). Furthermore, strategic stockpiles are already available or can be easily and safely built, contributing to energy security.

Fig. 7 shows that nuclear energy is one of the most competitive energies in Europe. This is even more striking when all external costs are taken into account, including carbon taxes*. A recent study performed in the EUSUSTEL project [3] clearly shows the advantage that nuclear energy has over hydrocarbon fuels.

** External costs are defined as costs that arise when the social or economic activities of a group have an impact on another group. For example, during the operation of a power plant, emissions damage human health, crops, and materials. This generates external costs. Other stages of the energy chains such as mining of fuel or decommissioning of the power plant also generate external costs. However, for nuclear energy the costs related to dismantling of facilities and to management and disposal of waste are already taken into account in the price of electricity in most European countries, i.e. these costs have been internalised.*

European practices for the development of nuclear energy

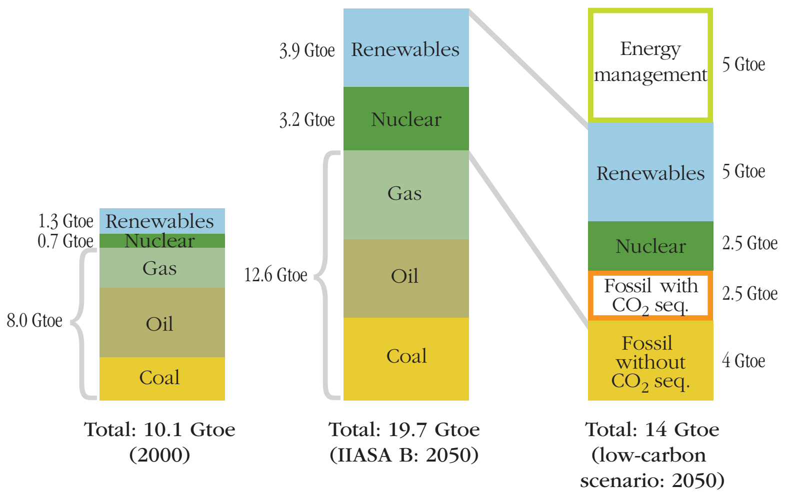
Europe has a long and successful history with nuclear energy in terms of safety, economics and technology development. Dissemination of information is now being improved and participation in decision-making processes is also being broadened. This should improve social acceptance of nuclear energy, which has decreased in the last two decades.

- The availability and capacity factors of nuclear power plants have steadily improved over the past 50 years, demonstrating the quality of the design, the reliability of operation as well as an efficient organisation in terms of regulations and safety.
- European-designed nuclear power plants have an excellent safety record. No severe accident has occurred in the EU. Safety is a primary concern for vendors, utilities, operators, safety authorities, and technical safety organisations.
- All EU Member States have signed the Euratom Treaty and the IAEA (International Atomic Energy Agency) nuclear safety and wastes management conventions. Regulations have been developed and implemented in each country. Sustained efforts are now being conducted to harmonise regulations all over Europe through WENRA (Western European Nuclear Regulators Association) [18] and to converge on technical nuclear safety practices within the TSO network ETSON (European Technical Safety Organisations Network)[19].
- Transparency and public information on nuclear energy issues are improving. The Århus Convention on access to information, public participation in decision making and access to justice in environmental matters entered into force in 2001 and was ratified by all EU-27 countries.
- These matters will also constitute elements for discussion in the European Nuclear Energy Forum and the High-level Group on Safety and Waste [15], which are in the process of being created. This technology platform will establish appropriate relations with these bodies.

Europe's safety record and technological excellence together with its regulatory framework ensures a high level for the future development of nuclear energy, inside the EU, but also outside, when its industry is involved.

Fig. 8: Possible role of nuclear energy in different scenarios for 2050: example of a 14-Gtoe/year scenario [22] where nuclear energy would represent 2.5 Gtoe (corresponding to an installed capacity of 1 300 GWe)

Seq. = sequestration



Important perspectives on the development of nuclear power in the world

In January 2007, 435 commercial nuclear reactors were in operation in the world [21]. In 2005 the total installed nuclear power capacity was 369 GWe in 30 countries. During the year 2006, power production was 2 630 TWhe, representing about 16 % of worldwide electricity production.

The majority of scenarios of energy growth predict that world primary energy needs, which are currently at around 10 Gtoe, will reach between 12 and 28 Gtoe by 2050. The three major energy consuming areas are projected to be the United States, Europe and Asia.

To be sustainable, this growth of energy consumption cannot follow a "business-as-usual" scheme but must combine a strong policy of energy savings, an ambitious expansion of renewable energies and a substantial development of nuclear power. The "medium" (modest growth) scenario WEC IIASA B forecasts a yearly consumption of 19.7 Gtoe by 2050 [8]. If a sober (ecologically-driven growth) scenario is considered, reducing consumption to 14 Gtoe by 2050, it is necessary to combine [22]:

- strong energy management – saving 5 Gtoe by 2050 – bringing the predicted demand from 19.7 to 14 Gtoe (in line with current energy-efficiency development curves),
- annual CO_2 emissions restricted to 3 Gt of carbon (or 4 Gtoe of fossil fuel energy),
- a strong renewable energy-based policy: 5 Gtoe, including hydropower (1.4 Gtoe) and wind power (0.8 Gtoe) etc.,
- nuclear power, even assuming that its contribution would be limited to partially filling the deficit left by other energy sources to meet global demand. It would see its potential production gradually rise from the current 0.7 Gtoe/year (7 %) to 2.5 Gtoe/year (18 %) in 2050, or three and a half times the current installed nuclear capacity.

These scenarios are illustrated in Fig. 8.

An industrial reality for the 21st century

A 'renaissance' of nuclear power can be observed all over the world [23]. Some 28 reactors are currently under construction, most of which are in Asia (Fig. 9):

- The USA has defined a new framework supporting nuclear power.
- China has decided to accelerate the development of its nuclear fleet, with 4 reactors under construction and 23 planned (i.e. approved and funded); a total of 50 have been announced.
- India, which currently operates 16 reactors, is constructing 6 and planning an additional 4, with 15 announced.
- Japan, which has 55 reactors, is constructing 2 and planning an additional 11.
- South Korea, which has 20 reactors, is constructing 1 and planning an additional 7.
- Russia, which operates 31 reactors, is constructing 5 reactors, planning an additional 8, with an additional 18 having been announced.
- Emerging countries are also planning to develop nuclear power.
- Finally, in Europe, Finland and France are each building a new generation-III reactor (European Pressurised-water Reactor – EPR) and the Baltic States and Poland plan to jointly build a new plant (Ignalina 3). A white paper in the UK supports the renewal of the fleet to avoid an energy crisis [20]. Among the countries which joined the EU since 2004, 1 reactor is in start-up phase (Romania), 4 are planned (Bulgaria, Slovakia) and more have been proposed (Lithuania, Romania and Slovenia).

Nuclear energy has become a very competitive industry worldwide. The EU is a major player in this market, with more than 30 % of its electricity currently produced by nuclear energy. It has developed third-generation nuclear systems and participates in the Generation IV International Forum (GIF) [24] to develop more sustainable nuclear technology.

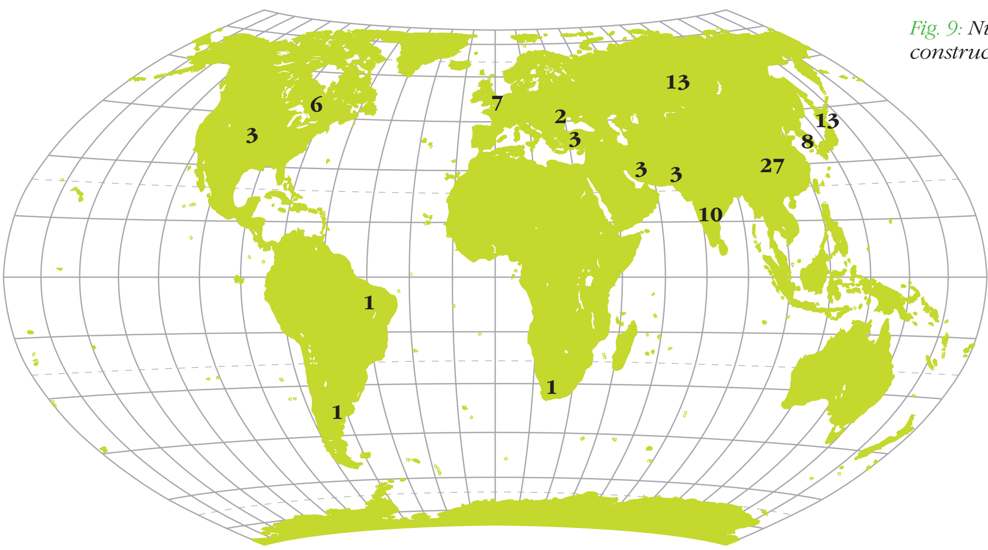


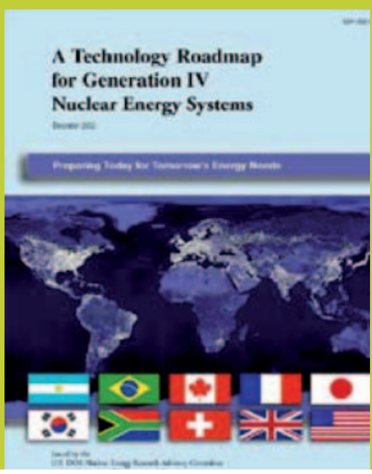
Fig. 9: Nuclear reactors under construction or planned [23]

Generation IV International Forum

Ten countries including France and Switzerland – as well as the EU represented by Euratom and with the JRC as implementing agent – are working together within the Generation IV International Forum (GIF) to perform pre-competitive R&D on key technologies likely to be implemented in future nuclear systems.

These systems must consider an optimum use of natural resources, whilst addressing nuclear safety, waste and proliferation resistance and public perception concerns in the countries in which they will be deployed.

Technological roadmaps have been defined for several systems. Europe has been a major contributor to many of them.



Uranium supply and fuel cycles

Although assured uranium reserves are currently in the region of 4.7 Mt, estimated resources [25] that could be exploited are in the range of 15 Mt. The current annual consumption rate (about 67 000 t/y) will rise to an anticipated value of about 90 000 t/y in 2025 for installed power around 500 GWe. Assuming that the present installed world nuclear capacity of 370 GWe increases to 1300 GWe in 2050 (with a consumption of natural uranium of 150 t/GW/year), the estimated uranium resources would at that time be completely earmarked for the lifetime requirements of light-water reactors (LWRs). Therefore, the deployment of a new generation of reactors – generation-IV fast-neutron reactors (FRs) – with closed fuel cycle, leading to a better use of natural resources (typically multiplying energy production by up to 100 for the same quantity of uranium), needs to be prepared.

Despite some uncertainties in the evaluation of uranium reserves, the scenario of deployment of fast-neutron reactors around 2050 is reasonably based, since an increase of 50 % in uranium reserves (an additional 7.5 Mt) would only delay the need for deployment of fast-neutron reactors by about ten years*. Nevertheless, an earlier deployment is possible if Europe's energy security is at stake.

** Assuming an annual increase of nuclear capacity of 65 GWe.*

Spent-fuel and waste management, closed fuel cycle strategy for sustainability

Technical solutions exist today for the safe disposal of nuclear waste:

- Continuous progress has been made in the processing of spent fuel, the recycling of nuclear material, and the conditioning of residual waste in a glass matrix.

The vision for future nuclear energy

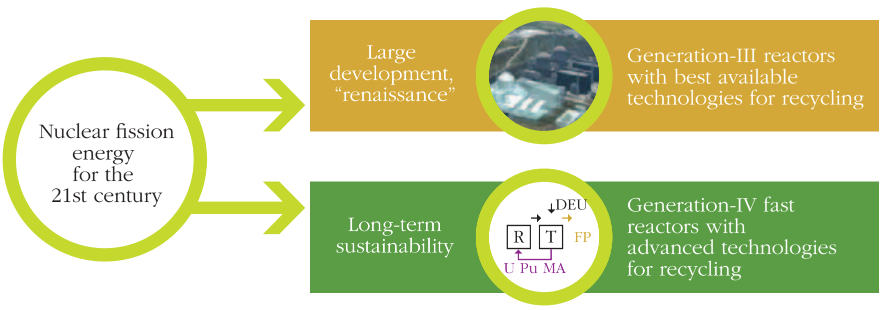


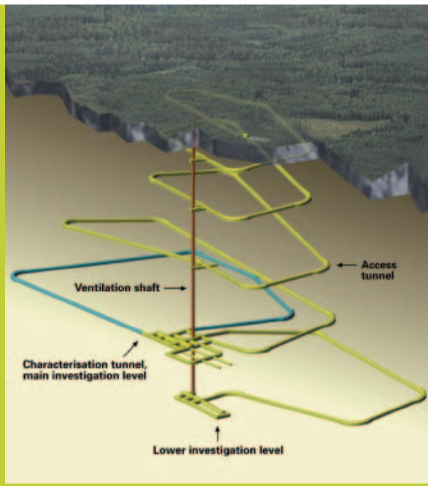
Fig. 10: Renaissance and long-term sustainability of nuclear energy

R: recycling
T: transmutation
U: uranium
Pu: plutonium
MA: minor actinides
DEU: depleted uranium
FP: fission products

Geological disposal of high-level waste

The ONKALO underground research facility in Finland is being built to prepare the final disposal facility for high-level nuclear waste (spent fuel) in Olkiluoto. A decision in principle to build such a repository has been approved by the Finnish Parliament in 2001.

Posiva Oy (www.posiva.fi) is responsible for practical preparations, R&D and the final disposal of spent fuel. The construction licence application for the repository is planned to be submitted to authority review in 2012.



- Nuclear waste represents a small volume compared to industrial waste: In France, with 59 nuclear power reactors, 1 kg of nuclear waste is produced per year and per inhabitant – of which only 10 g represent high-level long-lived waste, compared to 100 kg of residual industrial waste and 2 500 kg of municipal waste [26].
- Reversible geological disposal is now the object of an international technical consensus [27]. In Finland and in France, a precise final-disposal schedule has been adopted, following public debates and approval by relevant committees.

For current light-water reactors (LWRs), the spent fuel can be recycled at least once into mixed oxide (MOX) fuel. Spent MOX fuel is then stored, in order to recover the plutonium to be used for a future generation of fast reactors which can effectively burn this plutonium in a multi-recycling uranium-plutonium strategy. Basically, 50 years of operation of one LWR will produce the stock of plutonium needed to start a fast reactor – which could thus form a sustainable source of energy for thousands of years through the use of depleted uranium [28].

A step further is related to the recycling of minor actinides to reduce the thermal load, the volume and the needed isolation time [9] of the remaining waste requiring geological disposal. Recent R&D results have shown that minor actinides can be separated from spent fuel, thus opening the way for their burning in a fast-neutron system, thereby using their energetic potential, as well as eliminating them as long-lived radioactive material (Fig. 10).

Recycling of minor actinides still needs further research and development, and the technology selection will be made on a cost versus benefit basis, taking into account the impact of minor actinide recycling on the geological disposal specifications.

New applications of nuclear energy

Beyond the use of nuclear power for electricity generation, new applications are being developed, based on generation-III or -IV reactor features, in particular through the coupling of (very)-high-temperature reactors with chemical processing plants. A recent international conference [29] organised by the IAEA (International Atomic Energy Agency), in cooperation with the OECD/NEA (Nuclear Energy Agency) and the International Desalination Association, has provided a broad survey of non-electric applications of nuclear energy. These include:

- processes for producing alternative energy carriers replacing for example the use of oil for transport, including hydrogen and bio-fuel production;
- processes that require heat and/or electricity, such as desalination.

Harmonisation of safety approaches in Europe

Harmonisation of regulations at European level is ongoing through the Western European Nuclear Regulators Association (WENRA). It pursues goals such as ensuring that a design found suitable in one country does not have to be substantially modified to meet licensing requirements in another country.
(www.wenra.org)

ETSON, the newly established Network of European Technical Safety Organisations, has the following objectives:

- to be a forum for exchanges on analyses and R&D in the field of nuclear safety, to share experience, and to exchange technical and scientific opinions in this field;
- to foster the convergence of technical nuclear safety practices in Europe;
- to contribute to the definition of the needs for research programmes and to the formation of a network in the nuclear safety field.
(www.grs.de/tso)

2. A European vision for the development of sustainable nuclear energy systems

Nuclear fission energy is a proven technology which today represents 31 % of the EU's electricity production. With 152 reactors in operation in 2006, nuclear power is the main source of electricity generation, with very low greenhouse-gas emissions. Most of these reactors are pressurised- or boiling-water reactors that have been in operation for about 20 years on average. Current plans in most EU Member States are to extend their lifetime on a case-by-case basis beyond 40 years, and possibly beyond 50 years. Generation-III reactors, such as the EPR (European Pressurised-water Reactor), are evolutionary reactors derived from the experience of operating light-water reactors (LWRs) and developed to optimise their safety and economic performance. They are currently being deployed in Finland and in France, which both chose an EPR design, with commercial operation planned to start around 2010 and 2012 respectively. The operational safety and the commercialisation of LWRs are currently supported by national R&D programmes and actions of the Euratom R&D framework programmes dedicated to safety, performance, waste management, and radiation protection.

Because of Europe's ageing power-generation capacity, including nuclear power plants (Fig. 11 illustrates the rapidly declining capacity of thermal and nuclear power plants in EU-15), there is an urgent need for investment to meet the expected energy demand and to replace infrastructures. According to [12], around 800-900 GWe capacity will be required by 2030 to replace the existing capacity and to address increasing needs*. It is reasonable to assume that out of these potential new 800-900 GWe, at least 100 GWe will be produced by generation-III nuclear reactors. This corresponds to the construction of 60 to 70 big reactor units, a task which is certainly compatible with the industrial capacity of Europe. It represents an investment of EUR 150 billion over 20 years (for an average overnight construction cost of EUR 1 500 per kWe).

These new reactors are designed to be operated for 60 years. In the longer term, generation-IV systems will take over once they have reached technical maturity and met sustainable development criteria, particularly those pertaining to waste management and preservation of energy resources.

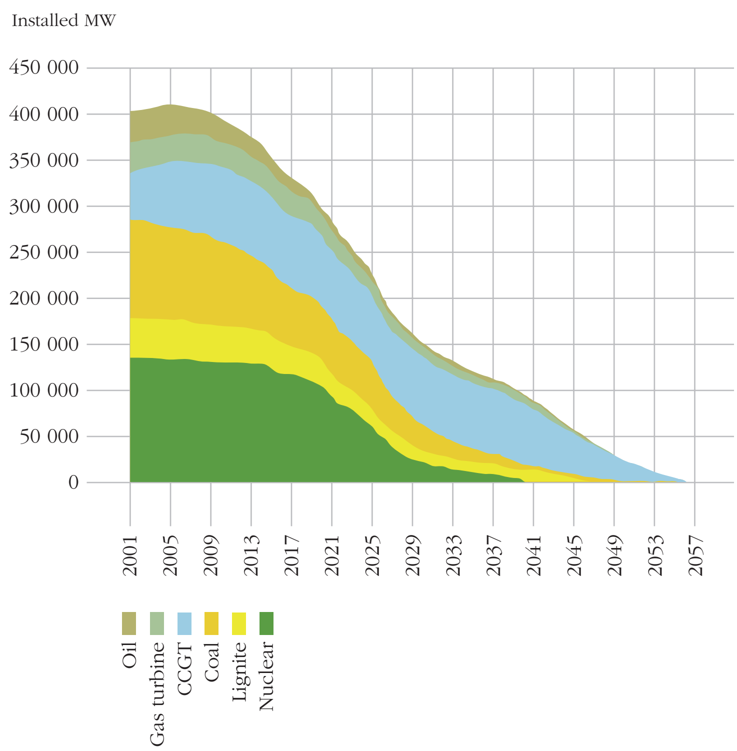


Fig. 11: Decline of installed fossil and nuclear power generation capacity (without renewal by new plants) in EU-15 per type of energy, showing a decrease of around 60 % by 2030

By courtesy of EDF

** Today, the EU-27 power-generation capacity stands at around 760 GWe, consisting of 600 GWe of thermal and nuclear generation and about 160 GWe of hydro and renewable power generation. Without replacement, there would be a 60 % decrease of electricity-generation capacity by 2030, with only 300 MWe still available at that time. To meet the demand, estimated to be 1130 GWe in 2030 [39], the construction of a capacity of 800 to 900 GWe will therefore be necessary.*

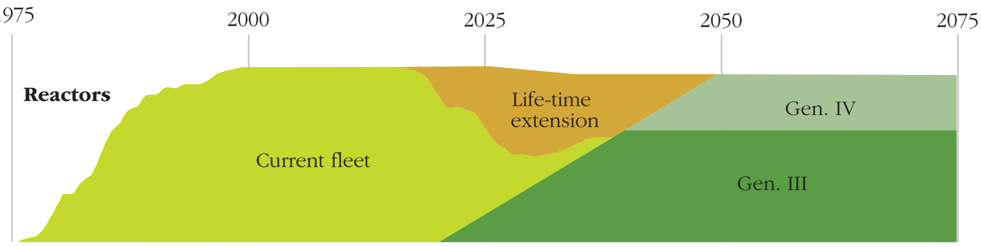


Fig. 12: Deployment of generation-III and -IV reactors in the 21st century

Source: EDF, ENC, 2002

Commercial deployment of such generation-IV systems is not expected to occur before 2040, since major technological breakthroughs are still needed to develop such reactors; preliminary roadmaps for these technologies are described in Section 4 of this document.

Thus, it is very likely that three reactor generations will co-exist during the 21st century, as illustrated in Fig. 12 dealing with a French scenario based on an almost stable nuclear production of electricity.

Each of the three generations faces specific technological challenges to be overcome on the path to sustainability, but all share the common goal of guaranteeing the highest level of safety. This goal requires the development and validation of modelling tools, experiments, as well as harmonisation of safety assessment methods.

Light-water reactors (LWRs)

Generation-II light-water reactors: lifetime management

Across the EU-27, a total of 152 reactors are in operation in 15 Member States. The average age of these power plants is approaching 25 years for a typical initial design life of 30-40 years.

To meet the growing concerns about security of energy supply and CO_2-emission reductions before LWRs of generation III can be built and operated, a first priority must be given to lifetime extension of generation-II LWRs. While maintaining a high degree of operational safety, the already well-proven economic competitiveness of nuclear energy can be further enhanced by research focused on improved availability, fuel performance and safety.

Generation-III light-water reactors for nuclear renaissance

With about 945 TWh in 2005 [30], the EU is the largest nuclear electricity producer in the world. Nuclear energy is one of the largest sources of CO_2-free energy in Europe. Nuclear energy generation has a major role to play in the context of the priorities identified in the European Commission's Green Paper [31]. Furthermore, to preserve its leadership in a growing worldwide market, Europe must define a strategy for the renewal of the current generating fleet by generation-III LWRs. In the coming 25 years, according to various scenarios, more than 100 GWe of new nuclear plants will have to be built in Europe to meet the energy challenges and maintain the current share of nuclear power in the European energy mix. Given the construction time of a plant and the demands that such a major construction programme would make on European industry, decisions on new investments are required without delay.

With the European Pressurised-water Reactor (EPR) in Olkiluoto (Fig. 13), Finland was the first country in Europe to launch the construction of a new nuclear power plant (NPP) for more than a decade. It was followed by France in 2006, with the decision to build another EPR plant in Flamanville.

Nuclear market renaissance with the construction of a large number of NPPs will necessarily rely on generation-III LWRs, which offer enhanced safety and reliability and the best available technologies for a responsible management of spent nuclear fuel. The latter, particularly, is a condition for nuclear acceptance.

Spent fuel treatment and recycling of uranium and plutonium are already an industrial reality in some countries, such as France, Japan and Russia.

This recycling strategy results in the significant reduction of volume, heat load and isolation time for high-level wastes requiring geological disposal. Through the use of plutonium in mixed-oxide fuel (MOX), it also saves natural resources (about 20 %), thus making a step towards sustainability, with a non-significant effect on the kWh cost (less than 5 %). In addition, recycling, as it is implemented today, buys some time. It opens a large range of options to optimise spent fuel management and contributes to the foundation of a future sustainable policy. For these reasons, the USA is now reconsidering the recycling option with a renewed interest [6].

Generation-IV reactors: towards sustainability

Spent fuel treatment and multi-recycling is the basis on which future generation-IV reactors will achieve sustainability. Fast-neutron reactors with a closed fuel cycle allow:

- significantly improved usage of natural resources,
- minimisation of volume and heat load of high-level waste.

This option has been selected by several countries, such as Japan (with JSFR, Japan Sodium-cooled Fast Reactor), Russia (with the BN 600 in operation and the BN 800 and BREST 300 reactors), India (with the PBFR prototype), China (with CEFR, China Experimental Fast Reactor) and the United States (with the advanced recycling reactor project). This option was also selected in Europe (with Phénix, PFR, KNKII, and Superphénix). In 2006, France launched a project to construct a sodium-cooled fast reactor (SFR) prototype by 2020, open to industrial and international partnerships. This could be considered as the first step towards a renewed European initiative.

Among the fast reactor systems, the sodium-cooled fast reactor currently has the most comprehensive technological basis, thanks to the experience gained internationally from operating experimental, prototype and commercial-size reactors such as the Phénix plant in France (Fig. 14), PFR in the UK, and MONJU in Japan.

The technological knowledge gained from these reactors includes key elements of the overall reactor design, fuel types, safety, and fuel recycling. Innovations are sought for a generation-IV sodium-cooled fast reactor (Fig. 15) in order to reduce costs and to further improve safety. They involve design simplification, improvement of in-service inspection and repair, fuel handling, high-performance materials, and practical exclusion of high-energy release in case of a hypothetical severe accident.

Given the maturity of sodium-cooled fast reactors, the next facility to be built in Europe will be a prototype reactor with a power-conversion system of 250 to 600 MWe to demonstrate innovations with respect to existing SFRs and to pave the way for a first-of-a-kind generation-IV commercial reactor.

Fig. 13: The EPR 1 600 MWe reactor under construction in Olkiluoto (Finland), status in June 2007

Fig. 14: Phénix sodium-cooled fast-neutron reactor in Marcoule (France)

© A. Gonin/CEA

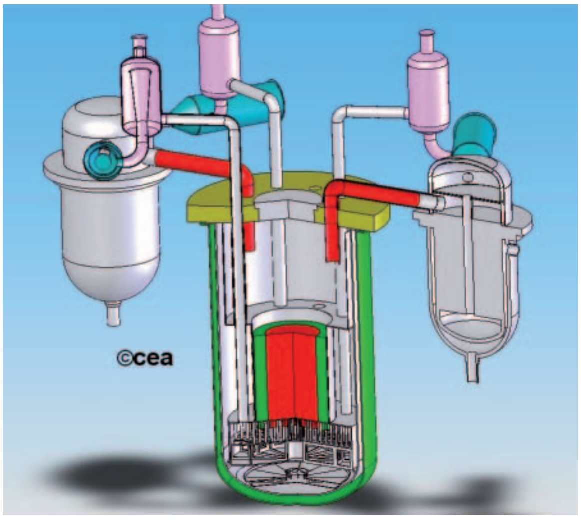
To face the major worldwide challenges described above, generation-IV fast reactors have to offer a choice of technologies so as to limit the overall technological risk and be able to satisfy various markets and degrees of public acceptance. Whilst the SFR remains the reference technology, two alternative technologies for fast reactors, namely the gas-cooled fast reactor (GFR) and the lead-cooled fast reactor (LFR) also need to be assessed at European level. After selection of an alternative technology, an experimental reactor in the range of 50-100 MWth will be needed to gain experience feedback by 2020 on this innovative technology.

Among the attractive features of the GFR, which is a high-temperature reactor, the chemically inert and optically transparent coolant (helium) should be mentioned as well as the potential for producing hydrogen, synthetic hydrocarbon fuels and process heat. The most important challenges for this type of reactor are the development of materials resistant to the combined effects of high temperature and high neutron flux (refractory and dense fuel, thermal barrier) and the safety systems.

The LFR is identified as another potentially promising alternative fast-reactor type. Russia has gathered experience in building and operating small lead-alloy-cooled reactors in the 100 MWth range for naval propulsion. Europe has recently gathered experience with the operation of several lead-bismuth facilities including the MEGAPIE lead-bismuth spallation target at PSI in Switzerland. The pure lead-cooled LFR system offers the same advantages as the lead-alloy-cooled reactors of operating primary systems at atmospheric pressure. As a power reactor, it also offers the potential of being competitive with present-generation LWRs in electricity generation, provided that the designers succeed in simplifying the primary system and eliminating the intermediate cooling system. Current R&D addresses some critical issues associated with using lead as a coolant for reactors in the power range of 1 GWe, such as weight and corrosion. In-service inspection, maintenance and repair remain also a common challenge for both liquid-metal coolants, sodium and lead.

Fig. 15: Design of an innovative loop-type SFR

By courtesy of CEA



Advanced fuel-cycle processes

In association with the development of a robust fast-reactor system, a flexible separation and treatment strategy needs to be assessed, aiming towards a closed fuel cycle which better uses the fertile resources by a multi-recycling of uranium and plutonium. This strategy includes the development of actinide chemistry, separation technology and minor actinide bearing fuels with reactor irradiation of such fuel. Such a coherent long-term strategy would allow the transition from the currently practiced mono-recycling of plutonium in light-water reactors (LWRs) to multi-recycling in generation-IV reactors.

Beyond this goal, recycling is also the cornerstone of a strategy for partitioning and transmutation of minor actinides, which would substantially reduce the radioactivity and heat load of the remaining high-level waste. As a result, the isolation time and repository space required in deep geological disposal would also be reduced.

For the incineration of minor actinides, the opportunities offered by accelerator-driven systems (ADS) will be compared to those of fast-neutron critical reactors on a technological and economic basis [32].

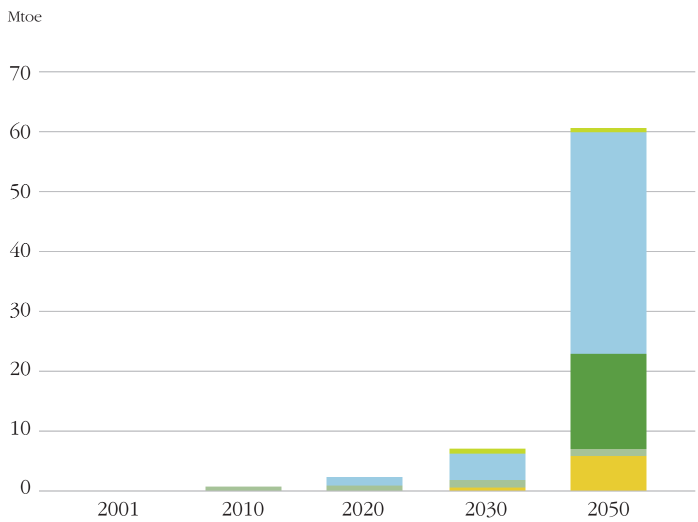


Fig. 16: H_2 production in Europe, from [13], showing the growth in anticipated H_2 production needs and the share of nuclear power in the production

Safety research for nuclear systems

The design of nuclear systems in Europe relies on the "defence in depth" principle. It consists in the prevention of accidents and the mitigation of their consequences, and the protection of workers and populations against radiological hazards through the use of multiple barriers and safety systems. For the more recent reactor systems such as generation-III reactors, even extremely improbable accidents are taken into account. For example, the European Pressurised-water Reactor (EPR) was designed so that in the very unlikely event of a severe accident, radiological consequences would necessitate only very limited protective countermeasures in a relatively small area and for a limited time for the surrounding population.

The safety analysis of nuclear systems relies on a thorough understanding of the behaviour of the system in normal and accidental conditions, and increasingly on the use of advanced numerical simulation software and its validation through experimental programmes. For future reactor designs, simplified tools can be developed and applied at first to carry out preliminary analyses of concepts and safety options. Once the design is known, more advanced safety evaluation software tools can be developed and applied. In order to contribute to the harmonisation of safety practices in Europe and to better compare the safety aspects of the different reactor systems, the development of common tools and methodologies is favoured.

Towards enlarged applications of nuclear energy

In the EU, fossil fuels account for almost 80 % of total energy consumption. Road, air and sea transportation, which is 98 % dependent on fossil fuels, will remain the main CO_2 emitting sector over the coming decades, if alternative fuels are not developed and deployed. Nuclear energy could be used as a source of process heat for the production of other energy carriers such as hydrogen, without CO_2 emissions, in addition to electricity production. Nuclear energy could further open the way to 'low-CO_2' synthetic fuels produced from biomass, gas or coal:

- Nuclear H_2 production (Fig. 16) could substitute large steam-reforming plants for refinery needs or for future transportation (internal combustion engines or fuel-cell vehicles). As H_2 production is energy intensive, nuclear power can be used to provide an economic source without CO_2 emission. Water splitting could be realised at low temperatures by alkaline electrolysis or at higher temperatures by either electrolysis or thermo-chemical processes. The (very)-high-temperature reactor (HTR/VHTR) system, which corresponds to a thermal neutron helium-cooled reactor concept operated at high (850 °C) temperatures, could deliver electricity and process heat with a high efficiency (47 % or more). Nevertheless, for industrialisation, many parameters have to be taken in account, including the temperature level of the nuclear heat source, the overall performance of the splitting reaction, the reactor coupling, the safety, and of course the costs involved.

- Gasification technologies have been developed around the world for fuel production from coal or natural gas. Fuels are also being developed from biomass. All these synthetic fuels need process heat and large amounts of H_2. The process performance (yield and CO_2 emissions) can be strongly improved by introducing external power (heat or electricity) and additional hydrogen from nuclear plants into the process. Using nuclear reactors to provide electricity, heat or H_2 would reduce the overall carbon impacts of the fuels.

Ongoing research and demonstration projects in Japan, China and South Africa aim at proving the capability of VHTRs to achieve high coolant outlet temperature and to use this high-temperature heat for combined electricity and heat application. Technological challenges for this type of reactor include the development of high- and potentially very-high-temperature helium systems, such as intermediate heat exchanges, and efficient processes to produce hydrogen at industrial scale, through high-temperature electrolysis or thermo-chemical decomposition of water.

The EU has already defined its vision on hydrogen and bio-fuels for 2030 and beyond [33]. With the applications of nuclear energy described above, obvious links between the Sustainable Nuclear Energy Technology Platform (SNE-TP) and the hydrogen and bio-fuels European technology platforms will be established.

Education and training, the renewal of competences

At the Lisbon 2000 European Union summit, the EU set itself the goal of becoming the most competitive knowledge-based economy, with more and better employment and social cohesion, by 2010. With respect to nuclear knowledge, specific concerns were expressed in two important studies by the EC and the OECD, concluding that expertise in nuclear science and technology is at risk. It was observed that in most countries there are fewer comprehensive, high-quality nuclear technology programmes at universities than before and that the ability of universities to attract top-quality students, to meet future staffing requirements of the nuclear industry and to conduct leading-edge research, is becoming seriously compromised. Thus, education and training in engineering and sciences is one of the cornerstones of Europe's vision for the development of nuclear energy.

The ENEN (European Nuclear Education Network) Association [34], currently comprising 41 members, plays a major role in shaping Europe's education system. ENEN facilitates exchanges and cooperation within academic institutions and strengthens their interactions with research centres. It delivers the European Master of Science in Nuclear Engineering certificate. It further develops, promotes and supports ENEN exchange courses in nuclear disciplines, including reactor safety, waste management and radiation protection. It facilitates and coordinates the participation of universities in European research projects. For the benefit of end users, the ENEN Association preserves nuclear knowledge and improves access to expertise by developing and establishing databases, websites and distance learning tools. It has a role as an interface between academia and industries, to define, disseminate and support interesting projects and research topics for internships, Masters theses and PhDs. By developing a framework for mutual recognition of professional training, licensing and professional recruitment throughout the European Union, ENEN is creating a nuclear 'European education and training area'.

Other initiatives to promote the renewal of competences are ongoing in various fields: nuclear safety courses organised by the SARNET Network of Excellence for severe-accident research [35], winter and summer schools in the field of actinide science organised by the ACTINET Network of Excellence [36], and the Frédéric Joliot and Otto Hahn Summer School on Nuclear Reactors [37] are examples of such initiatives. These and others will be coordinated at the European level by this technology platform.

For the development of more fundamental knowledge, the newly established European Research Council [38] should also address basic research needs in nuclear sciences and engineering, for example in the area of material and actinide sciences.

Research infrastructures

In addition to education and training, the availability of research infrastructures, and especially of the largest ones that need European funding, is a key element to maintain and further develop Europe's position in the field of nuclear fission and to support innovation. Major experimental reactors were built in the 1960s and 70s on a national basis. From a purely national approach to designing, constructing and operating research facilities and experimental reactors, Europe is now moving towards a community where large research tools are developed and used in common and where infrastructures are pooled in a complementary manner – a European research area (ERA) for infrastructures.

Two main objectives are sought:

- optimise the use of existing research infrastructures in Europe, by facilitating trans-national access, coordinating research programmes and networking of facilities and scientists, and promoting common experimental practices;
- renew, when necessary, infrastructures of common interest at European level and no longer on a national basis.

Material test reactors (MTRs) are examples of such essential research infrastructures: existing MTRs in Europe are ageing, as shown in Table 2. They will progressively be closed in the next decade, yet they are needed as a support for studies on ageing and life extension, safety, and fuel performance of generation-II and -III LWRs. MTRs are also needed to support material and fuel science advances for generation-IV reactors. In addition, they will continue to ensure the production of radio-nuclides for medical applications.

Table 2: Existing European material test reactors

Country	Reactor	Start/period of operation	Power (MWth)
Czech Republic	LVR 15	1957-	10
Norway	Halden	1960-	19
Sweden	R2	1960-2005	50
The Netherlands	HFR	1961-	45
Belgium	BR2	1961-	60/120
France	Osiris	1966-	70

Following a widely shared assessment of the situation, in particular in [40], a European vision on experimental reactors has been defined, building on three major initiatives:

- the construction of the high-performance Jules Horowitz Reactor (JHR) for material and fuel testing. JHR was identified in 2006 as a major research infrastructure in the ESFRI roadmap [41] and was recently launched for a start of operation in 2014, with the support of several European countries and the European Commission;
- a fast-spectrum experimental system, such as proposed by SCK•CEN (Belgian Nuclear Research Centre), to support the development and demonstration of an alternative technology to sodium;
- a reactor which should replace the high-flux reactor (HFR) and will be the main European provider of radionuclides for medical applications.

Finally, the proposed vision of a European fission research area for infrastructures would not be complete without the building of a research community through coordination and networking of scientists, research teams and through pooling of the existing and upcoming medium-sized research facilities. ACTINET [36], a Network of Excellence initiated in the Sixth Framework Programme (FP6) and devoted to actinide science, is an example of such a European network, pooling over twenty-five research institutions and several experimental laboratories operated as a multisite user facility. The SNE-TP will foster the coordination of the use and share of the research facilities and infrastructures at European level.

3. Role and presentation of the Sustainable Nuclear Energy Technology Platform

To remain competitive, European industry needs to specialise more in high-technology areas. Investment in research must be increased, coordination across Europe enhanced, and the technological content of industrial activity raised. Technology platforms address these challenges through:

- a shared vision of stakeholders;
- positive impact on a wide range of policies;
- reduced fragmentation of research and development efforts;
- mobilisation of public and private funding sources.

This is true especially for the energy sector, which is facing the objectives set out by the Commission of transforming the current energy system based on fossil fuels into a more sustainable one based on a diverse mix of energy sources and carriers, whilst addressing the challenges of security of supply, climate change, as well as increasing the competitiveness of Europe's energy industries. As the biggest provider of low-GHG-emitting energy in Europe, and one of the least expensive, nuclear fission has a key role to play in the future energy policy. Yet, research in Europe is still fragmented and suffers from a lack of funding, at national and industrial levels and at the level of the Euratom Framework Programme. Action is therefore needed now to enable Europe to retain its leading technological and industrial position in the field of civil nuclear technology.

To achieve this strategic goal, the nuclear RD&D community intends to establish a European technology platform. This platform should include the most important and innovative companies and other organisations working on nuclear energy in Europe and represent a balance of expert knowledge and stakeholder interests (industry, utilities, research organisations, universities, public bodies). It should establish a strategic research agenda (SRA) for developing technologies, taking into account users' requirements as well as safety considerations. The proposed Sustainable Nuclear Energy Technology Platform (SNE-TP) will fulfil the following tasks:

- establish a strategic research agenda (SRA) and a deployment strategy (DS) to ensure that nuclear fission energy is generated in a manner that meets the criteria for sustainable development in strict compliance with the safety requirements;

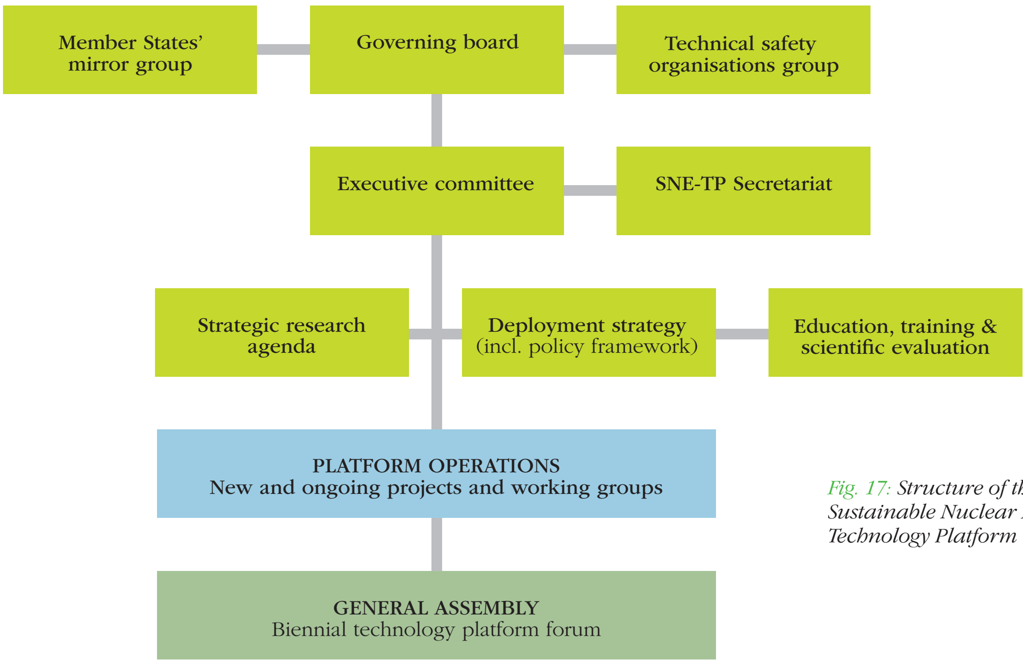


Fig. 17: Structure of the Sustainable Nuclear Energy Technology Platform

- coordinate techno-economic studies to monitor the advances of nuclear technologies and EU needs, and the role of nuclear energy in the EU energy mix;
- facilitate the integration of national programmes;
- seek synergies and links with other technology platforms (such as the Hydrogen and Fuel Cells Technology Platform and the future Geological Disposal Technology Platform) and interact with international initiatives in the field of energy, such as the Generation IV International Forum (GIF);
- provide expert advice and recommendations to the Commission and national governments for strengthening the European scientific base, integrating research teams and tools, optimising the use of existing research infrastructures, and creating new infrastructures (as needed), thereby contributing to the creation of a European research area (ERA);
- promote a coordinated training and educational system for developing nuclear competence in Europe;
- suggest topics for coordination or funding at European level, e.g. via the Euratom Framework Programme;
- foster joint initiatives between researchers, industry, utilities, Member States and the EU, such as joint undertakings;
- foster joint projects between Member States;
- disseminate the results of the above activities to appropriate policy-making and stakeholder bodies to ensure a common European vision;
- provide timely information about advances in nuclear energy to the general public.

As illustrated in Fig. 17, the Sustainable Nuclear Energy Technology Platform is steered and monitored by a governing board which provides guidance on how to initiate and push forward the strategic research agenda (Fig. 18) and the deployment strategy, building on existing European initiatives, networks and structures. The executive committee is responsible for running the platform and coordinating the different working groups and projects. It is supported by a secretariat. Three panels report to the executive committee, the first two draft and update the strategic research agenda and the deployment strategy respectively, and the third one coordinates education & training and conducts scientific evaluations of the different activities.

Two additional bodies provide input and recommendations to the governing board: the mirror group, providing information to ensure the effective coordination with national programmes, and the technical safety organisations (TSO) group.

The Member States' mirror group has as mission:

- to enhance the coordination and cooperation among interested Member States, the EC, and the technology platform (TP) by providing interfaces for coordination of Member-State activities within the TP;
- to provide opinion and advice to the TP governing board; and
- to advance the European Research Area (ERA) in sustainable nuclear fission energy.

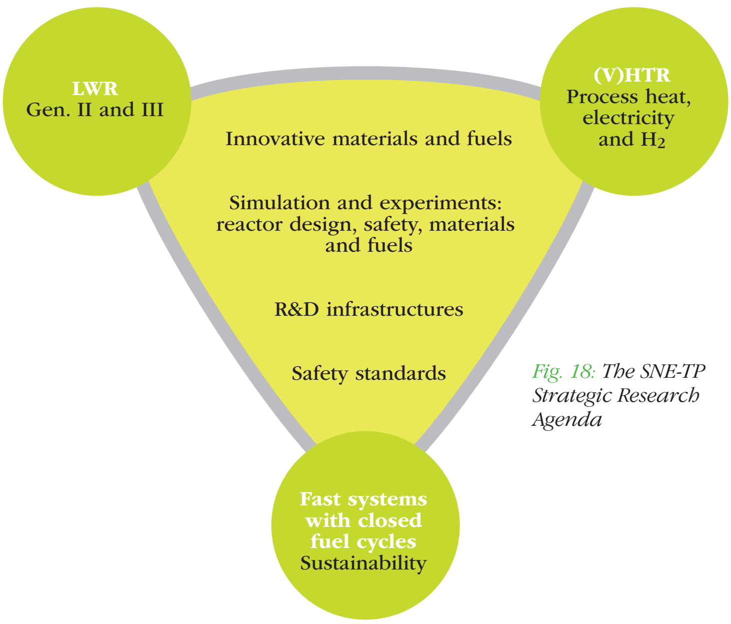


Fig. 18: The SNE-TP Strategic Research Agenda

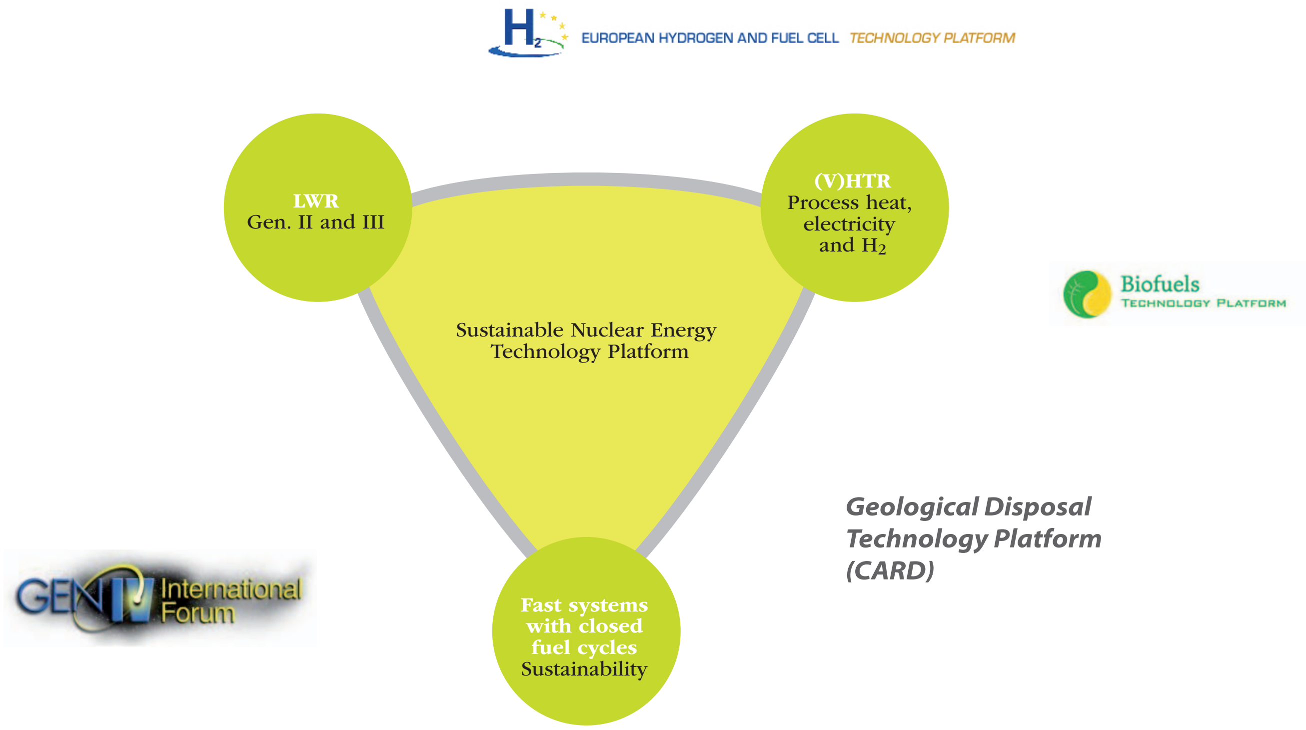


Fig. 19: Interaction of the SNE-TP with other technology platforms and international initiatives

The TSO group will provide advice on safety assessment-related R&D priorities with the objective to harmonise safety standards and methodologies in Europe. Its chairman will be a member of the executive committee. The TSOs will participate as active members in the working groups of the platform.

The ‘platform operations’ activities constitute the ‘heart’ of the SNE-TP, comprising:

1. ongoing and future projects, networks and initiatives including, where relevant, those supported via the Euratom Framework Programme;

2. national and regional programmes and initiatives.

All of these projects and initiatives are implemented according to the strategic research agenda and the deployment strategy. The activities of ‘platform operations’ include projects and initiatives encompassing three system programmes (light-water reactors, fast reactors with associated plants of the closed fuel cycle, and the (very)-high-temperature reactors), including waste conditioning, and transverse activities (materials and fuels development, development of simulation tools for reactor design, and R&D infrastructures). Of course, the elaboration, implementation and deployment of all of the activities within the SNE-TP are guided by the strategic research agenda and the deployment strategy. It should be noted that research and development activities related to residual high-level long-lived waste behaviour in geological disposal will be carried out within the framework of the proposed Geological Disposal Technology Platform currently being evaluated as part of the CARD project (Euratom Framework Programme) by the European waste agencies (Fig. 19).

Finally, every one or two years, the general assembly is convened as a means to facilitate the widest involvement of interested stakeholders, providing feedback, interaction, networking, and building commitment towards attaining the goals of the SNE-TP. These events will also allow new participants to join the platform, since membership is not limited to the contributors and endorsers of this present report.

4. Preliminary roadmaps: towards the strategic research agenda

The Strategic Research Agenda (SRA) of the SNE-TP will propose roadmaps for:

- optimising operating and next-generation light-water reactors (generations II and III)
- preparing the deployment of sustainable nuclear systems for the future, including advanced fuel cycles
- widening the range of nuclear energy applications.

Fig. 20 (next page) illustrates the different roadmaps of the platform up to around 2040, when industrial deployment of fast-neutron reactors can be envisaged.

To be deployed successfully, the SRA will require significant investments to support the R&D needed to meet the technological challenges, but also to update the necessary large infrastructures.

Currently identified large infrastructures of European interest for nuclear fission are:

- the Jules Horowitz high-performance material test reactor, identified in the European Strategy Forum on Research Infrastructures (ESFRI) roadmap as a mature project (evaluated at EUR 500 million in 2005) to replace to a large extent Europe's ageing materials test reactors (MTRs) (over 40 years old) when it will come into operation in 2014. The Jules Horowitz Reactor (JHR), launched recently with the support of several European countries and the European Commission, will in the short term support studies for generation-II and -III light-water reactors on ageing and life extension, safety and fuel performances, and support material and fuel developments for generation-IV reactors;
- the prototype sodium-cooled fast reactor with a power conversion system of 250 to 600 MWe to be built through a research-industry partnership, together with a fuel-fabrication pilot plant. The overall project costs are estimated at about EUR 2 billion;
- a fast-spectrum experimental system with a power range between 50 and 100 MWth to support the development and demonstration of an innovative reactor-cooling technology and whose cost is evaluated at EUR 600 million;
- a reactor to replace the high-flux reactor (HFR) as the main European provider of radio-nuclides for medical applications and as such should be supported by the medical industry. Estimated costs are around EUR 200 million;
- a first-of-a-kind very-high-temperature reactor (VHTR) to demonstrate cogeneration technologies, depending on the market need for hydrogen or synthetic fuel, typically costing EUR 1.5 to 2 billion.

Besides these major research infrastructures, other experimental facilities are needed to support technology developments and safety studies. These include experimental loops (e.g. sodium, lead and gas loops) as well as material-development facilities and those necessary to develop fully closed fuel cycles.

Networking of existing facilities and construction of new ones operated as 'European user facilities' are essential for meeting the R&D needs described above, for advancing the European Research Area (ERA), and for attracting a new generation of scientists and engineers to contribute to new and challenging programmes. Modern research infrastructures are essential for enabling the scientific community to remain at the forefront of nuclear fission science and technology and to support the development of industrial innovations for nuclear reactors, fuels and fuel cycle.

Fig. 20: Preliminary research roadmaps for the different technologies

Reactors

Gen. II-III LWRs

- 2010: Harmonised lifetime extension methodology
- 2010-12: Optimisation of severe accident management procedure for LWRs
  Continuous optimisation of fuel performances and safety
- 2010: Improved fuel-cycle economy; viability of high conversion ratio designs
- 2012: Viability of SCWR

Gen. IV fast-neutron reactors: Sustainability

- Sodium-cooled fast reactor (SFR) R&D programmes to bring innovations (safety, competitiveness):
- 2009: Pre-selection of design options
- 2012: Confirmation of design options – preliminary and detailed design, safety analysis reports, validation R&D, construction of a prototype SFR in the range of 250-600 MWe
- 2020: Start-up of operations
- R&D to assess viability and performance of gas- and lead-cooled fast reactors, as well as accelerator-driven systems:
  - Selection in 2010-12 of a second type of fast-neutron system of importance for Europe. Construction of a 50-100 MWth first experimental facility in Europe
  - 2020: Start-up of operations
- 2020-2040: Further R&D to design and optimise full-scale systems, to build a first-of-a-kind fast reactor and start of commercial deployment

New applications of nuclear energy

- Development of alternative fuels to oil for transport, including hydrogen and synthetic hydrocarbon fuel production, as well as processes that require heat and/or electricity, such as desalination
- Tentative R&D agenda to support the realisation of first-of-a-kind VHTR reactor around 2020 could be the following:
  - 2010-12: Confirmation of key technologies (fuel, materials, components, power conversion, hydrogen production)
  - 2015-20: Construction of a VHTR and demonstration of cogeneration applications

2010 — 2020 — 2030 — 2040 — 2050

Fuel cycle

Advanced recycling processes

- 2012: Selection of technologies for the closed fuel cycle with the development of minor actinide bearing fuels; selection made on a technological and economical basis, with an optimisation of the waste form in terms of long-term radio-toxicity and thermal load impact on the required volume for the geological repository
- Support the operation of a fast-reactor prototype from 2020 onwards:
  - Construction in the period 2012-2017 of:
    - a fuel-manufacturing workshop
    - a micropilot for minor actinide recycling (separation and minor actinide bearing fuel manufacturing)
- 2020-2040: Further R&D to design and optimise full-scale systems and to deploy advanced fuel-cycle facilities around 2040

5. Recommendations

To maintain its role as a worldwide player in the context of a global increase in energy demand, Europe needs an energy mix that tackles the following challenges: increased security of supply, cost-competitiveness, and reduction of greenhouse-gas emissions to combat climate change.

With these challenges in mind, it should be noted that:

- to fulfil Europe's commitment to substantially reduce CO_2 emissions by 2020 and beyond, a long-term energy policy urgently needs to be implemented. Nuclear power and hydro power are currently the only sustainable large-scale means for producing continuously available base-load and almost carbon-free electricity. Sustainable nuclear energy has the potential for further reducing CO_2 emissions over the very long term;
- to secure Europe's energy supply and its competitiveness, generation-III light-water reactors should be developed and supply a significant share of the EU's energy needs. Gradually, generation-IV fast reactors with closed fuel cycles should be introduced. Through multi-recycling, such nuclear systems will maximise the use of the energy potential of the fuel, thereby ensuring that nuclear energy remains an economical and sustainable source of energy for thousands of years. Increasing the relative share of nuclear electricity production will reduce Europe's external dependency on fossil fuels, thereby further enhancing the security of its energy supply;
- to effectively combat climate change, the cost of greenhouse-gas emissions must be taken into account at a worldwide level. Nuclear power must be included in the post-Kyoto international negotiations, as a part of clean development mechanisms, contributing to sustainable development.

The authors of this document therefore recommend establishing the Sustainable Nuclear Energy Technology Platform (SNE-TP), with the following objectives:

- preserve and strengthen the European technological leadership and nuclear industry through a strong and long-term R&D programme, involving fuel cycles and reactor systems of generation-II, -III and -IV types.
  - In order to ensure the development of sustainable nuclear power on a large scale worldwide, the fuel cycle must be closed, i.e. recycling uranium and plutonium. Such fuel-cycle strategies can already be implemented with currently available technology in conjunction with generation-II and -III reactors. With further technological breakthroughs and R&D efforts, multi-recycling of all actinides can be implemented in conjunction with generation-IV reactors.
  - In order to maintain its technological leadership in a worldwide context of nuclear market renaissance, Europe has to build a generation-IV prototype. The construction of a sodium fast-neutron reactor prototype is planned in France with international and industrial partnerships. In parallel, Europe should work on an alternative design of fast-spectrum experimental system (helium-cooled or lead-cooled fast reactor). Sustained research and technological breakthroughs are needed to design and build such generation-IV systems. Dedicated R&D for this purpose needs to be supported from public funds, including as part of the Euratom Framework Programme. The European R&D programmes could benefit from international cooperation with corresponding activities within Generation IV International Forum (GIF) and other international activities.
  - In order to maintain a high level of safety, based on national and international standards, safety regulations and guidelines have to be further developed and harmonised. Research programmes on reactor safety and protection against radiological hazards should continue to be conducted. Risk-governance methodologies with participation of representatives from the public at large should be further developed;
- enhance Europe's technological leadership in nuclear science and engineering by the production of scientific and technical skills to keep pace with the corresponding industrial and R&D demand. Therefore, education and training in nuclear science and engineering must be strengthened. In addition, R&D infrastructures of European interest must be renewed and consolidated;
- in an environmentally benign and sustainable economy, contribute to the production of synthetic fuels and hydrogen needs on the basis of non-GHG-emitting production sources. Therefore, in addition to electricity production, the use of nuclear power to produce hydrogen and industrial heat should become a high-priority R&D topic.

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Annex III
List of acronyms

ADS	accelerator-driven system
CCGT	combined-cycle gas turbine
DS	deployment strategy
EM	energy management
EPR	European Pressurised-water Reactor
ERA	European Research Area
ESFRI	European Strategy Forum on Research Infrastructures
FP	(Euratom research) framework programme
GFR	gas-cooled fast reactor
GHG	greenhouse gas
GIF	Generation IV International Forum
HFR	high-flux reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
JHR	Jules Horowitz Reactor
LFR	lead-cooled fast reactor
LWR	light-water reactor
MOX	mixed oxide (fuel)
MTR	material test reactor
NEA	Nuclear Energy Agency
NPP	nuclear power plant
R&D	research and development
RD&D	research, development and demonstration
SCWR	super-critical water reactor
SET Plan	Strategic Energy Technology Plan
SFR	sodium-cooled fast reactor
SNE-TP	Sustainable Nuclear Energy Technology Platform
SRA	strategic research agenda
TSO	technical safety organisation
VHTR	very-high-temperature reactor
WENRA	Western European Nuclear Regulators Association

Units:

k	kilo
M	mega
G	giga
T	tera
t	tonne
toe	tonne of oil equivalent
We/Wth	watt electric/watt thermal
Wh	watt-hour

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This report, endorsed by a large number of stakeholders – technology suppliers, utilities, research organisations, technical safety organisations – accompanies the launch of the Sustainable Nuclear Energy Technology Platform (SNE-TP). It proposes a vision for nuclear fission energy up to the middle of the century, as part of Europe's future low-carbon energy mix.

The report outlines the current situation of nuclear energy, which provides a third of Europe's electricity with nearly no greenhouse-gas emissions. It presents a short- and medium-term view, the renaissance of nuclear power with generation-III reactors. It also presents a long-term view on how to overcome the barriers for the development of a sustainable nuclear fission technology with generation-IV reactors.

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