Prospects for nuclear energy in Europe

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Abstract: This paper adds to the debate about the role of nuclear power in sustainable development by providing an overview of its current status and future prospects in Europe. The main economic and environmental concerns that nuclear energy could mitigate – energy dependency, air pollution and climate change – are analysed over three time frames. Particularly important are five problematic features of nuclear energy: waste management, proliferation security, operation safety, economic competitiveness and public acceptance. The main conclusion is that Europe's nuclear capacity is unlikely to change significantly over the next two decades. Its prospects beyond 2025 will depend on the relative weight given to the benefits and drawbacks of nuclear power, as well as the long-term sustainability implications of the use of all energy resources.

Keywords: nuclear energy in Europe; sustainable development; supply security; air pollution; climate change; waste management; nuclear proliferation; reactor safety; energy economics; public acceptance.

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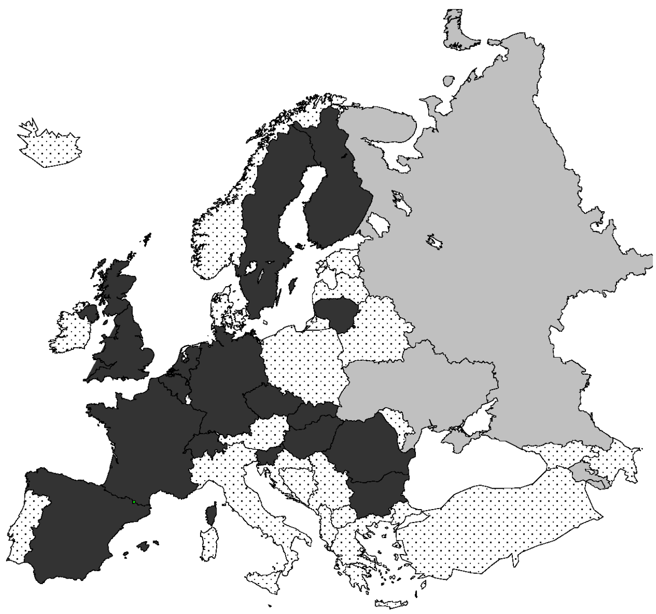
1 Introduction

It is difficult to predict with any confidence what the 21st century will hold for nuclear power. Still, the factors that will shape its future are rather clear. The aim of this paper is to analyse the possible contribution of nuclear energy to sustainable development in Europe, on the basis of a concise inspection of the main driving forces involved. Arguments regarding radioactive waste, nuclear proliferation, reactor accidents, economic competitiveness and public opinion continue to create justified concerns and thereby hinder nuclear energy policy-making. Still, worries over energy supply security, local air pollution and global climate change provide reason to reassess its potential share in European power production. While some European countries (like Austria and Italy) have presently no plans to build nuclear power capacity or are legally committed to gradually phase out domestic nuclear power production (such as Germany and Sweden), others (e.g., Finland and France) decisively continue to preserve a significant part of nuclear energy in their national electricity generation portfolio. Recent policy directions in yet other countries (amongst which the Netherlands and the UK) show that nuclear energy is reappearing on the political agenda. This paper reviews some of the main issues concerning the long-term prospects for nuclear energy in Europe, as well as the major relevant sustainability arguments in this context.

In this paper 'Europe' refers to all European countries that were not part of the former Soviet Union except the three Baltic States. Hence, not only members but also non-members of the current European Union (EU) are covered, including for example Turkey. In practice, however, this paper will mostly focus on the countries in this geographic area that presently possess nuclear power (see Figure 1): 15 EU members (Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, Lithuania, Netherlands, Romania, Slovakia, Slovenia, Spain, Sweden, UK) and Switzerland. Occasionally some of the remaining 20 countries that today do not produce nuclear energy domestically are referred to.[1] Note that Figure 1 also shows some countries not covered by this study, among which three with domestic nuclear power: Armenia, Russia and Ukraine.

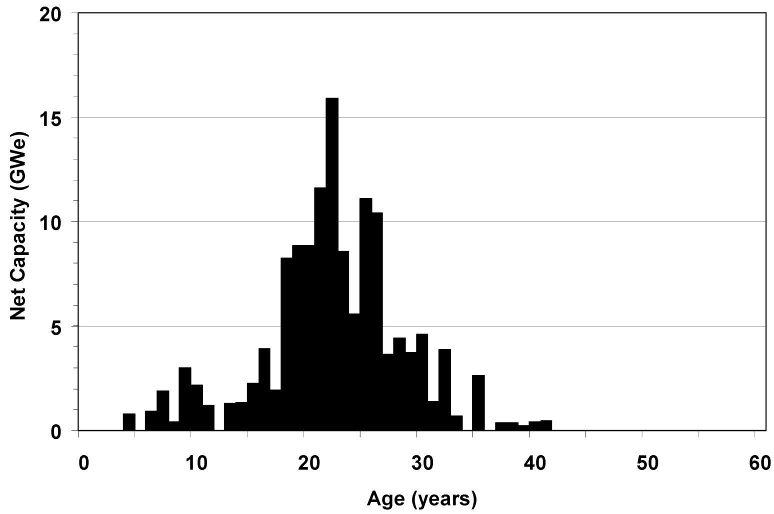
Figure 1 Nuclear power in Europe



In the geographic area considered, currently 16 countries (depicted in dark) produce nuclear energy domestically and 20 countries (in light) do not. In grey are depicted countries possessing nuclear power that are not included in this analysis, that is, Armenia, Russia and Ukraine.

Projections for the future contribution of nuclear power in Europe vary widely depending on the underlying assumptions. Also, European countries hold different views on the specific role of nuclear power, as well as energy issues in general. As the current picture remains mixed, the purpose of this paper is not so much to provide a forecast, but rather to identify and succinctly analyse the factors that will influence the future of European nuclear power, while it is attempted to stay as descriptive as possible and avoid providing prescriptions. An assessment is made of how different assumptions regarding these factors may lead to different nuclear energy scenarios. One of the primary determinants for the future of nuclear energy in Europe is the age distribution of current nuclear power plants. Figure 2 shows the aggregate net capacity of grid-connected European nuclear reactors by years of operation. While only a small share of the total installed reactor capacity has reached an age of 40 years, the large majority has been operating for at least ten years. Although most reactors have been designed to operate for 30–40 years, there is a tendency today to extend the lifetime of reactors to 50–60 years.

Figure 2 Aggregated net capacity of nuclear power plants in Europe per age of operation



Source: IAEA-PRIS (2006), data from February 2006

Energy and electricity consumption in Europe are expected to continue to increase at least until 2030, and most likely beyond, although slower than in other parts of the world and notably developing countries (see, e.g., IEA, 2006a; IIASA/WEC, 1998). Growing energy demand will be one of the key arguments in the debate about nuclear power's future in Europe. The increase in European energy use cannot be explained on the basis of anticipated demographic changes, as Europe's population is expected to decrease at an average rate of a few per mille per year until 2050. The main driver for the projected increase in energy use is considered to be a growing European economy (expressed in GDP, Gross Domestic Product). GDP is estimated to increase by approximately 1.5%/year until 2050 for OECD (Organisation for Economic Co-operation and Development) counties in Europe and as much as 3.6%/year for European countries with economies in transition (EIT), in both cases plus or minus fairly large uncertainties (IEA, 2006b). The baseline scenario of IEA (2006b) assumes an efficiency gain in final energy consumption per unit of GDP (hence also called 'energy-GDP decoupling') of approximately 1.0%/year and 2.6%/year, for OECD Europe and European EIT respectively. This leads to a total energy consumption growth rate in Europe in the range of 0.5–1.0%/year until the middle of the century. As a large part of the prospected growth in energy use is foreseen in the electricity sector, all power generation options, including nuclear energy, will in principle receive accrued attention.

Section 2 of this paper describes the social and economic context in which the future of nuclear energy in Europe should be understood, and describes the main environmental concerns that nuclear power could contribute to alleviate. In particular, climate change, air pollution, resource availability, energy security, economic competitiveness, as well as public opinion and acceptance are discussed. Section 3 examines three fundamental and negative characteristics of nuclear power that are still of great concern – radioactive waste, nuclear proliferation and reactor accidents – and assesses each of them, qualitatively, in terms of the potential risks they involve. The section ends with an assessment of the prospects for nuclear energy in Europe in three time periods, up to 2025, 2050 and 2100, based on the arguments put forward in Sections 2 and 3. As the future of nuclear energy in Europe will also be affected by its evolution and events taking place in other parts of the world, Section 4 briefly sketches some of the relevant 'extra-regional linkages'. Section 5 concludes and provides a few final remarks.

2 Socio-economic and environmental context

Addressing the role of nuclear energy in establishing sustainable energy paths requires an analysis of environmental, economic and social indicators, used for nuclear energy in the same way as for other energy options (Bruggink and van der Zwaan, 2002; NEA, 2001; Rothwell and van der Zwaan, 2003).

2.1 Climate change and air pollution

According to a business-as-usual scenario, the prospected growth in energy consumption worldwide and in Europe will lead to a gradual but steady increase in the level of greenhouse gas (GHG) emissions, due to the predominance of GHG-intensive fossil fuels in primary energy supply (IPCC, 2000). By way of contrast, nuclear power emits low levels of GHGs, even when considering the complete nuclear fuel chain, including the mining and enrichment of uranium and the construction of the power plant. Typically, nuclear power emits no more than a few percent of GHGs per unit of generated electricity in comparison to coal-, oil-, or even natural gas-based power production, and its GHG emission levels are in the same order of magnitude as those of renewables like wind or solar power. Today, nuclear power is, along with hydropower, the only low-GHG-emitting source of electricity that is commercially deployed on a large scale, and as such already avoids worldwide, by replacing fossil fuels, the annual emission of about 2 $GtCO_2$, on a total of 25 $GtCO_2$ anthropogenic CO_2 emissions. As the mitigation of climate change is now increasingly being recognised as one of the largest global challenges for mankind, low-GHG emitting technologies such as nuclear energy receive renewed consideration.

If nuclear power is kept in the energy mix for reasons of achieving GHG emission reductions, it can only contribute to addressing the problem of climate change when it is expanded significantly on a global scale (Sailor et al., 2000). If nuclear energy were expanded 10-fold (however unimaginable such an expansion today may be, notably in terms of the rate at which new reactors would need to be built – factors higher than the historically observed reactor construction rate of, for example, the 1980s), it could contribute to reducing total annual CO_2 emissions in the second half of the 21st century by about 30% (van der Zwaan, 2002). Hence, under such a challenging scenario, nuclear energy can still at best only be part of the solution, and should be complemented by drastic fossil fuel decarbonisation efforts, e.g., through the application of CO_2 capture and storage (CCS) technology, a massive deployment of renewables, solutions that stretch beyond the power sector (as nuclear energy is at present not suitable for the transport sector), and/or far-reaching efficiency measures, in order to attain a reduction of CO_2 emissions down to about one third of the present level by the end of the century. Such a CO_2 emissions profile would preclude more than a doubling of the atmospheric CO_2 concentration. A doubling of the atmospheric CO_2 concentration with respect to the pre-industrialisation level would correspond to an increase of the average atmospheric temperature by typically a few degrees Celsius.

It is evident that nuclear energy can constitute no panacea to the desired reduction of GHG emission levels. If the GHG mitigation ambitions of some European countries remain as high as at present (involving, for example, a reduction of CO_2 emissions by 50% by the middle of the century), nuclear energy could well prove, for the moment at least, an essential component in the portfolio of emission reduction options. Europe is the largest nuclear energy region in the world, and has 137 GWe installed nuclear capacity, compared to a global figure of around 330 GWe. Since nuclear energy thereby generates about one third of the EU's electricity use, Europe is in principle in a good position to increase the role of nuclear energy for climate change management. In spite of the fact that nuclear energy growth in Europe currently faces stagnation, and that the planning and construction of new nuclear power plants involve long lead times, nuclear power can, nonetheless, significantly contribute to additional CO_2 emission reductions in a couple of decades from today. This would require a substantial expansion of nuclear capacity, that would also help mitigating several environmental and health problems related to local and regional air pollution, as nuclear power does not generate emissions of, for example, SO_2, NO_x, Hg or particulates, unlike its fossil counterpart coal-based power, and releases (like coal-based power) only low levels of radioactive effluents into the atmosphere.

2.2 *Resource availability and energy security*

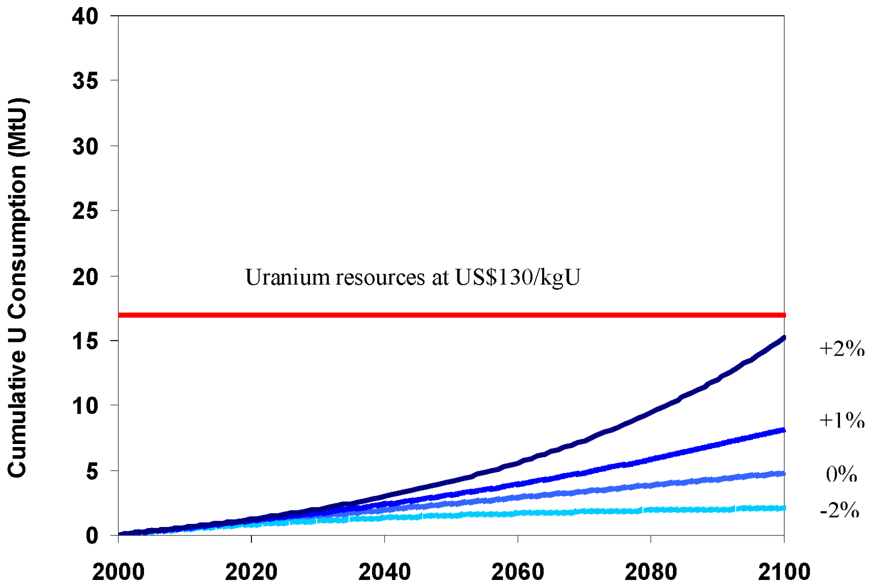
Today, another reason for maintaining or expanding nuclear power capacity would be to enhance Europe's energy security and reduce its dependency on imports of fossil fuels, especially natural gas from the Middle East and Russia.[2] In a business-as-usual scenario, the EU's dependency on imported energy would increase from 50% today to about 70% in 2030 (EU, 2000). Concerns regarding energy supply security drove the investments in nuclear power in Europe during the oil crises of the 1970s, even though Europe does not possess large domestic uranium resources. Similar events in the future could well again lead to an invigorated interest in nuclear energy and an associated impulse to the construction of new nuclear power plants. The presence of domestic natural uranium resources is hereby not a necessary condition for enhancing energy security through nuclear power. The reasons are that uranium is widely available, easily storable and (in terms of the contribution of resource expenses to overall electricity production costs) cheaply acquirable. Globally a diverse roster of stable uranium producers exists, and the relatively small space required for uranium storage implies that strategic reserves can easily be built. Furthermore, since uranium resource costs contribute only little to total electricity generation costs, nuclear power is little sensitive to fluctuations or even significant increases in the price of uranium, so that price shocks and market volatilities as experienced in the oil and natural gas sector are largely absent.

Given the large global uranium resource base, Europe can safely include nuclear energy among the options presumed fit for reducing its dependency on imported energy carriers. A few caveats exist. First, nuclear energy remains, at least for the time being, an alternative in the electricity sector only. It is no substitute for oil as transport fuel, probably for a long time to come, unless the sizeable technical, chemical and economic hurdles with regard to the production of hydrogen through nuclear power, in conjunction with the use of fuel cells, can be overcome.[3] Second, irrespective of nuclear energy's advantage over the use of coal in terms of the latter's bulkiness and corresponding resource transport needs, there are limits to nuclear power's substitution value given the abundance, spread and affordability of coal worldwide. Third, nuclear energy possesses in principle great value in its capacity to improve energy independence, especially when it replaces imported natural gas, and even more so when this gas originates from unstable regions outside Europe. Some natural gas-based power generation, however, will be difficult to replace, since nuclear energy does not have the flexibility and adjustability of gas-fired power plants that are particularly fit for peak-loading and balancing requirements. Nevertheless, the energy security merits of nuclear power remain sizeable.

Still, sometimes concerns are expressed regarding the estimated amounts of uranium recoverable at a given price and whether global resources are in agreement with scenarios of uranium consumption during this century. There are several reasons to believe that these worries are unjustified (Bunn et al., 2005). A doubling of the uranium price typically affects the production cost of electricity only by several percent. Therefore, while large quantities of uranium are still recoverable at the current price of US$40–US$50/kgU, uranium reserves are often quoted at higher prices such as US$130/kgU. The Nuclear Energy Agency (NEA) estimates that total world conventional uranium resources, available at less than US$130/kgU, amount to about 17 MtU (OECD NEA and IAEA, 2002). For several reasons this estimate may be judged conservative. First, many countries do not report resources in the lower-confidence categories or with costs as high as US$130/kgU. Second, the estimate of 17 MtU is limited to conventional resources, i.e., deposits in which the uranium ore is rich enough to justify mining at the indicated price, and does not take into account cases where uranium can be produced as a by-product. Third, low uranium prices and released military stocks over the last two decades virtually eliminated incentives for supplementary uranium exploration, so that large quantities of undiscovered uranium, not included in the NEA estimates, are still likely to exist, particularly in the higher-cost categories. Hence, there is high probability that the amount of uranium that will ultimately prove recoverable below US$130/kgU is significantly greater than 17 MtU. Figure 3 shows four scenarios of global cumulative uranium consumption given annual nuclear electricity production growth rates of –2%, 0%, +1% and +2%. The growth rates correspond to nuclear power expansion factors of 0.1, 1.0, 2.7 and 7.2, respectively, in 2100 compared to the normalised value of 2500

TWh generated in 2000 – assuming an average uranium requirement of 19 tU/TWh based on a once-through fuel cycle. The horizontal line represents the conservative estimate of 17 MtU for the world-total of uranium resources at a maximum price of US$130/kgU. Figure 3 demonstrates that even under a significant expansion of nuclear energy during the 21st century, sufficient uranium resources will be available at prices that have only limited effect (<10%) on overall electricity production costs.

Figure 3 Scenarios of cumulative uranium consumption (see online version for colours)

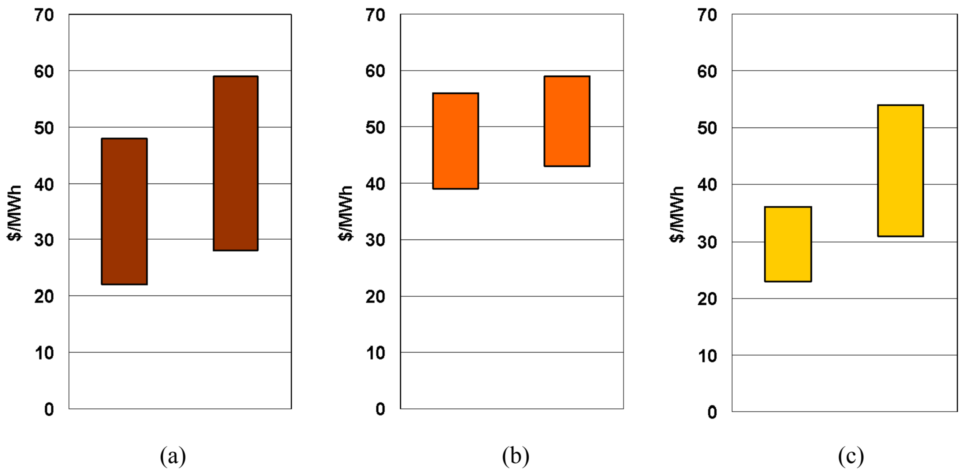


Assumptions include annual nuclear electricity production growth rates of –2%, 0%, +1% and +2%, a once-through fuel cycle, an average uranium requirement of 19 tU/TWh and 2500 TWh nuclear power generated in 2000. The horizontal line represents the estimated uranium resources at US$130/kgU.

2.3 Costs and economic competitiveness

Costs and economic competitiveness, as well as additional stimuli like government subsidies in some cases, are among the principal determinants of whether specific technologies can acquire a sizeable share in the power sector. Basically, nuclear energy is able to compete well with its two main counterparts in the electricity sector, coal- and natural gas-based power generation. Figure 4 depicts the range of total levelised electricity production costs for coal, natural gas and nuclear power plants, and for two discount rates to reflect different valuations of future costs and benefits or, alternatively, different investment environments. The more investment-intensive the technology, the more sensitive the levelised costs to the value of the discount rate. The upfront investment part of these costs may be twice as high for coal as for natural gas and three times higher for nuclear power (OECD, 2005). Still, as a result of the low fuel cost component for nuclear energy in comparison to coal- and especially natural gas-based power, in terms of overall levelised costs the former generally constitutes a good competitor to the latter two. Naturally, the projected costs of generating electricity from fossil fuels are highly dependent on the prevailing price of fuels. The electricity costs presented in Figure 4 cover investment, fuel, and operation and maintenance costs (including costs associated with waste disposal and reactor decommissioning), but do not include CO_2 emission (permit) prices and do not account for possible power plant lifetime extensions. They account for modest fossil fuel price increases over the coming decades, but do not reflect the possibility of sustained high price levels as experienced recently for oil and natural gas. Such sustained high prices would increase the competitiveness of nuclear power. For all three alternatives a dependency exists on where and under what operating conditions the electricity is produced. The cost ranges indicated by the bars in the three charts of Figure 4 mostly reflect different domestic circumstances in OECD countries. If one takes the average of these cost ranges as a measure for comparison, nuclear power marginally proves to be the least cost option, with total levelised costs of about 30 US$/MWh when a 5% per year discount rate is applied and a little over 40 US$/MWh with a discount rate of 10% per year.

Figure 4 Range of total levelised electricity generation costs (in US$/MWh): (a) coal; (b) gas and (c) nuclear (see online version for colours)



Costs for (a) coal, (b) natural gas and (c) (generation-II) nuclear power plants for two discount rates (left bar 5% per year, and right bar 10% per year).

Source: OECD (2005)

Nevertheless, the high capital cost necessary for the construction of a nuclear power plant forms an impediment for investors. Regulatory, legal and political incertitude often exacerbates the hesitation of potential investors. In fact, every European country that has developed nuclear power has had some form of government support to address these uncertainties. The ongoing process of electricity market liberalisation and deregulation in Europe, and the associated decreasing influence of national authorities on strategic energy planning, disadvantages new investments in nuclear energy. Still, the recent cases of Finland and France demonstrate that it is possible to build new nuclear power plants in this modified economic environment. If attractive financial conditions (involving, for example, low capital interest rates) can be guaranteed elsewhere, similar to those allowing new construction in Finland and France, Europe can continue to profit from the levelised cost-competitiveness of nuclear baseload electricity. Furthermore, possible reductions in the construction cost of nuclear power plants can narrow the gap between the investments needed to develop a nuclear reactor and those required for the construction of a coal- or natural gas-based power plant (if the latter are assumed to remain constant). Similarly, a reduction in building times and operation and maintenance costs can increase the interest for nuclear energy, even if more stringent reactor safety and waste disposal requirements were adopted (MIT, 2003).

If climate change concerns are seriously addressed, with targets well beyond the Kyoto Protocol, and consequently CO_2 abatement considerations become a permanent economic parameter in project appraisal, nuclear energy and renewable resources will profit from their low levels of GHG emissions. In some cases nuclear energy may be the preferred climate-friendly option for baseload power production, depending particularly on the availability and affordability of renewables in the locality considered. If for climate control purposes coal- or natural gas-based power production is complemented with CCS – supposing that CCS develops into the affordable and realisable clean technology innovation it presently promises to become – the difference in capital costs between fossil fuel-based and nuclear power generation can turn in favour of nuclear energy. CO_2 emission credits, as enacted since January 2005 in the EU-25 through the Emissions Trading System (ETS), give nuclear energy in principle a cost advantage relative to fossil-fuelled power production. The economic benefits for nuclear power associated with the ETS, however, have so far become little apparent. In the longer run on the other hand, a sustained and stable ETS may lead to renewed investments in the construction of nuclear power plants. While ETS CO_2 prices have already had a market impact with prices varying between 10–20 €/tCO_2, investments and electricity prices will be truly affected by CO_2 prices that eventually are prospected to increase by an order of magnitude, in favour of nuclear energy.

2.4 Public opinion and acceptance

Issues of public opinion and acceptance apply in principle to all forms of energy but they have particularly done so for nuclear power. Whereas current debates on climate change and energy supply security positively influence the public attitude towards nuclear energy, for the moment support for new nuclear power plants remains tentative. Findings of a recent survey, conducted among 18,000 citizens of 18 countries representing the major regions of the world, show that 62% believe that existing nuclear reactors should continue to be used, but 59% are not favourable of building new nuclear plants (Globescan, 2005). Also, when citizens from the EU-25 were asked what national governments should focus on in order to reduce the EU's energy dependency, only 12% answered that the use of nuclear energy should be further developed first (Eurobarometer, 2006). As the impacts of climate change and the vulnerability of the European economy to foreign fuel imports become more evident, it is likely that the gradual shift in public opinion observed over the last decade will further develop towards less scepticism or in favour of nuclear energy. The Chernobyl accident has dramatically demonstrated that a single event can abruptly change the public acceptance of a technology. Inversely, a catastrophe associated with climate change, or a long-lasting disruption in the supply of, for example, natural gas as a result of geopolitical tensions, may lead to a step-change in the support for nuclear power, in Europe as elsewhere. So, public opinion that on a time scale of decades appears constant may nonetheless be subject to significant variability in the longer run.

The controversy over nuclear energy has mostly been related to the problems of radioactive waste, nuclear proliferation and reactor safety, although antinuclear sentiments also stem from other less identifiable origins. Progress on these three drivers of public scepticism is likely to positively influence support for the nuclear industry in general. For example, once an underground waste repository is in operation in Europe and proves, during at least human time scales, to contain radioactive waste safely, the general public may start accepting it as a satisfactory and potentially permanent solution for the back-end management of the nuclear fuel cycle. Similarly, a positive shift may take place if some of the presently salient nuclear proliferation concerns can be addressed, such as those regarding the nuclear ambitions of Iran and North Korea, or if reactors, installations and materials can be used that are more proliferation-resistant to nuclear weapons development than current ones. Nuclear energy may also be viewed more confidently if the nuclear industry can further increase its reliable safety record of the past two decades. Of course, any severe incident related to these aspects, such as the use of a nuclear or radiological device ('dirty bomb') by terrorists, or another major nuclear reactor accident, will likewise imply a major setback for the popularity of nuclear energy. Other issues, such as the connection of nuclear energy with its military origin (and the associated secrecy and costs involved), the technical complexity of nuclear science and engineering, or the invisibility of radioactivity, probably continue to play a role in forming the larger public's opinion about the civil use and applications of nuclear technology. How to address these aspects is often not well understood, but they will be affected by the extent to which the nuclear industry proves capable of raising public confidence in the safety, efficiency and relative advantages of nuclear power through appropriate modern information and communication means.

3 Nuclear concerns and prospects in Europe

Whether or not nuclear energy will significantly contribute to mitigate global climate change, decrease local air pollution and enhance energy supply security will be determined in particular by how well the three critical concerns unique to the use of nuclear energy (i.e., radioactive waste, nuclear proliferation and reactor accidents) are addressed during the 21st century (see, for example, MIT, 2003).

3.1 Radioactive waste

While radioactive waste production occurs at basically every stage of the nuclear fuel cycle in solid, liquid and gaseous states, spent nuclear fuel is the most problematic form of waste, since it generates heat during many years after offloading from the reactor core and remains highly radioactive for thousands of years. The attitude towards managing spent fuel consists of 'concentration and protection' (as opposed to 'dilution and exposure', practiced in some industrial sectors): radioactive contamination of the external environment from spent fuel storage is minimised through several layers of physical containment, most likely including geological deposition deep underground. Studies have been undertaken that demonstrate the technical reliability of such depositories. In terms of actual implementation, however, the management and final disposal of spent nuclear fuel remains a challenge for national governments and the nuclear industry. To this date, no country has yet implemented a permanent solution for nuclear waste storage from the civil nuclear industry.

While many European governments delay decisions on this subject, progress on deep geological disposal has been made in Finland, France and Sweden. The Finnish government has made a decision to start building a final repository for spent nuclear fuel in 2011 near Olkiluoto, which would be in operation around 2020. On the basis of studies performed between 1991 and 2005, the French government has initiated in 2006 a debate in Parliament to choose a solution for the long-term disposal of spent nuclear fuel. Sweden is planning to make a site proposal in 2007 on the basis of ongoing geological investigations at two candidate locations. The main issue concerning underground storage remains uncertainty about the integrity of spent fuel canisters, and whether the isolation offered by geological formations will be sufficient over a period of thousands of years. The fear is that canisters, as a result of corrosion, will start to leak and consequently contaminate groundwater at some point in the future. By and large, this explains not only the hesitation by governments to implement final waste depositories but also the sceptical attitude of the general public.

The influence of public opinion on governments' decision-making regarding underground nuclear waste burial, notably through local opposition (the Not-In-My-Back-Yard or NIMBY syndrome), is an important determinant for the current authorities' irresolution. The problem of high-level radioactive waste, however, is dynamic, since solutions that contribute to its reduction are being investigated. Two main channels exist through which the problem could be mitigated: reducing the radioactive lifetime of the long-living isotopes the waste contains by transmutation processes and organising its disposal regionally through Internationally Monitored Waste Repositories (IMWRs). The European Commission is preparing legislation that creates a regulatory framework for EU states to undertake concrete and timely action for the development of permanent, underground and aboveground, disposal facilities. Unfortunately, no process yet exists for designing a pan-European approach towards nuclear waste disposal, for example, through EURATOM. The public is expected to become less sceptical once the first geological repositories become operational and disposal technologies are demonstrated in practice. Progress in the fields of transmutation technology and the establishment of multinational IMWRs is also likely to benefit the public attitude regarding the nuclear waste problem.

3.2 Nuclear proliferation

Nuclear power generation inherently involves the risk that nuclear industry related technologies and materials are diverted for non-civil purposes. Among nuclear energy's main proliferation threats are the use of enrichment facilities and the production of fissile materials. Countries operating enrichment technologies or organised terrorist groups possessing highly enriched uranium (HEU) may relatively easily construct a basic fission device and use it for military or terrorist purposes. Several plutonium isotopes contained in (reactor-grade) spent fuel, accounting for 1–2% of its volume, are fissile and can serve to fabricate a nuclear explosive device. Especially when spent fuel from the civil nuclear industry is reprocessed, this problem becomes apparent: plutonium contained in spent fuel is reasonably safe against diversion for weapons use because of the highly radioactive waste materials in which it is embedded, but its separation during reprocessing makes it vulnerable for direct military or terrorist use, even while it is of lower quality than weapon-grade plutonium. The current political crises between the international community and countries like Iran and North Korea demonstrate the breadth of nuclear proliferation concerns and negatively affect the use of nuclear energy for power production worldwide.

The global control of sensitive technologies, monitoring of nuclear activities, and safeguarding and deletion of fissile materials like HEU and plutonium, are central to the solution of nuclear proliferation. In order to avoid fissile materials being diverted for non-civil purposes, dedicated technical efforts and effective international institutions are required. Their improvement is important irrespective of the future share of nuclear energy in total power production. Elaborated supranational means and an expanded mandate of the International Atomic Energy Agency (IAEA), or possibly also EURATOM, are fundamental (Lubbers, 2005; ElBaradei, 2005a). Even while most nuclear proliferation in the past has occurred through dedicated uranium enrichment technology or specific (heavy water-based) research reactors, rather than common nuclear power plants, reactors are being designed that are less prone to proliferation and diversion of nuclear technology and materials than the currently deployed generation-II reactors. Plans exist for the development and fabrication of such reactors, in particular the generation-IV type (see Table 1 and NERAC/GIF, 2002). Nuclear reactors, however, including newly designed ones incorporating progressive proliferation-resistant techniques, will always involve some risk of diversion. Progress over the coming decades in solving international nuclear crises, managing the trade of sensitive nuclear technologies, safeguarding nuclear materials, and strengthening the efficacy of the IAEA can positively influence the extent to which a significant or expanded role can be reserved for nuclear power globally.

Since the September 2001 terrorist attacks on the USA, nuclear risks in particular have gained attention. As a result, international nuclear security activities have been expanded in scope, notably through IAEA efforts in assisting countries to better control nuclear material and radioactive sources, protect nuclear facilities and strengthen border controls (ElBaradei, 2005b). Progress has been made but much remains to be done, as an incident in which terrorists explode a fission or radiological device, or severely damage a nuclear installation, is certainly not unimaginable. Apart from the physical devastation, as well as the economic, social, and emotional consequences it would entail, such an attack would probably give a severe blow to the prospects of the civil nuclear power industry.

3.3 Reactor accidents

Among the intrinsic risks associated with nuclear reactor operation is the occurrence of incidents and accidents. As the consequences of severe accidents can be large, the continuing non-zero probability for such accidents troubles the future and acceptability of nuclear energy. According to part of the European population, nuclear energy still provides insufficient safety guarantees. The potentially pervasive scale of a reactor meltdown was experienced during the Chernobyl accident in 1986, involving some 40 immediate deaths, a radioactive contamination of a large area surrounding the power plant and an estimated aggregate of several thousands of people developing a lethal cancer as a result of radiation exposure. Following the Chernobyl accident several countries in Europe abandoned large nuclear energy expansion programmes causing a shock to the nuclear industry from which it still has not recovered. Another severe accident of this magnitude will probably hit the nuclear power sector comparably hard, and may be fatal for its development in Europe for decades to come.

Table 1 Nuclear reactor types in Europe

Generation	*Today*	*Short to medium term*	*Long term*
	I and II	*III*	*IV*
Reactor type	PWR (92)		
	WWER (22)	EPR (PWR)	GFR
	BWR (19)	AP1000 (PWR)	LFR
	AGR (14)	WWER (PWR)	MSR
	GCR (8)	ABWR (BWR)	SFR
	LWGR (1)	ESBWR (BWR)	SCWR
	PHWR (1)	HTR (e.g., pebble bed)	VHTR
	FBR (1)		

Currently deployed (with reactor numbers between brackets), deployable in the short to medium term (non-exhaustive) and possibly developed in the long term (speculative).

PWR: Pressurised Water Reactor
WWER: Water Power Reactor
BWR: Boiling Water Reactor
AGR: Advanced Gas-cooled Reactor
GCR: Gas-Cooled Reactor
LWGR: Light Water Graphite Reactor
PHWR: Pressurised Heavy Water Reactor
FBR: Fast Breeder Reactor
EPR: European Pressurised Water Reactor
AP1000: Advanced Pressurised Water Reactor
ABWR: Advanced Boiling Water Reactor
ESBWR: Economic Simplified Boiling Water Reactor
HTR: High Temperature Reactor
GFR: Gas-cooled Fast Reactor
LFR: Lead-cooled Fast Reactor
MSR: Molten Salt Reactor
SFR: Sodium-cooled Fast Reactor
SCWR: Super-Critical Water Reactor
VHTR: Very High Temperature Reactor.

Source: IAEA-PRIS (2006) and NERAC/GIF (2002)

Over the past 20 years, however, reactor safety has improved significantly, both in and outside Europe. No early generation Soviet (Chernobyl-type) Light Water Graphite Reactors (LWGRs) are in use in Europe and the present cohort of European reactors has had a good overall safety record. Since 1986, accident probabilities have decreased substantially as a result of improvements in reactor technology, peripheral equipment and operation practices. European reactors are equipped with confinement domes, ascertaining that in the occurrence of an accident radioactive material cannot be released to the external environment, and consequences can be maximally controlled. Man-machine interactions in plant operation have been considerably perfected and a better safety culture has been established through the creation of an international 'early notification system', obliging operators to report any incident on the International Nuclear Event Scale (INES).

Continued efforts in maintaining and elaborating high safety standards are among the *desiderata* for an expansion of nuclear power in Europe. Opportunities exist for reactor safety enhancement through R&D on new reactor types. Innovative designs for power plants that make greater use of passive safety features and build on the construction and operating experience gained in today's plants already exist: examples are the European Pressurised water Reactor (EPR) and pebble-bed High Temperature Reactor (HTR). EPRs are among the likely candidates for construction in Europe in the near term – both reactors presently planned in Finland and France are of this type – while for the longer run HTRs may be added to existing nuclear capacity. Table 1 provides a non-exhaustive list of names and types of generation-III reactors for possible short- to medium-term deployment in Europe. All will contribute to improving the safety level of the European nuclear reactor fleet. Furthermore, the EU is in the process of creating new directives to further improve reactor operation safety, develop regulatory safety oversight and orchestrate this presently largely national affair on a European level. Among the issues that are also being addressed are measures to:

- ascertain sufficient funds for the complete decommissioning of power plants
- exchange best operating practice for existing installations
- maintain high safety standards for plants whose operation licences are extended
- provide transparency for citizens.

These measures and new reactor types need to continue to comply with stringent cost requirements in order to ascertain nuclear energy's continued economic competitiveness.

3.4 Prospects in Europe

What do the arguments above imply for the prospects for nuclear energy in Europe? As demonstrated by the age distribution of installed nuclear capacity in Figure 2, the scenario for the short run, until 2025, will be strongly determined by whether or not the current tendency to extend the lifetime of power plants will be continued. If no license extension beyond the typical reactor design age of 40 years takes place, the use of nuclear power will be decimated by 2025. Still, even then nuclear energy will not have disappeared from the European energy scene. If, on the other hand, some or all ageing power plant parts are replaced by new ones and/or license extensions up to 60 years are granted for ageing plants, the installed European nuclear capacity in 2025 may be little different from today. Perhaps one to two dozen reactors, including, for example, some of those built in the 1960s in the UK or in the 1980s in several East-European countries during the Soviet era, will be decommissioned after 30–40 years of operation (see Table 1 for an overview of the types and numbers of generation-I and -II reactors currently in use in Europe). Given the economic attractiveness of lifetime extension, there is reason to believe that licence renewal for reactor operation, as already granted to several nuclear power plants in Europe, will persist and eventually be applied to the majority of the current stock of nuclear plants. Still, some countries may stick to their plans to gradually phase out domestic nuclear electricity generation, while others are likely to construct new reactors during the coming two decades. Meanwhile, some states currently not possessing nuclear energy may change their attitude and decide in favour of nuclear power, like Italy, Poland, Turkey or a few of the smaller European nations.

Without lifetime extension and the construction of new plants, nuclear energy will have virtually disappeared from the European power sector by 2050. Even if all current nuclear reactors are operated until they reach the age of 60, not more than 15 GWe of today's capacity will be available by the middle of the century. Therefore, the construction of new nuclear plants during the coming decades will be determining the extent to which nuclear power will contribute to European electricity generation in 2050. Decisions regarding new nuclear plant construction will be positively influenced if commitments by European states to significantly reduce GHG emissions, improve air quality and enhance energy security prove serious, as well as by further progress made by the nuclear industry in dealing with nuclear power's fundamental intricacies. Setbacks on any of the five 'classic' challenges (i.e., radioactive waste management, proliferation security, operation safety, economic competitiveness and public acceptance), however, will hinder new construction or an extension of Europe's nuclear capacity. Among the imaginable impediments to such an expansion are a further postponement of resolving the nuclear waste problem and realising the permanent geological storage of spent nuclear fuel, the use of a nuclear or radiological device by a terrorist group or rogue state, another major reactor accident, the absence of an active role by governments in providing liability guarantees and an appealing financial investment environment, or a return to public nuclear scepticism as a result of any of these. Apart from the occasional appearance of 'green' and 'white' papers, the EU has so far not been able to formulate a common energy strategy for its member states (EU, 2000). If the EU is able to realise a collective vision for long-term energy planning, the development of options involving long scheduling horizons and construction lead times, like nuclear power, could receive an overt impetus. On a global level, the contribution of nuclear energy to total power production until 2050 is likely to remain between an upper bound of constant share (i.e., in relative terms) and a lower bound of constant capacity (i.e., in absolute terms). For Europe a similar statement holds but with a lower bound that allows for a (small) decrease in capacity. It is possible for nuclear energy in Europe to retain a constant share in power generation until 2050, but only if a majority of the drivers mentioned above evolve in favour of nuclear energy.

The extent to which new nuclear power plants are built during this half-century will determine the contribution of nuclear power to electricity production during the second half of the 21st century. Predicting the nature of the energy system on a time frame until 2100 is notoriously difficult. In the long run, a determining factor for the development of nuclear power will in particular be whether Europe succeeds in establishing sustainable economic development and energy infrastructures. In this perspective, also the sustainability aspects of nuclear power should be contemplated, as well as the scope for nuclear energy to contribute to creating transition paths towards sustainability. However, it has been argued that nuclear power today cannot be considered a sustainable form of energy, and also that no such energy resource has yet been identified, including renewables (Bruggink and van der Zwaan, 2002). Many significantly different reactor types and distinct nuclear power plus fuel cycle technologies exist, the qualification of which in terms of sustainability may vary substantially and should therefore be evaluated separately. Of the 158 operational power reactors in Europe today, 133 are of the Light Water Reactor (LWR) type. As present gas-cooled reactors in the UK are gradually being phased out over the coming decades, this ratio may well shift further in favour of LWR technology and its most common version the Pressurised Water Reactor (PWR). Because LWRs continue to dominate the commercial nuclear power industry until at least the middle of the century, their properties determine for the moment the sustainability of nuclear energy.

LWR technologies violate several criteria of sustainability over the foreseeable future. Some authors emphasise the social institutions required to restrict the proliferation of nuclear materials and techniques and the difficulties the LWR industry faces today in maintaining its capital stock (Rothwell and van der Zwaan, 2003). While in the short to medium term, the nuclear industry is required to address these issues, in the very long run LWRs should also be more fuel-efficient, as they rely on the eventually depletable resource uranium. If LWRs cannot meet these and other challenges, nuclear energy must at some point switch to other technology in order to qualify as sustainable. Advanced generation-III systems are the present evolutionary successors to the actually deployed reactors, while for the medium term a promising candidate is the pebble-bed HTR (see Table 1). These reactors incrementally render nuclear energy more sustainable. For the long-term, the US Department of Energy has engaged governments, industry and the research community in a worldwide dialogue on the development of more advanced, generation-IV, systems (Table 1 and NERAC/GIF, 2002). The purpose of this discussion is to assess the challenging question which nuclear power technologies, including fast neutron reactors, in the long run (ideally in a few decades, but probably not before 2050) best meet generic sustainability criteria and address arguments regarding uranium resources, economic competitiveness, radioactive waste, nuclear proliferation and reactor safety. For sustainability reasons, also the type of fuel cycle will ultimately need to be reassessed. For decades to come there are no economic or resource arguments for countries to develop a reprocessing fuel cycle, unless perhaps these countries already possess extensive recycling facilities like France and the UK (see Bunn et al., 2005). At the time scale of a century and more, however, a choice may need to be made between the once-through cycle, in which spent nuclear fuel is directly destined for long-term disposal, and the closed cycle, in which uranium and plutonium are recovered from spent fuel for reuse. Since 'sustainable development' is rarely precisely defined and can be interpreted in many different ways, as well as being a relative and subjective measure, nuclear energy's sustainability only obtains real meaning in comparison to that of other energy resources. For all its dimensions, nuclear power should thus be put into perspective with the opportunities and shortcomings proffered by alternatives like renewables and CCS applied to fossil-fuelled power plants.

4 Extra-regional linkages

Nuclear developments in the USA influence the European nuclear power sector, even while the latter is autonomous in its reactor building and fuel fabrication capacity (see notably the North America paper in this special issue). Several trends in the USA may soon positively affect the evolution of nuclear energy in Europe. First, a majority of USA nuclear power plants are in the process of receiving operation licence extensions of 20 years. If fully achieved, this phenomenon would reinforce European nuclear regulatory authorities to approve similar reactor lifetime extensions. Second, politically and financially more favourable conditions have recently been created in the USA for the construction of new nuclear power plants. Once new reactors start being built in North America, European countries complementary to those already dedicated to build new plants may follow suit. Third, while the operation of the Yucca Mountain repository in Nevada has experienced extensive delays and has had to overcome multiple technical, institutional and social obstacles, it is now planned to open around 2012. Once Yucca Mountain starts receiving nuclear waste currently dispersed across the country, thereby becoming the first operational repository for waste produced in the nuclear power sector, an impulse will probably be given for accelerated realisation of similar storage at various places in Europe. Fourth, those Europeans who are convinced that an expansion of nuclear energy is desirable will be reinforced in their judgment, if the sceptical public opinion mollifies, for example, as a result of the above developments. Of course, delays in the USA in any of these respective areas may likewise slow down European progress in nuclear energy development.

Arguments related to energy supply security will continue to motivate countries outside Europe to develop and expand domestic nuclear power facilities, not only in industrialised states, such as Japan and Russia, but including those in the developing world with presently modest or no shares of nuclear energy in electricity generation, such as China, India and Indonesia (see various other contributions to this special issue). The large expansion plans of nuclear power notably in China and India will strengthen the position of the global nuclear industry and thus bolster the sector also in Europe. As European countries will be among the prime candidate exporters of nuclear reactors, technology and related equipment to these nations, irrespective of the likelihood that the importing countries may simultaneously further develop domestic nuclear energy technology, a growing commercial market for the European nuclear industry will come into being. The expansion of market demand may generate mutual spillovers of learning effects and produce economies-of-scale, as well as increase returns to R&D expenditures, which may reduce the fixed costs on the total bill of nuclear power production in Europe. Similarly, economic development in other parts of the world will matter for the condition of the European nuclear industry and the prospects of Europe's own nuclear energy capacity. Countries in the Middle East, as well as South and East Asia, will affect the role of nuclear energy globally, and thus in Europe, as in those regions it will become apparent how well problems related to nuclear proliferation and terrorism can be mastered. Furthermore, not only the proficiency of nuclear reactor operation worldwide and the effectiveness of storing fissile and radioactive materials from notably the nuclear military apparatus of the former cold war superpowers will affect the reputation of nuclear energy's safety culture, but especially also how the 'Soviet nuclear legacy' problems in the former republics of the USSR are being solved. Nuclear activities in all these regions require a balanced international cooperation and coordination, and the success thereof will be central to the future of nuclear energy.

5 Conclusions

This paper has given a brief overview of the current status of nuclear power in Europe, as well as its future prospects over three time periods, until 2025, 2050 and 2100. For the short run (2025), Europe's nuclear capacity is unlikely to be very different from that of today, given that the capacity loss resulting from the decommissioning of some older reactors will probably be balanced, at least partially, by the construction of new ones, while operating extensions of 10–20 years are likely to be licensed to many existing reactors. For the medium term (2050), the extent to which European countries and the EU will decide (and manage) to seriously address a number of socio-economic and environmental concerns, which nuclear energy could contribute to alleviate, will importantly influence its prospects. Whether and how European states, as elsewhere, will be able to address the five 'classic' problematic features of nuclear energy – that is, in terms of the challenges associated with radioactive waste management, proliferation security, operation safety, economic costs and public acceptance – will determine the extent to which they will be able to exploit its comparative advantages. The relative weights attached to the benefits and drawbacks of the future use of nuclear power, as well as the intricacy of their interdependence, will remain dynamic. The evolution of these dynamics will determine the prospects of nuclear energy until the middle of the century and beyond. In the long run (2100), the main determining factor will be, or at least should be, the extent to which nuclear power may gradually develop into a more sustainable form of energy production.

How much more sustainable other resources will become also strongly influences the long-term prospects of nuclear energy. The potential transitional role of fossil fuel-based energy services during the 21st century, which are based on an exhaustible resource and are thereby intrinsically non-renewable, will be determined by how clean they can be rendered and how much they can be decarbonised, in addition to aspects of availability and costs. Globally, renewables have so far not been used on a large scale, so their external impacts and environmental drawbacks, related to, for example, their land requirements, are not yet fully apparent: their true sustainability is still to be proved in practice, while many of them need to achieve further cost reductions to become fully competitive. The extent to which fossil fuels continue to dominate our energy system, the scale at which renewables can be sustainably expanded, and the degree to which energy savings measures may be realised, will all affect the future of nuclear energy. Whether or not nuclear energy will play a significant role in the long run remains a difficult question. At any rate, the continuous analysis of the prospects of nuclear energy, as well as that of all other energy technologies, should be conducted in terms of their potential to contribute to goals of sustainable development, i.e., including the full set of environmental, economic and social risks involved. Given that climatic, political and technical uncertainties abound, adopting a hedging approach today is prudent. Such a strategy implies that the energy spectrum is kept diverse and does not exclude at this time any of the alternatives that could contribute to decreasing GHG emissions, improving air quality or ascertaining secure supplies of energy under a growing demand for electricity, globally and in Europe.

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Notes

[1]In the current EU-27, the ratio between domestic nuclear power 'haves' and 'have-nots' is 15 to 12.

[2]Note that arguments regarding energy security first really emerged during the 1970s. They were barely existent when the Atoms for Peace programme was launched in the 1950s.

[3]Another such future application of nuclear technology outside the electricity sector could be the use of nuclear power for the production of oil from tar sands.