Prospects for Nuclear Energy in Europe

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Abstract

The aim of this paper is to add to the current debate about the role of nuclear power in sustainable energy development, through an overview of its current status and future prospects in Europe. In three time frames – until 2025, 2050, and 2100, respectively – the main socio-economic and environmental concerns are analysed that nuclear energy could contribute to alleviate, among which energy supply dependency, local air pollution, and global climate change. Particular attention is paid to the five 'classic' problematic features of nuclear energy, as applied to Europe, i.e. in terms of the challenges associated with radioactive waste, proliferation security, operation safety, economic competitiveness, and public acceptance. The main conclusion is that the coming couple of decades the installed nuclear capacity in Europe is unlikely to change significantly, while the relative weights associated with the benefits and drawbacks of nuclear power, as well as broader long-term sustainability arguments related to the ensemble of all energy resources, will determine its prospects beyond 2025.

Keywords: *nuclear energy, sustainable development, Europe, supply security, air pollution, climate change, five concerns: waste, proliferation, safety, economics, 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 article is to analyse the possible contribution of nuclear energy to the establishment of sustainable development in Europe, on the basis of a concise inspection of the main driving forces involved. Arguments concerning radioactive waste, nuclear proliferation, reactor accidents, economic competitiveness, and public opinion continue to create justified concerns and thereby hinder nuclear energy policy making, but the issues of energy supply security, local air pollution, and global climate change provide reason to reassess its potential share in European power production. Whereas some European countries (like Austria and Italy) have today no plans to build nuclear power capacity, and others (such as Germany and Sweden) are officially committed to gradually phase out domestic nuclear energy supply, recent policy directions in other countries (among which the Netherlands and the United Kingdom) show that nuclear energy is reappearing on the political agenda, while some governments (of e.g. Finland and France) decisively continue to preserve a significant part for nuclear energy in their national electricity generation. This article briefly 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.

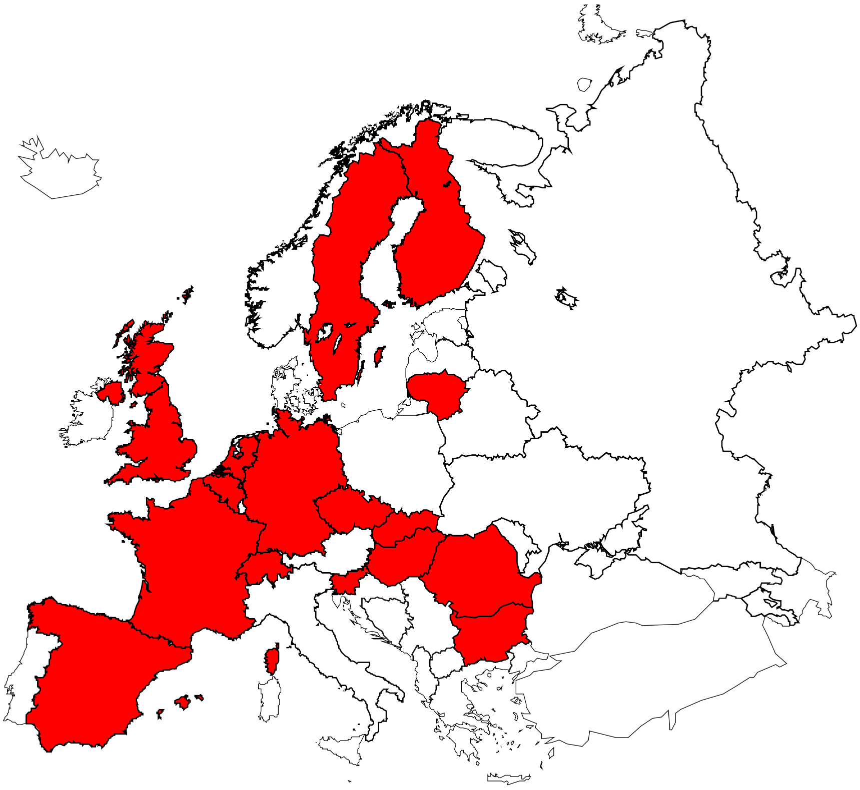

Figure 1. Nuclear power in Europe: in the geographic area considered, 16 countries today produce nuclear energy domestically and 20 countries do not.

‘Europe’ in this paper refers in principle to all European countries, in the broad sense of the word, 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 article will mostly focus on the countries in this geographic area that presently possess nuclear power (see Figure 1): 13 EU members (Belgium, Czech Republic, Finland, France, Germany, Hungary, Lithuania, Netherlands, Slovakia, Slovenia, Spain, Sweden, United Kingdom), 2 EU accession states (Bulgaria and Rumania), and Switzerland. Occasionally some of the larger remaining 20 counties that today do not produce nuclear energy domestically are referred to.[1]

Projections for the future of nuclear power in Europe vary widely depending on a range of underlying assumptions. Moreover, the diversity between different European countries in this respect, and energy issues at large, is great. As the current picture remains mixed, the purpose of this paper will be 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 aggregated net capacity of grid-connected European nuclear reactors per age by years of operation. Only a small share of total capacity has reached the age of 40 years, and the large majority of installed reactors have been operated for at least 10 years. Whereas basically all reactors have been designed for operating during 30-40 years, there is today a tendency to extend the reactor lifetime to 50-60 years.

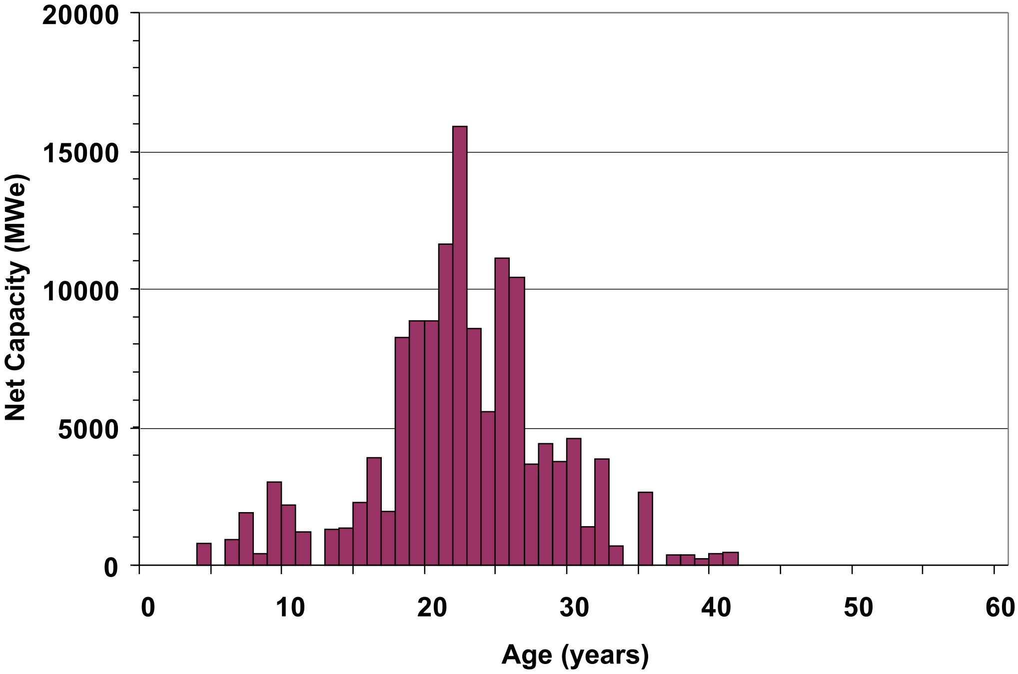

Figure 2. Aggregated net capacity of nuclear power plants in Europe per age of operation. *Source: IAEA-PRIS (2006), data from February 2006.*

Although less pronounced than in other parts of the world and notably developing countries, energy and electricity consumption in Europe are expected to continue increasing

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[1] In the current EU-25, the ratio between domestic nuclear power 'haves' and 'have-nots' is 13 : 12.

over the foreseeable future, at least until 2030, and most likely beyond (see e.g. IEA, 2001, 2005, and IIASA/WEC, 1998). This growth in energy consumption will be among the broad drivers for the future of nuclear power in Europe. Since the European population is expected to decrease with on average a few per mille per year until 2050, the main explanation for the likely increase in energy use is the prospected growth of the European economy (expressed in GDP, Gross Domestic Product), typically by about 1.5%/yr until 2050 in countries in Europe that are member of the OECD (Organisation for Economic Co-operation and Development) and as high as 3.6%/yr for countries with economies in transition (plus or minus fairly large uncertainties; see IEA, 2006). The baseline scenario of this study assumes an efficiency gain in final energy consumption per unit of GDP (hence also called 'energy-GDP decoupling') of approximately 1.0%/yr and 2.6%/yr, for these two categories of countries respectively, implying thus an overall energy consumption growth rate in the range of 0.5-1.0%/yr until the middle of the century. As a large part of this prospected growth is foreseen in the electricity sector, all power generation options, including nuclear energy, will in principle receive accrued attention.

Section 2 of this article describes the social and economic context in which the future of nuclear energy in Europe should be viewed, and describes the main environmental concerns that nuclear power could contribute to alleviate. In particular, the issues of climate change and air pollution, resource availability and energy security, costs and economic competitiveness, and public opinion and acceptance are described in terms of the most relevant of the multiple dimensions they involve. In section 3 the three fundamental, negative, and more technical aspects of nuclear power are examined. Since these characteristics constitute unique concerns for nuclear energy and are intrinsic to its use – radioactive waste, nuclear proliferation, and reactor accidents – they are assessed, qualitatively, in terms of the potential risks they involve. The section ends with an assessment of the prospects for nuclear energy in Europe, on the basis of the arguments made in both sections 2 and 3, and in three time perspectives: up to 2025, 2050, and 2100. As the future of nuclear energy in Europe will also be affected by its evolution and events 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-economics 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

With the current predominance of fossil fuels in our energy system, accounting globally for almost 90% of commercial primary energy supply, the prospected growth in energy consumption (world-wide and in Europe) will in a business-as-usual scenario lead to a gradual but steady increase in the level of greenhouse gas (GHG) emissions (IPCC, 2000). Nuclear power emits essentially no such GHGs. Even when the complete nuclear fuel chain is considered, including notably the mining of uranium and the construction of power plants, nuclear energy emits typically 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 around the same order of magnitude of GHGs as renewables like wind or solar power. Today, nuclear power is, along with hydropower, the only non-carbon-emitting energy resource that is commercially deployed on a large scale, and as such, by replacing fossil fuels, already avoids yearly world-wide 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 present global challenges, nuclear energy receives 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), it could contribute to reducing total annual CO_2 emissions in the 2nd 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 (nuclear energy is at present not suitable for e.g. 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 reaching over a doubling of the atmospheric CO_2 concentration, corresponding to an increase of the average atmospheric temperature by typically a few degrees Celsius.

Also in Europe it is evident that nuclear energy can constitute no panacea to the desired reduction of GHG emission levels. If climate change control ambitions of some countries remain as high as their current intentions to cut down CO_2 emissions with 50% by the middle of the century, nuclear energy could well prove, for the moment at least, an essential component of the required mix of emission reduction options. Given that Europe is with 137 GWe installed capacity and corresponding infrastructure (one-third of the EU's electricity use being produced by nuclear power), on a global figure of around 330 GWe, world-wide the largest nuclear energy region, it is in principle in a good position to increase the role of nuclear energy for climate change management. As the development of nuclear energy in Europe currently faces stagnation, and because both the planning and construction of new nuclear power plants involve long lead times, however, nuclear power can significantly start contributing to realising further CO_2 emission reductions in only a couple of decades from now. The required expansion of nuclear capacity installed for GHG emission reduction purposes would simultaneously contribute to mitigating several environmental and health problems of local and regional air pollution, as nuclear power does not generate emissions of e.g. SO_2, NO_x, Hg, or particulates, unlike its fossil counterpart coal-based power, and releases 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 while Europe does not possess large domestic uranium resources. Similar events in the future could well again lead to an

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[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.

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 cheaply acquirable. Globally a diverse roster of stable uranium producers exists, and the small storage space required implies that strategic reserves can easily be built. Furthermore, 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. While 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 for the moment, and probably a long time to come, only a substitute in the electricity sector. It is therefore today no substitute for oil as mobile fuel and can only be used in the transport sector through e.g. the production of hydrogen in conjunction with the use of fuel cells when the related economic, technical, and chemical hurdles are overcome.[3] Second, nuclear energy possesses worth as substitute for coal in the power sector (e.g. as coal requirements are bulky), but there are limits to this substitution value, given the abundance, spread, and affordability of coal world-wide. Third, nuclear energy has great value in terms of energy independency for power generation when it comes to replacing natural gas imported from especially instable regions outside Europe. But even in this case at least a share of natural gas based power remains difficult to replace by nuclear energy, given the flexibility and adjustability of the former as peak-load option. Nevertheless, the energy security merits of nuclear power remain sizeable.

Still, concerns are sometimes expressed regarding the estimates of the global amount of uranium ultimately recoverable at a given price, and their comparison to scenarios of uranium consumption this century. There are several reasons to believe that these worries are unjustified (see Bunn *et al.*, 2005). A doubling of the uranium price has typically only an effect at the percentage level on the production cost of electricity. Therefore, while large quantities of uranium are still recoverable at the current price of \$40-\$50/kgU, uranium reserves are often quoted at higher prices such as \$130/kgU. The Nuclear Energy Agency (NEA) estimates that total world conventional uranium resources, available at less than \$130/kgU, amount to about 17 MtU (NEA, 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 \$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 yet 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 \$130/kgU is significantly greater than 17 MtU. Figure 3 shows four scenarios of global cumulative uranium consumption under annual nuclear electricity production growth rates of -2%, 0%, +1%, and +2% – corresponding 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 \$130/kgU. Figure 3 demonstrates that even under a

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[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.

significant expansion of nuclear energy during the 21st century, uranium resources will be amply available at prices that have only limited effect (less than 10%) on overall electricity production costs.

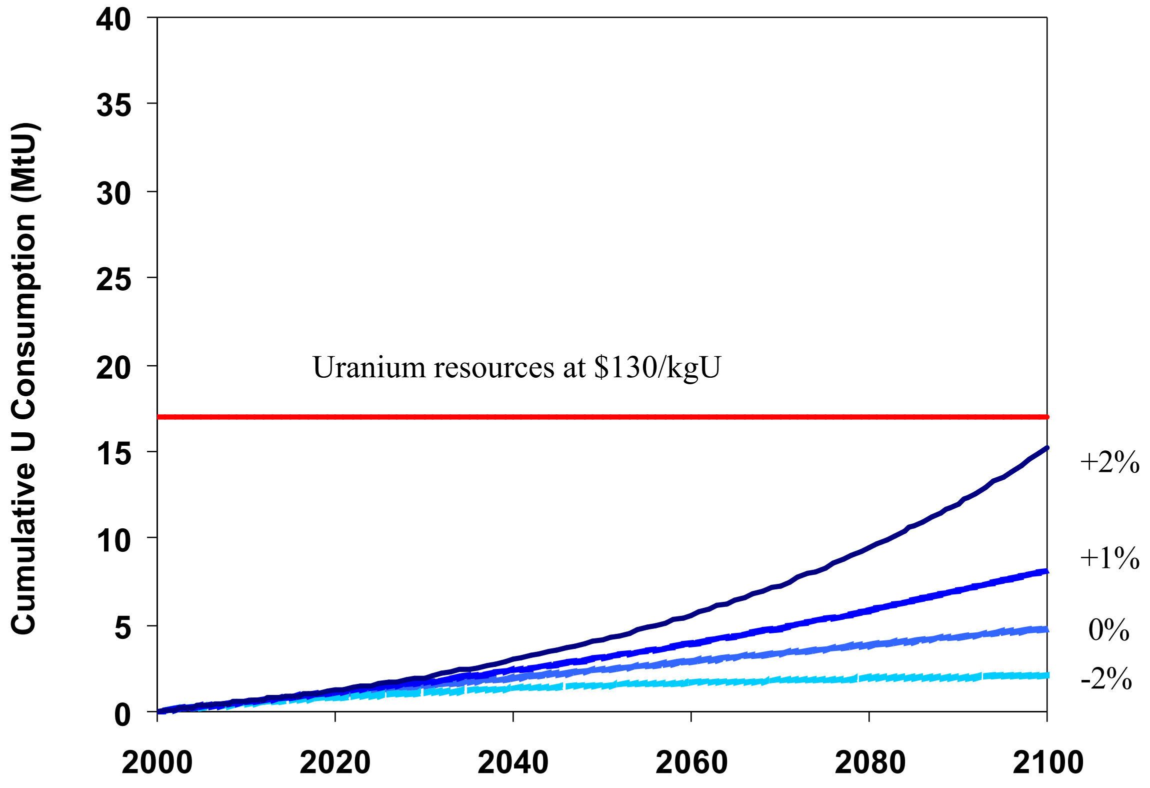
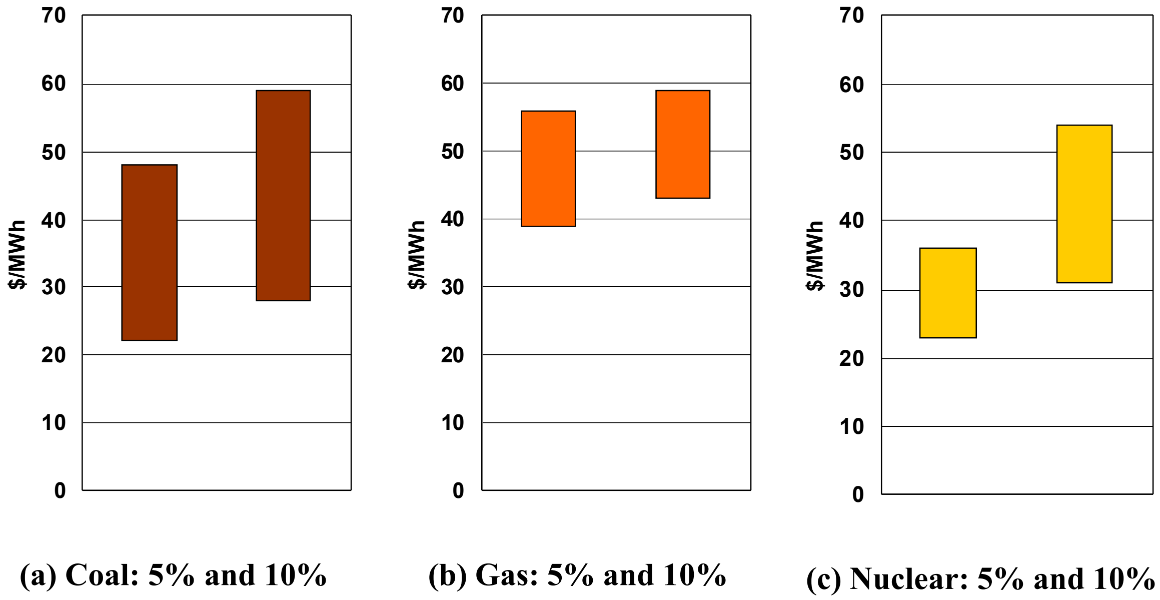


Figure 3. Scenarios of cumulative uranium consumption under annual nuclear electricity production growth rates of -2%, 0%, +1%, and +2%, assuming a once-through fuel cycle, an average uranium requirement of 19 tU/TWh, and 2500 TWh nuclear power generated in 2000. The horizontal line represents the estimated uranium resources at $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. Nuclear energy is basically well able to compete 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 for two values of the discount rate to reflect different valuations of future costs/benefits or investment environments. The more investment-intensive the option, the more sensitive the levelised costs to the value of the discount rate. The up-front investment part of these costs may for coal be twice as high as that for natural gas, and for nuclear power three times higher (OECD, 2005). Still, as a result of the low fuel cost component for nuclear energy with respect to both 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 & maintenance costs (including costs associated with waste disposal and reactor decommissioning), but do not include CO_2 emission (permit) prices. 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 endurable high prices would increase the competitiveness of nuclear power. For all three alternatives a dependency exists on where and under what operation conditions the electricity is produced. The ranges indicated by the bars in the three plots mostly reflect the dependency on in which (OECD) country the power is generated. If one takes the average of these uncertainty ranges as a measure for comparison, nuclear power marginally proves to be the most competitive option, with total levelised costs of about 30 US$/MWh when a 5% discount rate is applied, and a little over 40 US$/MWh with a discount rate of 10%.



(a) Coal: 5% and 10% **(b) Gas: 5% and 10%** **(c) Nuclear: 5% and 10%**

Figure 4. Range of total levelised electricity generation costs (in US$/MWh) for (a) coal, (b) natural gas, and (c) (generation-II) nuclear power plants for two values of the discount rate (left bar 5%, and right bar 10%). *Source: OECD, 2005.*

The high capital cost necessary for the construction of a nuclear power plant nevertheless forms an impediment for the sector to invest in nuclear energy. Regulatory, legal, and political incertitude often exacerbates the hesitation of potential investors. In each of the European countries in which nuclear energy has been developed, an active role of government has been indispensable 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 financial conditions (involving e.g. low capital interest rates) can be guaranteed elsewhere similar to those allowing new construction in these two countries, Europe can continue to profit from the levelised cost-competitiveness of nuclear base-load electricity. Also, even under more stringent reactor safety and waste disposal requirements, plausible reductions by industry in power plant construction costs could reduce the gap between nuclear investments and those required for coal and natural gas based power production, and, along with a reduction in building times and operation & maintenance costs, increase the interest for nuclear energy (MIT, 2003).

If climate change concerns are seriously addressed (with targets beyond the Kyoto Protocol) and consequently CO_2 abatement obtains an enduring economic value, 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 base-load power production, depending particularly on the availability and affordability of the 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 attractive and realisable innovation it presently promises to become – the capital intensity difference between this decarbonised fossil electricity generation and nuclear power reduces, which benefits the latter. CO_2 emission credits, as enacted since January 2005 in the 25 present EU countries through the Emissions Trading System (ETS), gives nuclear energy in principle already a cost advantage relative to fossil-fuelled power production. In the longer run, a sustained and stable ETS may lead to renewed investments in the construction of nuclear power plants. While ETS CO_2 prices varying today between 10-20 €/tCO_2 already have a market impact, 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 the 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 in 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 current 25 member states of the EU were asked what national governments should focus on in order to reduce its energy dependency, only 12% answered that first the use of nuclear energy should be further developed (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 of 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 may abruptly modify the public acceptance of a technology. Inversely, a catastrophe associated with climate change, or a long-lasting rupture in the supply of e.g. natural gas as a result of geopolitical tensions, may lead to a step-change in the support for nuclear power, in Europe as elsewhere. Public opinion that on a time scale of decades appears constant, may in the longer run be subject to significant variability.

The controversy over nuclear energy has mostly been related to the problems of waste, proliferation, and safety, although anti-nuclear sentiments also stem from other less identifiable origins. Progress on these three drivers of public scepticism towards nuclear power is likely to positively influence support for the nuclear industry. For example, once in Europe an underground permanent storage site is in operation and proves to safely contain radioactive waste, the general public may start accepting it as a satisfactory solution for the back-end of the fuel cycle. A similar positive shift may take place if some of the present salient proliferation problems can be addressed, such as related to Iran and North Korea, or reactors, installations, and materials can be used that are less sensitive for use in fission weapons than current ones. Nuclear energy may also be viewed more confidently when the nuclear industry can maintain and further increase its reliable safety record of the past two decades. Of course, any severe incident related to these aspects, such as the use by terrorists of a simple atomic bomb or radiological device, or another major civil 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 nuclear energy will significantly contribute to mitigating global climate change, decreasing local air pollution, and enhancing energy supply security will predominantly be determined by how in particular three critical concerns unique to the use of nuclear energy 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 fuel is by far its most problematic form, since it generates heat during many years after de-loading 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 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 with Parliament on which solution to choose for the long-term disposal of spent nuclear fuel. Sweden plans 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, after a long time will start to leak and consequently contaminate groundwater. This mostly explains the hesitation towards final waste disposal implementation by governments and 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 (Not-In-My-Back-Yard or NIMBY), is an important determinant for the current authorities' irresolution. The problem of high-level nuclear 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 preparedness yet exists for designing a pan-European approach, e.g. through Euratom, towards nuclear waste disposal. The public is expected to become less sceptical once the first geological repositories become operational and disposal technologies are demonstrated in practice. Progress booked 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 risks of non-civil diversion of nuclear industry related technologies and materials. 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 bomb 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. 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 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 broad bearings 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 of fissile materials like HEU and plutonium lie at the heart of the solution to the proliferation problem. In order to avoid them 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 via Euratom, are fundamental (see Lubbers, 2005, and ElBaradei, 2005b). 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 second-generation 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. The progress achieved 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, will contribute to the extent to which a significant or expanded role can be reserved for nuclear power globally.

Since the September 2001 terrorist attacks on the U.S., in particular nuclear risks 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, 2005a). Progress has been made but much remains to be done, as a scenario in which terrorists explode a fission or radiological device, or severely damage a nuclear installation, is not unimaginable. Apart from the devastation, and economic, social and emotional shock such an attack would cause, it almost certainly would give a severe blow to the prospects of the civil nuclear power industry.

Table 1. Nuclear reactor types in Europe: currently deployed (with reactor numbers between brackets), deployable in the short to medium term (non-exhaustive), and possibly developed in the long term (speculative). *Source: IAEA-PRIS (2006) and NERAC/GIF (2002).*

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

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

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 accident 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. The Chernobyl accident was followed by several countries in Europe abandoning large nuclear energy expansion programmes, and produced 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.

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 is not released to the external environment and consequences are controlled to a minimum. 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 operation 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 also addressed are the ascertaining of sufficient funds for the complete decommissioning of power plants, the exchanging of best operation practice for existing installations, the maintaining of high safety standards for plants whose operation licences are extended, and the providing of transparency for citizens. These measures and new reactor types need to continue complying with cost requirements in order to ascertain nuclear energy's 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 capacity age distribution of Figure 2, the scenario for the short run until 2025 will be strongly determined by whether 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, ageing power plant parts are replaced, allowing license extensions up to 60 years, the European nuclear capacity in 2025 may be little different from that installed today in absolute terms. Perhaps one to two dozen reactors, including e.g. 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 to 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 the consideration of licence renewal for nuclear power plants, as for several ones today, persists and will eventually apply to a majority of them. 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, and Turkey, or a few of the smaller European nations.

Under no lifetime extensions nuclear energy will have disappeared from the European power sector by the medium-term perspective up to 2050. Even if all reactors are operated until they reach the age of 60, not more than 15 GWe nuclear capacity will be available by the middle of the century. New construction of nuclear power plants during the coming decades will be determinant for how much nuclear power will contribute to European electricity generation in 2050. Decisions regarding new build will be positively influenced if commitments of European states prove serious to significantly reduce GHG emissions, improve air quality, and enhance energy security, as well as by progress made by the nuclear industry in dealing with its five fundamental intricacies. Setbacks on any of these five 'classic' challenges, however, will hinder 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). Given the role in this prospectus of a nuclear energy contribution by countries in Asia, 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 this half-century new nuclear power plants are built will determine the contribution of nuclear energy to electricity production during the 2nd half of the 21st century. Predicting the nature of the energy system on a time frame until 2100 is notoriously difficult. Most determinant for how it will develop in the long run will be whether Europe succeeds in achieving the ultimate goal of 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. It has been argued that nuclear power today cannot be considered a sustainable form of energy, but that no such energy resource yet exists, including renewables (Bruggink and van der Zwaan, 2003). Many significantly different reactor types and distinct nuclear power 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, 133 are today of the Light Water

Reactor (LWR) type. As gas-cooled reactors in the UK are gradually phased out over the coming decades, this ratio is likely to further shift in favour of LWR technology and its most common version the PWR (Pressurised Water Reactor). 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 emphasize 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 it is required to address these issues, in the (very) long run it should also be more fuel-efficient, as it relies on the eventually depletable resource uranium. If LWRs cannot meet these and other challenges, nuclear energy must eventually 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 incrementally render nuclear energy more sustainable. For the long term, the U.S. Department of Energy has engaged governments, industry and the research community in a world-wide discussion on the development of more advanced generation-IV systems (Table 1 and NERAC/GIF, 2002). The purpose 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 re-assessed. For decades to come, there are no economic or resource arguments for countries to develop a reprocessing cycle unless they already possess extensive recycling facilities like in France and the United Kingdom (see Bunn *et al.*, 2005). At the time scale of a century, 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 re-use. Since ‘sustainable development’ is not precisely defined and can be interpreted in many different ways, and is in any case 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 proffered by alternatives like renewables and CCS applied to fossil-fuelled power plants.

4. Extra-regional linkages

Nuclear developments in the U.S. 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 article in this special issue). Several trends in the U.S. may soon positively affect the evolution of nuclear energy in Europe. First, a majority of U.S. nuclear power plants are in the process of receiving operation licence extensions for 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 U.S. for the construction of new nuclear power plants. Once new reactors start being built in North America, European countries complementary to those dedicated to build new plants already today may follow suit. Third, even while the operation of the Yucca Mountain repository in Nevada has experienced delays and has had to overcome multiple technical, institutional, and social obstacles, it is now decidedly 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, if as a result of these developments the sceptical public opinion mollifies, also in Europe those convinced that an expansion of nuclear energy is desirable will be reinforced in their judgment. Of course, U.S. delays in any of these respective areas may likewise slow down European progress in nuclear energy development.

Arguments of especially energy supply security will continue to motivate countries outside Europe to develop and expand domestic nuclear power facilities, not only in industrialised states, among which Japan and Russia, but including those in the developing world with presently modest or absent shares of nuclear energy in electricity production, such as China and India (see various other contributions to this special issue). The envisaged large expansion plans of nuclear power in notably China and India will strengthen the position of the global nuclear industry and thus bolster the sector in Europe. As European countries will be among the exporters of nuclear reactors, technology, and related equipment to these nations, irrespective of the likelihood that the latter will further develop domestic nuclear energy technology, an attractive and rapidly growing commercial market for the European nuclear industry will exist. The expansion of market demand may generate mutual spill-overs of learning effects and produce economies-of-scale and increasing returns to R&D expenditures, which may also 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 fitness of the European nuclear industry and the prospects of its own nuclear energy capacity, among which in e.g. Argentina, Brazil, Indonesia, and South Africa. Countries in the Middle East, as well as South and East Asia, will affect the chances for 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. The proficiency of nuclear reactor operation and effectiveness of storage of fissile and radioactive materials from the nuclear military apparatus and Soviet legacy in the former republics of the USSR will affect the reputation of nuclear energy's safety culture. Nuclear activities in all these regions demand for balanced cooperation and coordination, the success of which will be at the heart of 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 in three time frames until 2025, 2050, and 2100, respectively. For the short run (2025), Europe's nuclear capacity is unlikely to be very different from that of today, given that the capacity loss by the decommissioning of some of the older reactors will probably be balanced, at least partially, by the construction of new ones, while operation extensions of 10-20 years are likely to be licensed for scores of other 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, however – that is, in terms of the challenges associated with radioactive waste, proliferation security, operation safety, economic costs, and public acceptance – will be determinant for 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 for the middle of the century and beyond. For the long run (2100), the main determinant factor for its future will be, or at least should be, the extent to which it may gradually develop into a more sustainable form of energy production.

How much more sustainable other resources prove to become will also strongly influence the long-term prospects of nuclear energy. For fossil-fuel based energy services, while relying on an exhaustible resource and thereby intrinsically non-renewable, their potential transitional role during the 21st century will be determined by how clean they can be rendered and how much they can be decarbonised, in addition to conventional arguments regarding availability and costs. Globally, renewables have so far not been used on a large scale, so their external impacts and environmental drawbacks, related to e.g. their land requirements, cannot yet be fully apparent: their true sustainability is yet 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 conjointly energy savings measures may be realised, will affect the future of nuclear energy. Whether or not nuclear energy will play a role of significance in the long run remains a difficult question, but the continued analysis of its prospects should be conducted, in a similar way for all energy technologies, in terms of its 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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