ENERGY FOR THE FUTURE

The Nuclear Option

A position paper of the EPS

European Physical Society
more than ideas

Energy for the Future - The Nuclear Option

The EPS position

The European Physical Society (EPS) is an independent body funded by contributions from national physical societies, other bodies and individual members. It represents over 100,000 physicists and can call on expertise in all areas where physics is involved.

The Position Paper consists of two parts, the EPS position, summarising the recommendations, and a scientific/technical part. The scientific/technical part is essential to the Position Paper as it contains all facts and arguments that form the basis of the EPS position.

(i) The objective of the Position Paper (Preamble)

The use of nuclear power for electricity generation is the subject of worldwide debate: some countries increase its exploitation substantially, others gradually phase it out, still others forbid its use by law. This Position Paper aims at a balanced presentation of the pros and cons of nuclear power and at informing both decision makers and the general public by communicating verifiable facts. It aims to contribute to a democratic debate which acknowledges scientific and technical facts as well as people's proper concerns.

(ii) Future energy consumption and generation of electricity (Section 1)

The increase of the world population from 6.5 billion today to an estimated 8.7 billion in 2050 will be accompanied by a 1.7% increase in energy demand per year. No one source will be able to supply the energy needs of future generations. In Europe, about one third of the energy produced comes in the form of electric energy, 31.0% of which is produced by nuclear power plants and 14.7% from renewable energy sources. Although the contribution from renewable energy sources has grown significantly since the beginning of the 1990s, the demand for electricity cannot be satisfied realistically without the nuclear contribution.

(iii) Need for a CO_2 free energy cycle (Section 1)

The emission of anthropogenic greenhouse gases, among which carbon dioxide is the main contributor, has amplified the natural greenhouse effect and led to global warming. The main contribution stems from burning fossil fuels. A further increase will have decisive effects on life on earth. An energy cycle with the lowest possible CO_2 emission is called for wherever possible to combat climate change. Nuclear power plants produce electricity without CO_2 emission.

(iv) Nuclear power generation today (Section 2)

Worldwide, 435 nuclear power plants are in operation and produce 16% of the world's electricity. They deliver a reliable base-load and peak-load of electricity. The Chernobyl accident resulted in extensive discussions of nuclear power plant safety and serious concerns were expressed. European nuclear capacity will probably not expand much in the near future, whereas a significant expansion is foreseen in China, India, Japan, and the Republic of Korea.

(v) Concerns (Sections 3 and 4)

As any energy source nuclear energy generation is not free of hazards. The safety of nuclear power plants, disposal of waste, possible proliferation and extremists' threats are all matters of serious concern. How far the associated risks can be considered acceptable is a matter of judgement that has to take into account the specific risks of alternative energy sources. This judgement must be made rationally on the basis of technical arguments, scientific findings, open discussion of evidence and in comparison with the hazards of other energy sources.

(vi) Nuclear power generation in the future (Section 5)

In response to safety concerns, a new generation of reactors (Generation III) was developed that features advanced safety technology and improved accident prevention with the aim that in the extremely unlikely event of a reactor-core melt down all radioactive material would be retained inside the containment system.

In 2002 an international working group presented concepts for Generation IV reactors which are inherently safe. They also feature improved economics for electricity generation, leave reduced amounts of nuclear wastes needing disposal and show increased proliferation resistance. Although research is still required, some of these systems are expected to be operational in 2030.

Accelerator Driven Systems (ADS) offer the possibility of the transmutation of plutonium and the minor actinides that pose the main long-term radioactive hazard of today's fission reactors. They also have the potential to contribute substantially to large-scale energy production beyond 2020.

Fusion reactors produce CO_2-free energy by fusing deuterium and tritium. In contrast to fission reactors there is essentially no long-lived radioactive waste. This promising option may be available in the second half of this century.

(vii) The EPS position (Section 6)

Given the environmental problems our planet is presently facing, we owe it to ourselves and future generations not to forgo a technology that has the proven ability to deliver electricity reliably and safely without CO_2 emission. Nuclear power can and should make an important contribution to a portfolio of sources having low CO_2 emissions. This will only be possible if public support is obtained through an open democratic debate that respects people's concerns and is informed by verifiable scientific and technical facts.

Since electricity production from nuclear power is opposed in some European countries and research into nuclear fission is supported in only a few, the number of students in this field is declining and the number of knowledgeable people in nuclear science is likewise decreasing. There is a clear need for education in nuclear science and preservation of nuclear knowledge as well as for long-term research into both nuclear fission and fusion and methods of waste incineration, transmutation and storage.

Europe needs to stay abreast of developments in reactor design independently of any decision about their construction in Europe. This is an important subsidiary reason for investment in nuclear reactor RD&D and is essential if Europe is to be able to follow programmes in rapidly developing countries like China and India, that are committed to building nuclear power stations, and to help ensure their safety, for instance, through active participation in the IAEA.

The EPS Executive Committee
November 2007

ENERGY FOR THE FUTURE

The Nuclear Option

Scientific/Technical Part

Preamble

The European Physical Society has the responsibility to state its position on matters for which physics plays an important role and which are of general importance to society. The following statement on *The Nuclear Option* and its role in future large-scale sustainable CO_2-free electricity generation is motivated by the fact that many highly developed European countries disregard the nuclear option in their long-term energy policy. Climate change, the growth of the world's population, the finite resources of our planet, the strong economic growth of Asian and Latin American countries, and the just aspirations of developing countries for reasonable standards of living all point inescapably to the need for sustainable energy sources.

The authors of this report are members of the Nuclear Physics Board (NPB) of the EPS who are active in the field of fundamental nuclear studies, but with no involvement in the nuclear power industry. The report presents our perception of the pros and cons of nuclear power as a sustainable source for meeting our long-term energy needs. We call for the revision of phasing out of nuclear power plants that are functioning safely and efficiently and we stress the need for future research on the nuclear option, in particular on Generation IV reactors, which promise a significant step forward with respect to safety, recycling of nuclear fuel, and the incineration and disposal of radioactive waste. We emphasise the need to preserve nuclear knowledge through education and research at European universities and institutes.

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1 Need for sustainable energy supply with a CO_2-free energy cycle

The availability of energy for everybody is a necessary prerequisite for the well-being of humankind, world-wide peace, social justice and economic prosperity. However, mankind has only one world at its disposal and owes the next generation a world left in viable conditions. This is expressed by the term "sustainable", the definition of which is given in the Brundtland report [1] from 1987: "Sustainable development satisfies the needs of the present generation without compromising the chance for future generations to satisfy theirs". This ethical imperative requires that any discussion on future energy include short-term and long-term aspects of a certain energy source such as availability, safety, and environmental impact. For the latter the production of and endangerment by waste is of utmost concern, be it CO_2 from burning fossil fuels or radioactive waste from burning nuclear fuel, to name only two. The following paragraphs delineate the situation of large scale primary energy sources and generation of electricity in Europe today and address the problem of CO_2-emissions. The world energy consumption in the future is also addressed.

Large scale primary energy sources

In 2004 the total production of primary energy of the 25 EU countries was 0.88 billion tonnes of oil equivalent or 10.2 PWh (1 PWh = 1 Petawatt hour = 1 billion MWh) [2]. This energy was provided by a range of large-scale primary energy sources (nuclear: 28.9%; natural gas: 21.8%; hard coal and lignite: 21.6%; crude oil: 15.3%) and their derivatives (coke, fuel oil, petrol) and on a smaller scale by renewable energy sources (biomass and waste: 8.2%, hydro-power: 3.0%; geothermal: 0.6%; wind: 0.6%; a total of 12.4%). Primary sources fulfill the need for concentrated energy for industry, in agriculture and private households, and for transportation. In addition, oil and gas can be used as distributed sources and have the versatility needed for small-scale energy production as required, for instance, in the transport sector. It is obvious from the numbers quoted above that nuclear energy provides a substantial part of the present-day energy supply.

About 58.7% of the total energy generation comes from the combustion of fossil fuels (hard coal, lignite, crude oil, natural gas) and is accompanied by the emission of CO_2 that makes up 75% of the anthropogenic greenhouse effect. The other important contributors are methane (CH_4, 13%), nitrous oxide (N_2O, 6%), and chlorofluorocarbons (5%) [2]. In order to combat the greenhouse effect, the use of fossil fuels should be minimised, or their net production of carbon dioxide drastically reduced wherever possible. The largest potential for the reduction of CO_2 emission is in the generation of electricity, in the transport sector and in the economic use, for instance, by saving, of energy.

Generation of electricity and CO_2 emission

The total electric energy production of 3.2 PWh by the 25 EU countries corresponds to 32.3% of all the energy produced by the 25 EU countries in 2004. The itemisation according to various sources is shown in Fig. 1. About 31.0% of this electrical energy came from nuclear power stations, 10.6% from hydropower plants, 2.1% from biomass-fired power plants, 1.8% from wind turbines, 1.5% from other sources among which geothermal contributes 0.2%; the contribution of photovoltaic was negligible [2]. None of these sources emit CO_2 when operating. In contrast, gas, oil, and coal fueled power plants emit CO_2; they together contribute 52.9% to the electric energy production.

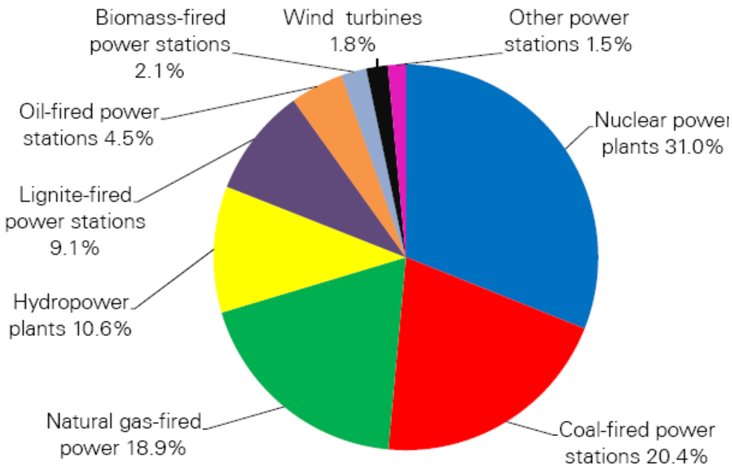

Fig. 1 Electricity generation by fuel used in power stations, EU-25, 2004 Source: [2]

It is obvious from these numbers that nuclear power plants provide the mainstay of the European electricity supply; they furnish on a large scale the stable base load and, on demand, peak loads. Reducing their contribution to electricity supply will cause a serious lack of electricity in Europe.

All sources of electricity require dedicated plants to be built and fuel to be supplied. These activities involve extraction, processing, conversion and transportation, and contribute themselves to CO_2 emission. Together they form the upstream fuel-cycle. There is also a downstream fuel-cycle. In the case of nuclear power plants this includes the handling and storage of spent fuel and, in the case of coal or oil fired plants, the retention of sulphur dioxide (SO_2), unburnt carbon, and in an ideal case the storage of CO_2 [3] to avoid emission into the atmosphere. However, this technique requires substantial research since the effects of long-term storage of CO_2 are not known at present. The decommissioning of a power plant is also part of the downstream fuel-cycle. Both the upstream and the downstream fuel-cycle inevitably involve CO_2 emission. The advantages or disadvantages of a particular process of electricity generation can be discussed realistically only if the whole life-cycle of a system is assessed.

The amount of CO_2 emitted for 1 kWh of electric energy produced, sometimes called the carbon footprint, can be calculated as a by-product of life-cycle analyses [4]. The results obtained depend on the power plant considered and yield a spread of values which are shown as pairs of bars for each fuel in Fig. 2.

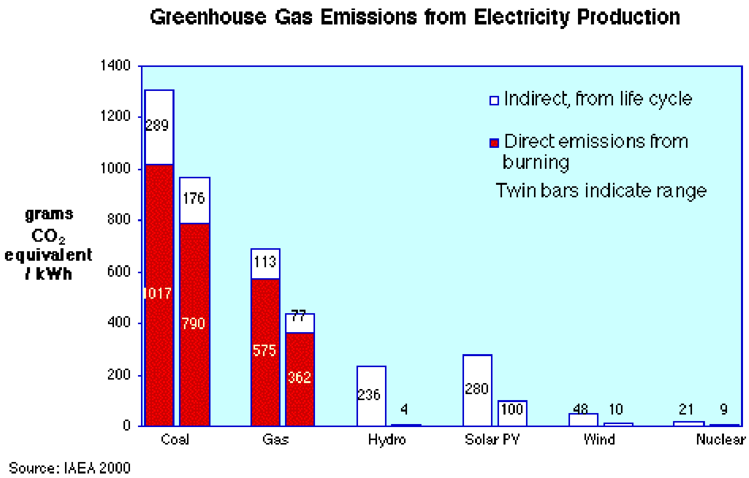

Fig.2: Results of life-cycle analyses for CO_2 emission from electricity generation by various methods (Source: [5])

Other studies use different weightings and arrive at slightly different values. The Global Emission Model for Integrated Systems of the German Öko-Institut [6] yields the following values for CO_2 in grams emitted per kWh: coal (app. 1000), gas combined cycle (app. 400), nuclear (35), hydro (33) and wind (20) (cited by [7]). These values are likely to reflect the German situation and may not be typical of other countries [8]. For example, France generates 79% of its electricity from nuclear power (Germany 31%) and therefore has lower CO_2 emissions than Germany. Even if one adopts the values of ref. [4] a power plant burning coal still emits 29 to 37 times more CO_2 than a nuclear power plant. That means nuclear electricity generation (31.0% of 3.2 PWh) avoids the emission of 990 to 1270 million tonnes of CO_2 every year, while all the renewable energy sourcess together (14.7% of 3.2 PWh) save less than half as much. The nuclear saving is more than the 704 million tonnes of CO_2 emitted by the entire car fleet in Europe each year (4.4 Tkm/year [2], 1 Tkm = 1 Terakilometer = 1 million million km; 160 g/km [9]). Replacing nuclear electricity production by production from fossil fuels in Europe would be equivalent to more than doubling the emissions of the European car fleet. The world-wide emission of CO_2 of about 28 billion tonnes [3] would increase by between 2.6 to 3.5 billion tonnes per year if nuclear fuel were to be replaced by fossil fuel.

These examples of life-cycle analyses show undoubtedly that nuclear electricity is a negligible contributor to greenhouse gas emissions and that this result is independent of the attitude towards nuclear energy taken by the institution that carried out the analysis.

Climate change

Since the beginning of industrialisation the world has experienced a rise in average temperature which is almost certainly due to the man-made amplification of the natural greenhouse effect by the increased emission of greenhouse gases [10]. Evidence for this temperature rise includes the melting of glaciers (Fig.3), permafrost areas, and the arctic ice cap at an accelerated rate.

Fig. 3: Pasterze–Glaciertongue with Großglockner (3798m) (Source: [11])

Over the same period the concentration of anthropogenic greenhouse gases in the atmosphere, among which carbon dioxide (CO_2) is the main contributor, has increased to a level not observed for several hundreds of thousands of years; Fig. 4 shows the development of CO_2 concentration over the last 10,000 years. There is a consensus among scientists that a further increase of the CO_2 concentration in

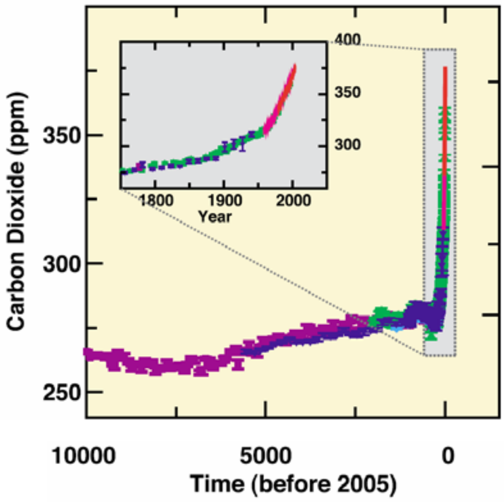

Fig. 4: CO_2 concentration (parts per million, ppm) in the atmosphere during the last 10,000 years; inset panel: since 1750 (Source: [10])

the atmosphere will have detrimental effects on life on earth [10,12]. Thus increased emission of greenhouse gases, stemming mainly from the burning of fossil fuels, must be controlled as agreed in the Kyoto protocol [13].

World primary energy sources

Scenarios for future world primary energy sources (as distinct from electricity sources) have been the subjects of many detailed studies. The sustainable development scenario of the IEA/OECD study [14] predicts the progression shown in Fig. 5 in Gtoe (1 Gtoe = 1 Gigatonne of oil equivalent = 11.63 MWh) with the world population growing from 6.5 billion today to an estimated 8.7 billion in 2050. To meet the escalated demand for energy all sources available at present will have to step up their contribution. After 2030, when fossil fuels start to contribute less primary energy, as indicated by Fig. 5, nuclear, biomass and other renewable energy sources (hydroelectric, wind, geothermal) will have to be increasingly exploited. According to the "World Energy Outlook, 2004" of IEA [16] both energy demand and energy-related CO_2 emission will increase, up to 2030, at a compounded rate of about 1.7% per year.

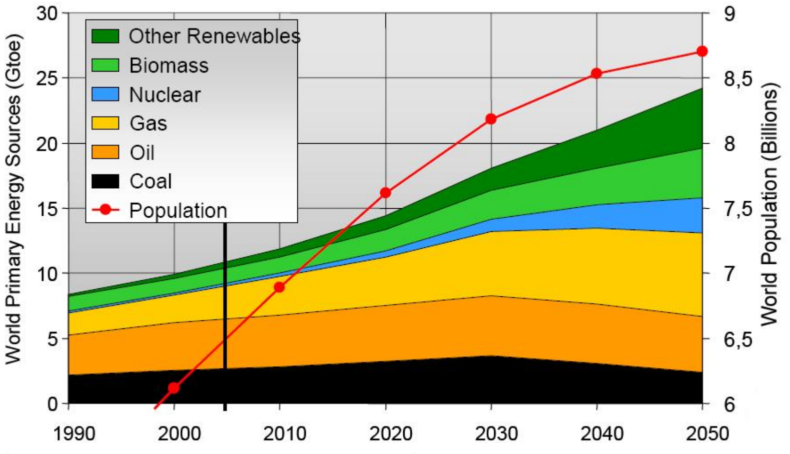

Fig.5: Scenario of world primary energy sources for a sustainable future (Source: [14], see also [15].) Note the suppressed zero point of the population scale.

It must be kept in mind that the main renewable source of electricity is hydropower (cf. Fig. 1), the contribution of which cannot be significantly increased in Europe in the foreseeable future [17]; the same holds true for electricity from geothermal sources [17]. Windmill farms for electricity generation have been built in large numbers in Europe since 1990; however, it is difficult to see how electricity generation from wind will replace electricity generation by gas, oil and coal (52.9% in total) or by nuclear (31.0 %) in the near future; the annual incremental increase is not nearly large enough, as can be deduced from Fig. 5. Therefore, all possible sources must be exploited in order to cope with the growing energy demand.

The most recent ambitious plan of the EU to reduce the CO_2 emissions by 20% below the level of 1990 by 2020 [18] relies on a significant reduction of CO_2 emission from the transportation sector, but also implicitly on a much faster growth rate of photovoltaic and windmill farms than in the past. However, electricity generation, for instance, by windmills, would have to increase by a factor of about 17 to draw level with nuclear electricity generation. It is difficult to see how this growth can be reached by 2020. This calculation does not even include the expected additional 1.7% increase in energy demand per year. In addition, energy storage devices are needed to supply a weather-independent load; they are not available yet. Thus, the objective of replacing nuclear electricity completely by renewable sources is debatable if not unrealistic (see also [12]). Therefore, the realisation of the CO_2 reduction plan of the EU depends heavily on the availability of electricity from nuclear power plants.

> Replacing nuclear power plants by coal burning plants is not an option since it would significantly increase the world's total CO_2 emission. Renewable sources will not grow fast enough to replace nuclear power in the near future. In order to meet the growing demand for electricity, the recent EU goal of CO_2 reduction, and to avoid potentially disastrous climate changes, the choice is not nuclear *or* renewable sources, but nuclear *and* renewable sources.

2 Nuclear power generation today

Nuclear energy is already used for large-scale electricity generation and is presently based on fission of uranium-235 (U-235) and plutonium-239 (Pu-239) in power plants. It corresponds to about 5% of the world's total energy generation, supplies about 16% (2.67 PWh) of the world's electricity [19] and saves between 2.6 – 3.5 billion tonnes of CO_2 emission per year. Using the new solutions mentioned below nuclear power has the potential to continue as a major energy source in the long-term, with facilities that incinerate nuclear waste and produce energy at the same time and involve inherently safe design concepts. At present (31 May 2007) 435 nuclear power plants are in operation world-wide, 196 of them in Europe [19]. There are 37 new units under construction, mostly in Eastern European and Asian countries, which are going to provide a power of 32 GW.

Table 1: European nuclear power reactors [19]

	Nuclear Electricity Generation 2006		Reactors in Operation May 2007		Reactors under Construction May 2007		Reactors Planned May 2007	
	TWh	% e	No.	MWe	No.	MWe	No.	MWe
Belgium	44.3	54	7	5728	0	0	0	0
Bulgaria	18.1	44	2	1906	0	0	2	1900
Czech Rep.	24.5	31	6	3472	0	0	0	0
Finland	22.0	28	4	2696	1	1600	0	0
France	428.7	78	59	63473	0	0	1	1630
Germany	158.7	32	17	20303	0	0	0	0
Hungary	12.5	38	4	1773	0	0	0	0
Lithuania	8.0	69	1	1185	0	0	0	0
Netherlands	3.3	3.5	1	485	0	0	0	0
Romania	5.2	9.0	1	655	1	655	0	0
Russia	144.3	16	31	21743	3	2650	8	9600
Slovakia	16.6	57	5	2064	0	0	2	840
Slovenia	5.3	40	1	696	0	0	0	0
Spain	57.4	20	8	7442	0	0	0	0
Sweden	65.1	48	10	8975	0	0	0	0
Switzerland	26.4	37	5	3220	0	0	0	0
Ukraine	84.8	48	15	13168	0	0	2	1900
UK	69.2	18	19	10982	0	0	0	0
Europe	**1194.4**	**35.4**	**196**	**169966**	**5**	**4905**	**15**	**15870**

Reactors in Europe supplying electric current to the grid and those under construction or being planned are listed in Table 1 (the letter "e" refers to electric power).

This capacity will probably remain unchanged in the near future with some upgrades (mainly in the Eastern European countries) and life extensions. Some countries (Belgium, Germany, The Netherlands, Sweden) are planning a gradual phase-out of nuclear energy while in others (Austria, Denmark, Greece, Ireland, Italy, and Norway) the use of nuclear power is prevented by law. The situation in the Far East, South Asia and Middle East is rather different: there are 90 reactors in operation and a significant expansion is foreseen, especially in China, India, Japan, and the Republic of Korea [19].

Nuclear power plants provide 16% of the world's electricity; they are a mainstay of Europe's electricity production and supply 31% of its electricity. A few new power plants are under construction in Europe, whereas a significant expansion of nuclear electricity generation is foreseen in South Asia and the Far East.

3 Concerns

Risks and safety

Our daily life involves hazards that are all associated with certain risks. This is also true for energy generation. Since mankind is dependent on energy one must evaluate the risks that are inherent to different sources of energy in order to judge their merits. Scientists have developed tools to quantify the level of risks.

For example, a risk-oriented comparative analysis was carried out by the Paul-Scherrer-Institute, Villigen, Switzerland [20], which focused on energy-related severe accidents in the years 1969 – 2000. One outcome is shown in Fig. 6 where the number of immediate fatalities per Gigawatt (electric) year is shown (note the non-linear vertical scale).

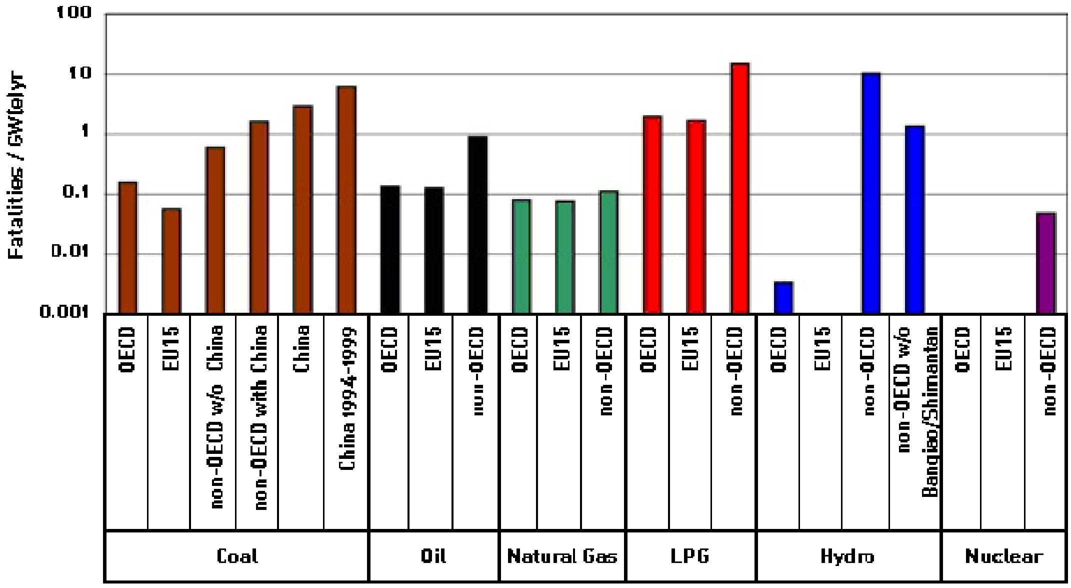

Fig. 6: Comparison of aggregated, normalised, energy-related fatality rates, based on historical experience of severe accidents that occurred in OECD countries, non-OECD countries and EU15 for the years 1969-2000, except for data from the China Coal Industry Yearbook that were only available for the years 1994-1999. For the hydro chain non-OECD values were given with and without the largest accident that ever happened in China, which resulted in 26,000 fatalities alone. No reallocation of damages between OECD and non-OECD countries was used in this case. Note that only immediate fatalities were considered here. (After [20]) LPG: liquefied petroleum gas

Nuclear power stations are seen to be the least fatality-prone facilities. In the case of the Chernobyl accident, however, the long-term consequences must be considered. This was done by the WHO study group in 2005 [21] which listed 50 immediate casualties among emergency workers who died of acute radiation syndrome and nine children who died of thyroid cancer. The question of the total number of deaths that can be attributed to the Chernobyl accident or expected in the future is a complex one and is also addressed in detail in the WHO report [21]. A clear conclusion in this report is that "poverty, 'lifestyle' diseases now rampant in the former Soviet Union and mental health problems pose a far greater threat to local communities than does radiation exposure." [21]

While it is possible to investigate accidents in the past, it is difficult to assess the possible impact of accidents that may take place in the future. Such a risk assessment was carried out by B. L. Cohen, who, in order to quantify risk, introduced a quantity he called "loss of life expectancy" [22]. This science-based analysis shows that the risk from electricity generation by nuclear power plants is far less than other risks of daily life [22].

This objective assessment of relative risk has to compete with the fact that there is frequently a significant difference between the perceived risk of an event and the actual chance of this event happening. A small risk of a major accident is perceived differently from a large risk of a minor accident, even though the total number of casualties per year may be the same for the two cases. This is particularly true in the public perception of nuclear energy where radioactivity comes into play.

Radioactivity - the phenomenon of spontaneous disintegration or transformation of an atomic nucleus into another, accompanied by the emission of alpha, beta or gamma radiation, referred to collectively as ionising radiation - is a facet of nature which existed long before the formation of our planet. Radioactive elements like thorium and uranium are found in various regions of the world. Their abundance in the earth's crust is about 7.2 mg of thorium per kg of crust [23] and 2.4 mg of uranium per kg of crust [24]. Both elements decay and produce radium and radon, a radioactive noble gas, which leaks from ore-bearing deposits and constitutes a particularly prominent source of natural radioactivity near such deposits. Natural radioactivity is also found in both flora and fauna. As an example, radioactive carbon-14 (C-14), which is continuously produced by nuclear reactions in the earth's atmosphere induced by the intense flux of cosmic radiation present in the solar system, enters the biosphere and the food chain of all living beings. Furthermore, the bones of all animals and humans contain, for example, the element potassium (K); its radioactive isotope K-40 (with 0.0117% abundance) has a lifetime longer than the age of the earth. In total, in the body of an average-sized person, aged 25 and of 70 kg weight, about 9000 radioactive decays take place per second [25].

It is often claimed that nuclear power plants emit radioactive material to a potentially hazardous extent. Many countries have regulations which set upper limits to both the emission of ionising material via exhaust air and effluents and immissions into the environment (e.g., the Federal Immission Control Act of Germany [26]), and compliance with them is kept under strict surveillance. In addition, the operation of power plants by the nuclear industry and research reactors are both subject to strict regulations, the compliance with which is monitored by independent governmental agencies who may be authorised to shut down a power station in the case of violations. It has been found that both emission and immission close to nuclear power plants is well within the spatial fluctuations of the background radiation [27]. It should be noted that coal-fuel power plants also emit radioactive material as coal contains 0.05 to 3 mg uranium per kg [28]. Uranium itself and its radioactive decay products cannot be completely retained by filters and are emitted into the environment [29].

Another widely spread assertion is that cases of leukaemia occur more frequently near nuclear installations. However, studies have shown that "the local clustering of leukaemia occurs quite independently of nuclear installations" [30], see also [31]. The number of cancer cases resulting from the Chernobyl accident was investigated by the WHO [21]. The results were discussed above.

The safety of nuclear power plants is an important issue. Its further improvement is one of the driving force behind the development of next generation reactors. They are constructed in such a way that either a reactor-core melt-down is physically impossible or this worst case scenario is incorporated into the reactor's design so that the consequences are confined to the reactor's containment system and do not affect the environment. The reactor's containment system is also designed to withstand the impact of any aircraft.

Waste

Yearly, 10,500 tonnes of spent fuel are discharged from nuclear reactors world-wide [32]. The spent fuel must be either reprocessed or isolated from the environment for hundreds of thousands of years in order to prevent harm to the biosphere. All radioactive nuclei contained in the waste will decay with time to stable nuclei. Different nuclides in radioactive waste, if ingested or inhaled, pose a different threat to living beings depending on their decay properties, decay rates and retention time. This threat can be quantified as radiotoxicity, a measure of how noxious it is. Examples of nuclides with a high radiotoxicity are the long-lived isotopes of plutonium and the minor actinides (MA), mainly neptunium, americium, and curium, while the generally shorter-lived fission products are less radiotoxic and their radiotoxicity diminishes rapidly with time. Radioactive waste originates not only from the operation and decommissioning of nuclear power plants but also from nuclear medicine and scientific research laboratories. The storage of this low- and medium-activity waste in suitable repositories is not of major concern and is currently practiced by several countries. It should be noted that all European countries that operate nuclear power plants (see Table 1) and others that make use of radioactive material or ionising radiation have signed the "Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management" of the IAEA [33].

However, the handling of spent fuel in the long-run is a major concern. In the short-run, the handling of spent fuel has been practiced safely since the earliest days of nuclear reactors. After discharging a reactor, the spent fuel is temporarily stored on site under water to allow short-lived radioactive nuclei to decay. Afterwards, the spent fuel is either reprocessed so that uranium and plutonium are chemically removed and reused as reactor fuel, or, in the once-through cycle, packaged (mainly by vitrification) for future long-term storage in deep underground repositories. In the once-through cycle spent fuel has to be stored for at least 170,000 years to reach the radiotoxicity level of the uranium from which it originated. Removing 99.9% of the plutonium and uranium reduces the storage time to about 16,000 years and future advanced recycling technologies, which also remove the minor actinides (MA) would reduce the safe storage time of the remaining fission products to a little more than 300 years [34]. The MA recovered need to be transmuted into shorter-lived fission products or incinerated in dedicated facilities, which will be discussed later.

The long-term exclusion of water is the main problem to be dealt with in deep underground repositories. Possible sites for such repositories have been identified in several countries and their long-term geological safety has been investigated in detail (cf. handling of spent fuel of the Finnish reactor under construction at Olkiluoto [35]). This kind of storage solves the waste problem, at least temporarily, and in some cases does not preclude retrieving this material for future reprocessing [35], [36].

Proliferation and extremists' threat

The non-peaceful use of fissile material is a matter of utmost concern; see [37]. When discussing this issue one should distinguish between the fabrication of nuclear warheads by the nuclear powers on the one hand and that of simple bombs by extremists on the other hand. Nuclear warheads are built by the nuclear powers from highly enriched uranium (HEU) or from weapons grade plutonium; the latter is not produced in reactors of nuclear power plants but in special purpose reactors, that are tailored to yield mainly Pu-239 [38]. Low-enriched uranium (LEU), as used as fuel in nuclear power plants, is not suitable for an explosive device. Plutonium extracted from spent nuclear fuel does not have the right isotopic composition for convenient and efficient warhead production. It must be stressed, therefore, that the output of plutonium from nuclear power plants is not useful for the production of nuclear warheads. The possibility for a given country to develop a nuclear weapons programme does not depend simply on the presence of nuclear power plants in that country but also on the availability of reprocessing and/or enrichment facilities.

A separate issue is the use of fissile material by extremists. A discussion of this threat can, for example, be found in [39]. The fissile material chemically extracted from spent nuclear fuel can, in principle, be used by extremists to build a nuclear device which has a relatively low explosive yield, maybe as much as a few kilo tonnes of TNT equivalent [40], but releases copious amounts of radioactive debris into the environment (cf. [41]). It is also conceivable that a conventional bomb could be used to vapourise a rod of spent fuel and disperse its radioactivity. To prevent such acts, the whereabouts of fissile material are tightly monitored by international agencies like the International Atomic Energy Agency (IAEA), see also

[42]. Since reprocessing of nuclear fuel requires a major industrial plant the process can indeed be tightly safe-guarded and thus diversion of material can be impeded effectively. In the foreseeable future, some Generation IV reactors will produce far less plutonium compared with current reactors (see section 5) [43].

Another threat which cannot be ignored lies in the possibility that extremist groups might acquire nuclear weapons directly from the dismantling of nuclear weapons arsenals. It is clear that in this case the extremist threat has no connection with the peaceful use of nuclear technology.

As any energy source nuclear energy generation is not free of hazards. The safety of nuclear power plants, disposal of waste, possible proliferation and extremists' threats are all matters of serious concern. How far the associated risks can be considered acceptable is a matter of judgement which must take into account the specific risks of alternative energy sources. This judgement must be made rationally on the basis of scientific findings and on open discussion of evidence and in comparison with the hazards of other energy sources.

4 Fuel cycles

Most of the reactors in use today are based on the fission of U-235, which occurs when bombarded with thermal (slow) neutrons; hence the term thermal reactors. The same process occurs for Pu-239 and U-233, which are bred in thermal reactors via neutron capture by U-238 and thorium-232 (Th-232), respectively. In contrast, the nuclear chain reaction in fast reactors is sustained with fast (energetic) neutrons. Other thermal reactors include the Molten Salt Reactor and those of CANDU type. The latter are cooled and moderated with heavy water and able to run with natural uranium. Both can breed enough U-233 to keep running, although fission products have to be removed at regular intervals. Fast reactors can even breed more fuel (plutonium) than they consume (fast breeder reactors). In addition to this classification, two different types of reactors can be distinguished with respect to their fuel cycles: the once-through cycle (mainly used in the USA) and the closed-cycle (adopted, e.g., in France). These two will be discussed separately as each has its specific problems and advantages. At first, however, one needs to address the uranium ore reserves.

Uranium ore reserves

Conventional uranium resources are estimated to be 14.8 million tonnes. Among these are about 4.7 million tonnes of identified resources. These are readily accessible and recoverable at a cost of less than $130/kg of uranium [44, 45]. The balance of about 10 million tonnes is an estimate from detailed investigation and exploration and geological knowledge pointing to likely geographical areas. This figure is probably an underestimate as only 43 countries have reported in this category.

Other resources include unconventional uranium resources (very low grade uranium) and other potential nuclear fuels (e.g. thorium). Most unconventional resources are associated with uranium in phosphates (about 22 million tonnes), but other potential sources exist, for instance, seawater and black shale. These resources are likely to be exploited if the price of uranium increases. Thorium is abundant, amounting to more than 4.5 million tonnes [46], although this figure misses data from many countries with possible thorium deposits.

These figures should be compared with world annual uranium requirements of about 67 kilo tonnes in 2005 [19]. World reactor-related uranium requirements are projected to increase to between 82 kilo tonnes and 101 kilo tonnes by the year 2025. The requirements of the North American and Western European regions are expected either to remain fairly constant or decline slightly, whereas requirements will increase in the rest of the world [44]. These estimates suggest that there is enough uranium to fuel nuclear reactors in a once-through cycle for another 50 years. If a closed fuel cycle is used, the supply of uranium would suffice for thousands of years (see below).

The once-through, or open, cycle

After mining, the uranium ore is converted into uranium hexafluoride, UF_6. The UF_6 is isotopically enriched to increase the concentration of fissile U-235 nuclei to as much as 4.6%. The concentration of U-235 in natural uranium, 0.72%, is too low for use in most reactors except for the CANDU-type reactors, which can run with natural uranium. The fluoride form is next converted into enriched uranium oxide, UO_2, from which pellets are manufactured and assembled into rods. These rods stay in the reactor up to about four years while the controlled chain reaction of nuclear fission continuously releases energy that is transformed into electricity. Each stage of the production is a complete industrial process in itself.

Because the spent fuel rods are not reprocessed, all minor actinides and, in particular, the plutonium remain in the fuel rods in a form which cannot be used for convenient and effective weapon production. This inherent safety regarding proliferation is the major advantage of the once-through fuel cycle. Further advantages of this mode of operation can be found in [47].

The major disadvantage of this process is that it produces radioactive waste that has to be stored for hundreds of thousands of years in order to reduce its level of radiotoxicity to that of natural ore. This cycle wastes uranium and fissile plutonium. For example, in currently running light water reactors the initial enrichment of U-235 is 3.3% and, in spent fuel, is still 0.86% [48]. With this fuel cycle the world's uranium supply would only last for another 50 years.

The closed cycle

Processes in a closed-cycle reactor to a large extent follow the same steps as in the once-through cycle. The main difference is that the spent fuel is chemically processed (Plutonium-Uranium Recovery by Extraction, PUREX), and plutonium and uranium are recovered for further use as mixed oxide (MOX) fuel [49]. Extraction of uranium and plutonium from spent nuclear fuel is done routinely at La Hague (France), Sellafield (UK), Rokkasho (Japan), and Mayak (Russia). MA are not extracted and are the main constituents of the long-lived radioactive waste which must be safely stored (see above: Waste) or incinerated/transmuted (see below: Future perspectives of handling of spent fuel). Of course, partitioning is a large-scale process, the associated risks of which have been addressed above (see: Proliferation and extremists' threat). In facilities currently running the separated isotopes are strictly monitored by international bodies to keep records of their whereabouts.

An advantage of the closed fuel cycle is that there is a much smaller demand for uranium ore. The recycled material can be used in fast breeder reactors, which are a hundred-fold more efficient. With the currently known supply of uranium ore fission reactors could operate for 5,000 years instead of only 50 years with the once-through cycle. The smaller demand for uranium ore will reduce the environmental impact of mining and in addition ease geo-political and economic conflicts over uranium ore supplies. Another possible closed fuel cycle is based on thorium [50] which is 3 – 4 times more abundant than uranium.

Future perspectives for the handling of spent fuel

The alternative to very long-time storage of spent fuel is to incinerate (burn) it in dedicated reactors ([43], see below) or transmute long-lived isotopes into short-lived ones by accelerator driven systems (ADS). Both processes require the effective partitioning of not only U/Pu but also MAs. The efficiency of partitioning is as high as 99.9%; that of incineration/transmutation, however, is expected to be around 20%. Hence several cycles of partitioning and incineration/transmutation are needed to significantly reduce the amount of long-lived radioactive material [34]. Then, after a little more than three hundred years, a period for which safe storage is easily conceivable, the radiotoxicity of spent fuel is below that of the uranium from which the fuel originally came.

Promising transmutation schemes based on accelerator driven systems (ADS) have been studied in the last decades [51]. This new concept is being pursued in Europe as well as in Asia. The basic idea is to use a hybrid reactor combining a fission reactor with a high-current, high-energy proton accelerator. The latter is used to produce a very intensive neutron flux which induces fission in a target of uranium, plutonium and MA. The neutrons are needed to start and maintain the fission process and no self-sustaining chain-reaction is involved. In principle, such a hybrid system could transmute radioactive wastes into short-lived fission products and simultaneously produce energy.

A project in the 6th Framework Programme of the European Commission was launched which will design the first experimental facility to demonstrate the feasibility of transmutation with ADS. A conceptual design is being developed in parallel for a modular industrial-level realisation [52]. These studies must also encompass studies on reliability and economic competitiveness. Such hybrid systems have, besides the burning of waste, also the potential to contribute substantially to large-scale energy production beyond 2020. ADS are in strong competition with Generation IV reactors that are also designed for effective burning of MAs (for Generation IV reactors see next chapter).

> Open- and closed-cycle nuclear reactors both generate energy by neutron-induced fission with heavy nuclei as fuel, but treat the waste produced in different ways. The open-cycle system is attractive from the point of view of security. Closed-cycle systems recover useable fuel from the waste and hence have a substantially smaller demand for uranium ore.

5 Nuclear power generation in the future

Advanced nuclear reactors

The energy scenarios for the next 50 years show that it is vital to keep open the nuclear option for electricity generation. However, current reactor technologies and their associated fuel cycles based on U-235 produce a large amount of potentially dangerous waste while for some types of reactors the risk of a catastrophic event is unacceptably high. As a result of these safety problems and the association of nuclear energy with the Chernobyl accident and with nuclear weapons, the nuclear industry is facing strong opposition in some European countries.

In response, Generation III (GenIII) reactors have been developed, such as the European Pressurised Reactor (EPR) presently under construction at Olkiluoto, Finland, which presents a step forward in safety technology [35]. It features advanced accident prevention to even further reduce the probability of reactor-core damage. Improved accident control will ensure that in the extremely unlikely event of a reactor-core meltdown all radioactive material is retained inside the containment system and that the consequences of such an accident remain restricted to the plant itself. There will also be an improved resistance to direct impact by aircraft, including large commercial jetliners.

In 2001, over 100 experts from Argentina, Brazil, Canada, France, Japan, Korea, South Africa, Switzerland, the United Kingdom, the United States, the International Atomic Energy Agency, and the OECD Nuclear Energy Agency began work on defining the goals for new systems, identifying the most promising concepts, and evaluating them, and defining the required research and development (R&D) efforts. By the end of 2002, the work resulted in a description of six systems and their associated R&D needs [43]. In the development of the Generation IV (GenIV) reactors strong emphasis is placed on safety. A key requirement is the exclusion of an accident like Chernobyl, where considerable quantities of radioactive material were released into the environment. Additionally, these reactors will improve the economics of electricity production, reduce the amounts of nuclear waste needing disposal, increase the resistance to proliferation, and introduce new features such as hydrogen production for transportation applications [cf. Table 2]. There is also a possibility of using the thorium-uranium cycle. Its advantages – for instance, the impossibility, as follows from the laws of physics, to produce plutonium and/or minor actinides and, thus, the reduction of the radiotoxicity of the waste by a factor of about 1000 in comparison to the once-through uranium cycle - was discussed in a recent article [53].

Table 2: GenIV reactors and some of their specific properties, extracted from [43]

GFR	Gas-Cooled Fast Reactor	Efficient actinide management; closed fuel cycle. Delivers electricity, hydrogen, or heat.
LFR	Lead-Cooled Fast Reactor	Small factory-built plant; closed cycle with very long refuelling interval (15-20 years). Transportable to where needed for production of distributed energy, drinkable water, hydrogen. Also larger LFR are under consideration.
MSR	Molten Salt Reactor	Tailored to an efficient burn up of Pu and MA; liquid fuel avoids need for fuel fabrication; inherently safe. Ranked highest in sustainability; best suited for the thorium cycle.
SFR	Sodium-Cooled Fast Reactor	Efficient actinide management; conversion of fertile U; closed cycle.
SCWR	Super Critical Water-Cooled Reactor	Efficient electricity production; option for actinide management; once-through uranium cycle in the most simple form; closed cycle also possible.
VHTR	Very-High Temperature Reactor	Once-through uranium cycle; electricity production and heat for petrochemical industry, thermo-chemical production of hydrogen.

Although research is still required, some of these systems are expected to be operational by 2030. With the most advanced fuel cycles, combined with recycling, a large fraction of the long-lived fissile material is incinerated, so that isolation requirements for the waste are reduced to a few hundred years instead of hundreds of thousands of years.

It is too early to finally judge the relative merits of ADS and GenIV reactors as energy producing and waste incinerating/transmuting systems, but the overall favourable properties of both are obvious. For a comparative study see [54].

Nuclear fusion reactors

A further option for nuclear energy generation without fuel-related CO_2 emission is the nuclear fusion process. In 2005, an important step towards its realisation was taken by the decision to build the International Thermonuclear Experimental Reactor, ITER, [55] in Cadarache, France. In this reactor deuterium and tritium are fused to form helium-4 and a neutron that carries 80% of the energy set free. Helium-4 is the "non-radioactive ash" of the fusion process. Once in operation, such a reactor breeds the tritium needed as fuel from lithium. Deuterium is a heavy isotope of hydrogen and available in nature in virtually unlimited quantity. The world resources of lithium are estimated to be 12 million tonnes [56], enough to consider nuclear fusion as an energy source for some considerable time. The construction of a fusion power plant is going to use materials for which, after the unavoidable activation by neutrons, the activity decays relatively quickly to the hands-on level within a hundred years. Thereafter, the material can safely be handled on a workbench. Experience in handling radioactive tritium justifies the assertion that the fusion energy source is very safe. However, nuclear fusion might become a substantial energy supplier at the earliest in the second half of this century because the technology of fusion reactors needs considerable further elaboration.

New reactor concepts (GenIV) will meet stringent criteria for sustainability and reliability of energy production, and those for safety and non-proliferation. Nuclear fission and fusion have the potential to make a substantial contribution to meeting future electricity needs.

6 Conclusion

Our considerations have led to the following conclusions:

- No one source of energy will be able to fill the needs of future generations.
- Nuclear power can and should make an important contribution to a portfolio of electricity sources.
- Modern nuclear reactors based on proven technology and using advanced accident prevention, including passive safety systems, will make a Chernobyl-type accident with all its consequences practically impossible.
- Extensive and long-term research, development and demonstration programmes (RD&D), including all possible options for a sustainable energy generation, must be initiated or continued. RD&D for a specific option should be directed to the realisation and evaluation of a functioning demonstration system, for instance, one based on a Generation IV reactor.
- Waste transmutation using the promising accelerator-driven (ADS) or GenIV reactors should be pursued; again, the necessary next steps are engineering development and demonstration plants.
- The possibility of extending the life-time of existing reactors should also be studied.
- The nuclear option should mean consideration of energy production by both fission and fusion processes.
- In view of the long period between demonstration and realisation of any proposed scheme, the potential of the nuclear option for the period beyond 2020 can only be judged on the basis of considerably intensified and expanded RD&D efforts. Such efforts need the concerted efforts of scientists and politicians in order to assess the long-term safety and economic aspects of energy generation.
- The May 2006 proposal of the European Commission for a common European energy policy must be realised. This policy aims at enabling Europe to face the energy supply challenges of the future and the effects these will have on growth and the environment [57], and follows an EC-Green Paper on European strategy for the security of energy supply [58].
- An RD&D programme for the nuclear option also requires support for basic research on nuclear and relevant material science, since only in that way will the expertise needed to find novel technological solutions be obtained.

- Europe needs to stay abreast of developments in reactor design independently of any decision about their construction in Europe. This is an important subsidiary reason for investment in nuclear reactor RD&D and is essential if Europe is to be able to follow programmes in rapidly developing countries like China and India, who are committed to building nuclear power plants, and to help ensure their safety, for instance, through active participation in the IAEA.

- RD&D needs to be performed on a global scale. Problems connected with sustainable and large-scale nuclear energy production such as waste deposition, safety, non-proliferation and public acceptance go well beyond national borders.

- Policy makers decision must realise the urgent need to solve the green house problem within a well defined energy strategy, by stimulating and funding RD&D including the nuclear energy option. The European Commission has already taken on board this fundamental concept [59].

- In order to obtain public acceptance and support a responsible and unbiased information programme on all aspects of nuclear energy production is needed, supported by a public awareness programme which helps the general public to better appreciate and judge technological risks and risk assessments in an industrialised economy. Great efforts are needed to inform the general public of the short-term and long-term safety aspects and the ecological impact of the various technologies that contribute to highly industrialised regions in Europe. If nuclear technology is to contribute to meeting Europe's future energy needs and help to ameliorate the severe environmental effects of other energy sources, it is essential to obtain public acceptance. Otherwise, innovative developments could be hindered and even stopped by public opinion.

No one source will be able to fill the need of future generations for energy. The nuclear option, incorporating recent major advances in technology and safety, should serve as one of the main components of future energy supply. There is a clear need for long-term research, development and demonstration programmes as well as basic research into both nuclear fission and fusion and methods of waste transmutation and storage. Ways must be found to inform the general public on how to assess relative risks rationally. Everybody participating in the decision making process needs to be well informed about energy issues. It is an important task of European science and research to ensure this.

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