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The nuclear energy of the future*

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Resum. L'Agència Internacional de l'Energia Atòmica (AIEA), fundada el 1957 a les Nacions Unides i amb el lema "Àtoms per la pau", és el centre mundial de cooperació en el camp nuclear i té la finalitat principal de promoure tecnologies nuclears segures, protegides i amb finalitats pacífiques, tot vetllant perquè els materials nuclears mai no es desviïn a un ús militar. També ajuda els estats membres a posar al dia la seva seguretat i protecció i a estar preparats per a possibles emergències. El Departament de Cooperació Tècnica, que dirigeix A. M. Cetto, té actualment més de vuit-cents projectes en marxa per a tractar problemes que es poden resoldre l'aplicació de la tecnologia nuclear. En el pressupost actual, la partida més gran (aproximadament un 24 %) està dedicada a les aplicacions en salut, seguida de la seguretat en el transport i les radiacions, la ciència nuclear, i l'alimentació i l'agricultura (al voltant de l'11 % cadascuna). L'AIEA col·labora en la planificació de les necessitats nuclears dels països membres, entre les quals hi ha la generació d'energia. Aquest article descriu l'actual escenari global de l'energia i debat el paper que hi exerceixen les diverses fonts d'energia. A més, descriu les raons per a la diferent barreja de fonts d'energia que han triat els diferents països, i remarca que els costos de producció són un factor important en la selecció de la font d'energia. Tenint en compte que les preocupacions sobre l'energia en el context del desenvolupament sostenible són un fenomen nou, l'article discuteix els recents esforços internacionals per a tractar els assumptes energètics i avalua el paper de l'energia nuclear en el actual. S'hi descriu també l'expansió nuclear d'avui dia, així com la potencial sostenibilitat que té i el paper que pot tenir en la reducció dels gasos d'efecte hivernacle. L'article conclou amb una discussió sobre el suport que la IAEA ofereix als seus estats membres interessats en l'opció nuclear i acaba amb una visió de conjunt de dues grans aproximacions a la producció de l'energia nuclear en el futur.

Paraules clau: IAEA (Viena) · energia nuclear · ús pacífic de l'energia atòmica

Abstract. The IAEA is the world's center of cooperation in the nuclear field. It was set up as the world organization "Atoms for Peace" in 1957 within the United Nations. The Agency works with its Member States and multiple partners worldwide to promote safe, secure, and peaceful nuclear technologies, while ensuring that nuclear materials are never diverted to military use. It also helps its Member States to maintain up-to-date safety and protection levels and to be prepared for possible emergencies. The Department of Technical Cooperation, directed by Ana María Cetto, currently has more than 800 projects underway to address problems that can be solved with the use of nuclear technology. In the current budget, the largest item (approximately 24%) is dedicated to applications in health, followed by safety in transport and radiation, nuclear science, and food and agriculture (approximately 11% each). The IAEA collaborates in the planning of the nuclear needs of its Member States, including the generation of energy. This paper describes the current global energy scenario and discusses the role played by different energy sources. It describes the reasons for the different mix of energy supplies chosen by individual countries, and underlines that costs of production are an important factor in energy source selection. Noting that concerns about energy in the context of sustainable development are a recent phenomenon, the papers discusses recent international efforts to address energy issues, and assesses the role of nuclear energy in today's scenario. Current nuclear expansion is described, as well as its potential sustainability, and the role it can play in the reduction of greenhouse gases. The paper closes with a discussion of the support that the IAEA offers to Member States interested in the nuclear option, and ends with an overview of two major approaches to nuclear energy production in the future.

Keywords: IAEA (Vienna) · nuclear energy · peaceful use of atomic energy

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Global energy scenario

In 2000, the Intergovernmental Panel on Climate Change (IPCC) published a Special Report on Emissions Scenarios [1]. Forty long-term (until 2100) scenarios project a sustained increase in global energy demand, particularly by developing countries, and specifically in the electricity sector. Some scenarios predict a smaller increase in energy demand after 2050, or even a reversion of the trend due to expected decreasing population numbers, a life style that is less energy-intensive, and energetically more efficient technologies. However, overall, the scenarios show a rising curve. The median growth factor between 2000 and 2100 is about 3.5 (Fig. 1).

In the shorter term, these estimates coincide with those of the International Energy Agency of the OECD, which foresee the need to double the electricity generation capacity between 2004 and 2030 [2].

Role of different energy sources

The growing energy demand will have to be met in some way or another, or else the lack of sufficient energy production will hamper the development that is expected to take place, regardless of the projected scenario. Nearly every aspect of development—from reducing poverty and raising living standards to improving health care, education and productivity—requires reliable access to energy sources. How will the different countries, and the world as a whole, meet this challenge?

Figure 2 shows global energy consumption by energy

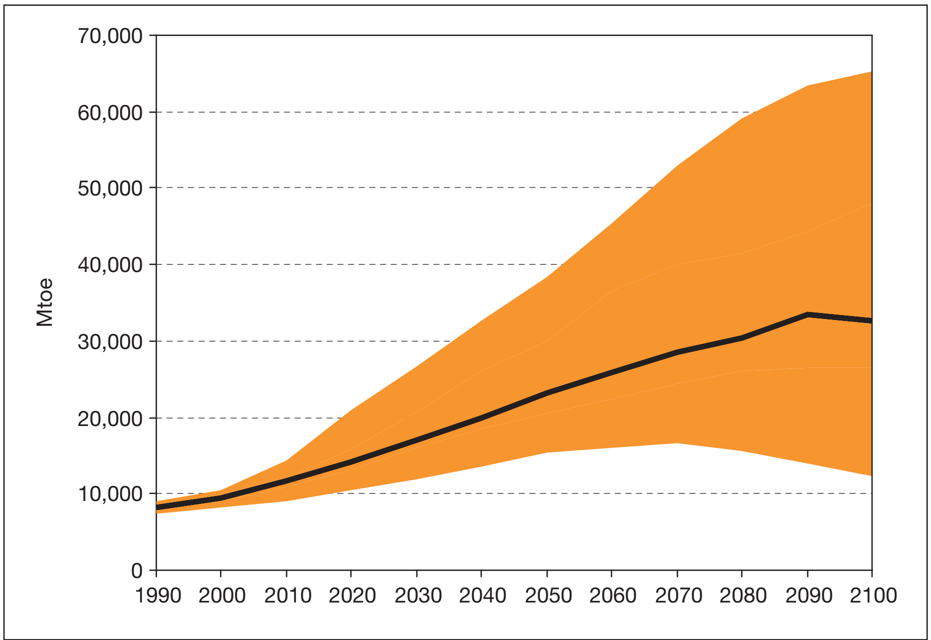

Fig. 1. Projected global primary energy consumption through 2100 (adapted from [1]). *Mtoe*, million tons of oil equivalents.

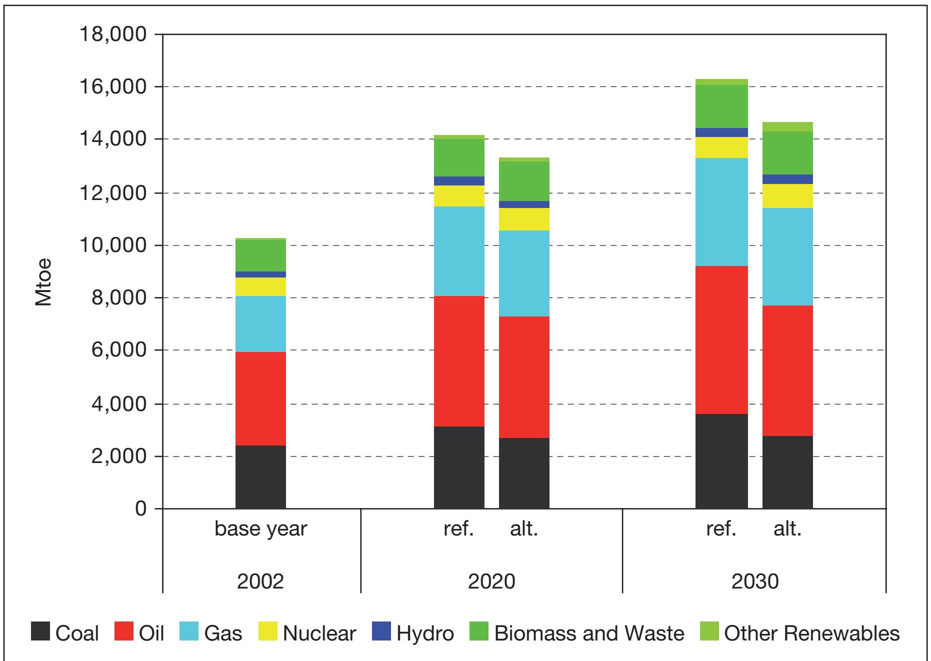

Fig. 2. Projected global primary energy consumption by fuel through 2030, in two scenarios: reference and alternative (adapted from [2]).

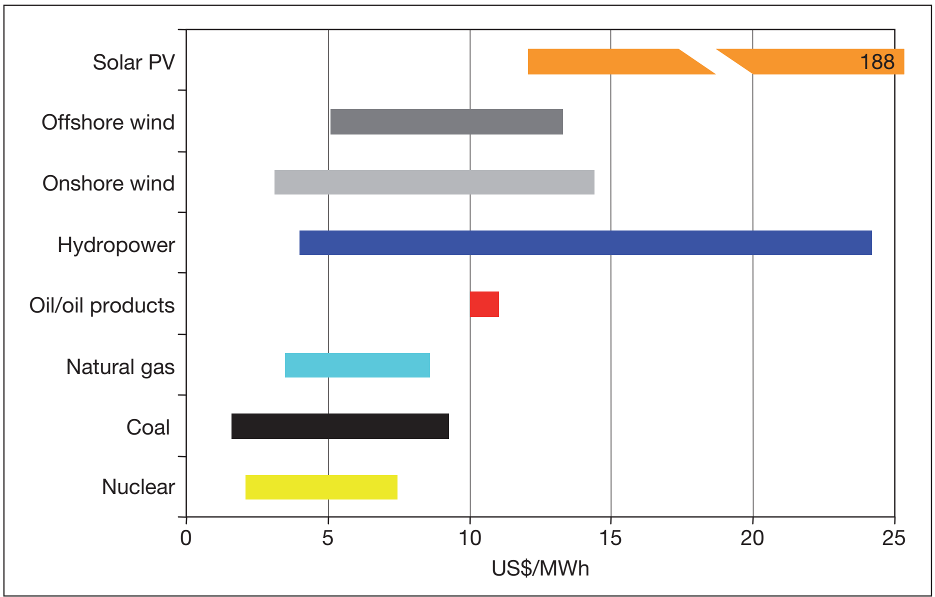

Fig. 3. Ranges of levelized generating costs of new electricity generating capacities [3]. *PV*, photovoltaic.

source in 2002 and two different projections for 2020 and 2030, according to the OECD/IEA [2]. It is interesting to note that the two scenarios (the conventional and the alternative one, the latter assuming the implantation of corrective measures) do not differ considerably as to the relative distribution of energy sources. On the whole, the various fossil fuels clearly continue to be predominant. It is important to recognize, however, that every country uses a different mix of energy supplies, because:

- Different technologies respond not only to the available resources but also to different needs, e.g., for baseload power in contrast to peak power, for concentrated demand in megacities in contrast to small users in remote areas.
- The evolution of supply does not go hand in hand with the development of demand, and new technologies do not appear continuously but replace the older ones in fits and starts and with overlaps.
- Investors select technologies based on different risk-benefit estimates and financing possibilities.
- Fast developing countries may need to expand all their energy options simultaneously.
- Decisions are also influenced by political factors, national priorities and preferences, development plans, dependence on imports, creation of working places, market regulations, and environmental considerations, in particular pollution and climate change.

One important factor for the choice of energy source is, of course, the expected cost of power production. It includes generation costs, expressed as levelized costs, and external costs. The levelized cost is the amount needed to cover the operational expenses and the costs of amortizing capital investment in the plant. Figure 3 shows the results of seven recent studies—except for the values for oil, which are based on a single study [3]. Some of the variations are due to different technological assumptions, others to national factors. Compliance with

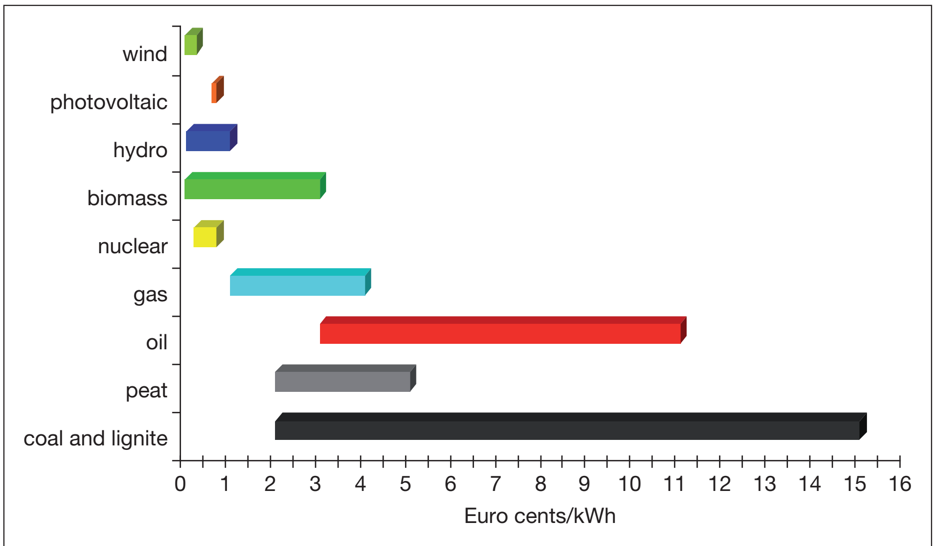

Fig. 4. External cost figures for electricity generation in the European Union for technologies available in 1999 [4].

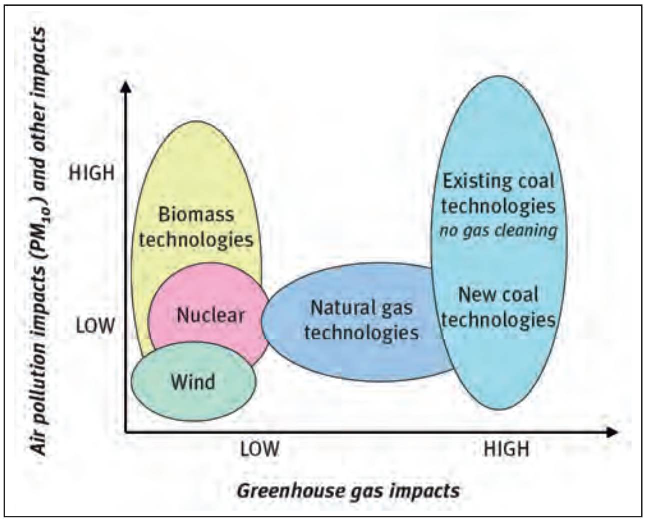

Fig. 5. Environmental impacts from emissions of existing electricity generating technologies [4]. *PM_{10}*, suspended particles <10 µm.

existing regulations was assumed in all cases; a regulatory change can obviously have a considerable effect on the costs.

External costs, as the second type of generation costs, are borne by the public and not by those who benefit from the electricity generation – as long as these costs are not internalized. Private investors do not take external costs into consideration, but for governments they are an important decision-making criterion. Figure 4 summarizes external costs calculated by the European Commission (EC) on the basis of technologies available in 1999, with health and environmental costs included [4]. However, much remains to be done to internalize costs, in particular those linked to issues of increasing concern such as the impact of greenhouse gas impacts and the security of the energy supply.

There is no form of energy production or consumption that does not have an impact on the environment—from the extraction of the raw material to the final consumption and waste management, in particular as regards air pollution through particles and greenhouse gases. Figure 5 provides a qualitative comparison of the various technologies presently used in the European Union. From this point of view, wind energy has clear comparative advantages and the use of conventional coal technologies has by far the worst impacts. The figure also shows the relatively low impact of nuclear energy on both greenhouse gases and air pollution.

Energy and sustainable development

The concern about energy in the context of sustainable development is a remarkably recent phenomenon: as late as 1992, the Earth Summit in Rio de Janeiro did not pay special attention to the topic, and of the 40 chapters of Agenda 21 not one is specifically dedicated to it [5].

The Commission on Sustainable Development (CSD), established to ensure the effective follow-up of the Summit and to examine the progress achieved in the implementation of Agenda 21, approached the subject of energy only at its 9th session, held in 2001 (CSD-9). Nuclear energy, in particular, was a highly controversial topic during the preparatory phase of CSD-9. The main outcomes of those discussions were: (1) a disagreement among countries on the role of nuclear energy for sustainable development, and (2) an agreement that selecting the nuclear energy option is the prerogative of the individual country.

At the Johannesburg Summit, in 2002, the participating countries were called upon to implement the recommendations of CSD-9 and to promote the availability of clean and accessible energies (in particular, renewable sources), advanced technologies (including nuclear and cleaner fossil-fuel technologies), and efficiency increases.

Presently, energy is part of a CSD thematic cluster, together with industrial development, air pollution/atmosphere, and climate change. At CSD-15 (held in May 2007), however, during which the Commission was expected to recommend future action on energy for sustainable development, climate change, industrial development ,and air pollution, no final text was agreed.

At the same time, the IPCC issued a report on the mitigation of climate change [6]. The main recommendations were: encouraging energy conservation and energy-efficient lifestyles, and rapidly developing more renewable energy technologies to eventually overtake dirty fossil sources of energy.

Meanwhile, another mechanism has been established, namely, UN-Energy, to reach coherence on the UN's response to the Johannesburg Summit and to assure the agreement of other parties to the decisions of the Summit, since there is not a single entity in the UN system that is responsible for the subject of energy.

The aim is to increase the contribution of energy to achieving the Millennium Development Goals, thus recognizing that development cannot take place without meeting energy needs. The correlation between energy consumption per capita and level of development of a country is strong, as can be appreciated from the graph in Figure 6. Presently, 1600 million people do not have access to electricity and 2400 million have no access to modern fuels, the vast majority of them living in poverty and lacking access to basic services [8]. Should there be a review of the Millennium Development Goals, it can be expected that energy will figure prominently, with access to energy possibly becoming a new goal in itself.

Nuclear energy today

What is the place of nuclear energy in the current scenario?

After a rapid initial expansion of installed nuclear energy capacity, reaching an average rate of increase of 25% per year in the 1970s, development slowed down considerably, the main influencing factors being the deregulation of electricity markets, the slow growth of electricity demand in industrialized countries, public perception as a result of the accidents of Three Mile Island and Chernobyl, and economic reforms in Russia and other Eastern European countries.

Yet, while nuclear electricity generation capacity has remained virtually stagnant in the last 15 years, actual electricity

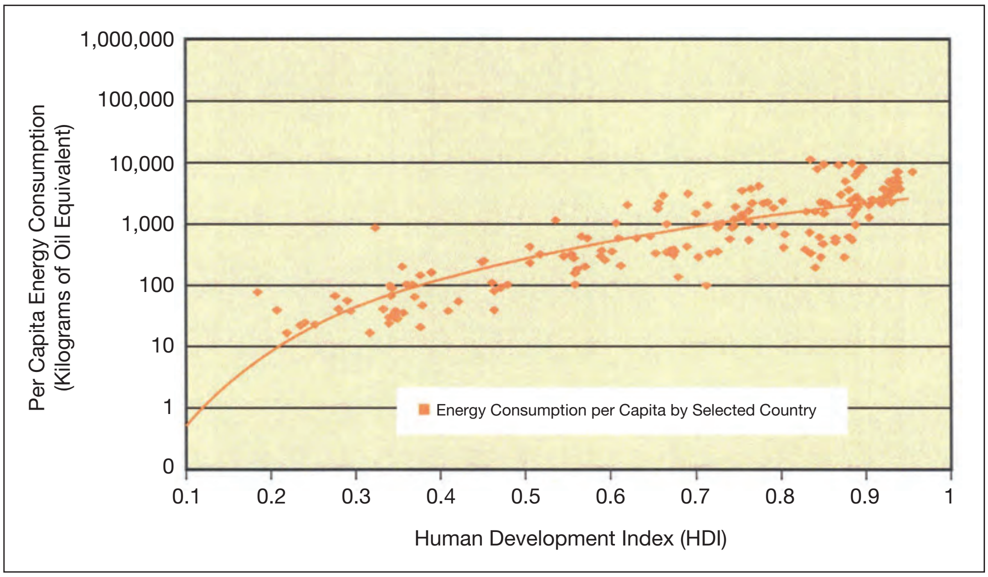

Fig. 6. Energy consumption and human development [7].

production has continued to grow because of increased operating efficiency and technical improvements [3]. Nuclear energy contributes 16% to total energy requirements, with about 435 reactors in operation producing 370 GW (e), most of them in developed countries, and eight of them in Spain [3]. Another 29 units are under construction around the world, most of them in developing countries (17 in Asia). Currently, 30 countries are operating nuclear power plants, and there is an almost equivalent number of countries in various stages of considering or planning their first nuclear power plant (Fig. 7)

The reasons for this new trend include concerns over rising fossil fuel prices, energy supply security, and the environment in meeting the growing energy demand in the quest for a better quality of life. Already ambitious nuclear expansion programs are in place in China and India. China is planning to expand its nuclear power capacity six-fold by 2020, India eight-fold or even more by 2022.

The IAEA annually updates its projection of the use of nuclear power in its Member States by collecting information from them. The low projection is by aggregation of data on plants already being built, planned, or firmly committed to, whilst the high projection includes those reasonably estimated for new construction. The 2006 low and high projections to the year 2030 shows increases of 15% and 70%, respectively, compared to the current capacity [9].

All reactors in operation or under construction use uranium as fuel. It is estimated that conventional uranium sources will last for another 270 years at the current rate of consumption, or for 8,000–16,000 years or more if a fast neutron system and a closed fuel cycle are put into use [10,11]. If unconventional uranium resources (uranium in phosphates) are used, these time periods will be further extended. The use of thorium would additionally enhance the almost unlimited supply of resources for nuclear power.

The understanding that nuclear energy may be an indispensable option to reduce greenhouse gas emission has spread among political, technological, and even financial spheres. The recent report of the Intergovernmental Panel on Climate Change (IPCC), mentioned above [6], acknowledged that nuclear power is and will remain a "key mitigation technology" and states that with a carbon emission cost of $50 per tonne of CO_2, its share of electricity generation could grow from 16%

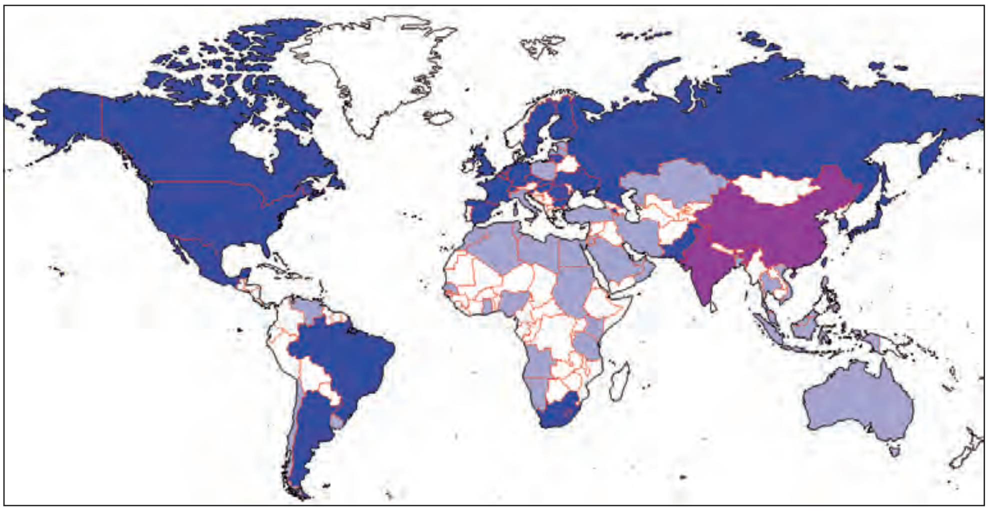

Fig. 7. Countries with operating nuclear power (NP) (dark blue and violet), with an ambitious nuclear expansion programs (violet), and considering nuclear power (light blue) [9].

now to 18% of demand by 2030, even as total energy demand is expected to double.

Role of the IAEA in the revival of nuclear energy

As a result of these recent trends, the IAEA has received a growing number of requests for orientation and advice on energy planning and on nuclear energy development n particular.

The role of the IAEA is to ensure that, wherever nuclear energy is produced, this is done safely, securely, and with a minimal risk of proliferation. For this purpose, it develops international safety standards and codes of practice, supports its Member States in creating the necessary regulatory infrastructure, and promotes commitment and adherence to safeguards agreements. In addition, it supports continued technological innovation in the field of nuclear power to improve its attributes in safety, security, economics, proliferation resistance, environmental impact, and waste management, ensuring in particular that the needs of developing countries are taken into account: The IAEA also provides services to evaluate different energy models in line with the characteristics of each country. With regard to the development of nuclear power stations, the aspects taken into consideration include safety and security, infrastructure, manpower training, and legal and normative matters. Altogether, six energy planning models are used in over 100 countries [10].

These services are provided through the Technical Cooperation program of the IAEA, following the Member State's requests. The Secretariat has established a special task force to ensure coordinated support to the countries considering the introduction of nuclear power or expansion from a small number of units (useful references are the technical documents [12,13] and the official document [14] describing the necessary preparatory steps to launch a nuclear power program and the various factors to be considered).

In 2003, a multilateral nuclear approach to the nuclear fuel cycle was proposed by the IAEA's Director General, with two purposes: insuring countries against possible political interruptions to nuclear fuel supplies and reducing the risk of proliferation of sensitive parts of the nuclear fuel cycle. New initiatives were put forward in 2006 by the US and Russia, under the Global Nuclear Energy Partnership and Global Nuclear Power Infrastructure, respectively. These proposals are intended to explore international cooperation in the development and deployment of nuclear reactors and fuel cycle facilities, with special attention to enrichment and reprocessing and to minimizing the risk of proliferation.

The nuclear energy of the future

International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). International and national programs intended for the development of innovative nuclear reactor and fuel cycle technology are very active. In particular, the Generation IV International Forum focuses on R&D for six reactor systems that will be utilized in the 2030s. In 2001, the IAEA established INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles) to provide an open forum that would bring together nuclear system supplier and user countries in order to study the opportunities and challenges associated with the introduction of innovative nuclear energy systems [15].

INPRO has developed an evaluation methodology with a set of principles and criteria for the assessment of innovative nuclear system (INS) in the areas of economics, safety, environment, waste management, proliferation resistance, physical protection, and infrastructure. This methodology can be applied for screening an INS, comparing different INSs to find one that is consistent with the needs of a given state, and identifying R&D needs. In 2006, INPRO moved to Phase 2, which includes infrastructure and coordination for the planning of collaborative projects to support the development of INS.

In August 2009, 31 IAEA Member States, including Spain, were participants in INPRO: Algeria, Argentina, Armenia, Belarus, Belgium, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, France, Germany, India, Indonesia, Italy, Japan, Kazakhstan, Republic of Korea, Morocco, Netherlands, Pakistan, Russian Federation, Slovakia, South Africa, Spain, Switzerland, Turkey, Ukraine, United States of America, and the European Commission (EC).

International Thermonuclear Experimental Reactor (ITER) Project. Nuclear fusion is the process by which two light nuclei fuse together to form a heavier one, thereby losing a part of their mass in the form of energy —as occurs on the surface of the sun. Efforts to obtain energy from nuclear fusion in the laboratory date back several decades. The aim of the controlled fusion research program is to achieve sustained energy generation, a process that is considered to have a huge potential to respond to future energy demands.

In the 1950s, some researchers shared a certain amount of optimism that electricity generation by fusion would be developed within the next 50 years; today it is considered that it will take another 50 years until this energy source will be on the market. The technological challenges of energy generation by fusion are much more complex than expected. Actually, it is still not possible to confirm with certainty that fusion presents a competitive source of energy, even if the experience so far has been encouraging.

The joint international R&D project ITER is aimed precisely at demonstrating the scientific and technical feasibility of fusion power for peaceful purposes. The IAEA has been actively involved in the project from its inception, providing backing and practical support. After much discussion between the project participants (EU, India, Japan, People's Republic of China, Republic of Korea, Russian Federation, USA), it was agreed, in 2005, to establish ITER in Cadarache, near Aix-en-Provence, France, with the possibility to conduct experiments from remote centers throughout the participating countries. In 2007, In 2007, the European Domestic Agency, based in Barcelona, was established to manage the EU's contribution to this major project [16].

The experimental device to be built is based on the tokamak concept, in which a hot gas contained in a torus-shaped vessel is confined using an intense magnetic field. The gas is heated to over 100 million degrees, producing 500 MW of fusion power. Since the conceptual design stage, which started in 1988, by 2001 it had moved through various phases, leading to a final design that provides the level of detail needed for cost projections.

Due to a host of completed and ongoing experiments, much is understood today about the basic science of nuclear fusion, and there is a clear path to its technical realization. Building ITER will advance this knowledge immeasurably, particularly with regard to optimization of the physical performance parameters, the technology to be used, and appropriate manufacturing techniques to be adopted; this will place participating countries in a much better position to decide on whether it is worth going further.

Nuclear fusion will have much to offer if the technology is eventually developed, one clear advantage being that fusion power plants would not contribute to acid rain or to greenhouse effects. Yet, specific problems associated with the release of radioactive substances and the generation of radioactive waste will have to be solved for nuclear fusion to become a widely used future energy source [17].

Additional information and documentation on matters referred to in this paper can be found on the IAEA's website (http://www.iaea.org).

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