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Overview of Nuclear Energy: Present and Projected Use

Fusion for Neutrons and Sub-critical Nuclear Fission

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Abstract. Several factors will influence the contribution of nuclear energy to the future energy mix. Among them, the most important are the degree of global commitment to greenhouse gas reduction, continued vigilance in safety and safeguards, technological advances, economic competitiveness and innovative financing arrangements for new nuclear power plant constructions, the implementation of nuclear waste disposal, and, last but not least, public perception, information and education. The paper presents an overview of the current nuclear energy situation, possible development scenarios, of reactor technology, and of non-electric applications of nuclear energy.

Keywords: Nuclear energy use, reactor concepts, non-electric applications.
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INTRODUCTION

Current renewed interest in nuclear energy is driven by the need to develop carbon free energy sources, demographics and development in emerging economies, as well as security of supply concerns. The pace at which the nuclear energy option is embraced seems to be accelerating worldwide, with the existing marked imbalances in energy availability causing more and more emerging economies to give it serious consideration.

Worldwide, there are 440 reactor units in operation, with a total installed capacity of 374 GW_{el} [1]. There are also 65 reactor units under construction, totaling 63 GW_{el} [1]. Nuclear Power will probably grow, but its share of global electricity may fall. Some countries have phase-out policies, others see advantages for energy security, and some plan to increase nuclear capacity. The International Atomic Energy Agency (IAEA) predicts growth of nuclear power generation from 2558 $TW_{el}\times h$ in 2009 to (low – high estimates) 3314 – 4006 $TW_{el}\times h$ by 2020, 4040 – 5938 $TW_{el}\times h$ by 2030, and 4342 – 10436 $TW_{el}\times h$ by 2050 [2].

Several factors will influence the contribution of nuclear energy to a future sustainable energy mix. Among them, the most important are the degree of global commitment to greenhouse gas reduction, continued vigilance in safety and safeguards, technological advances, economic competitiveness and innovative financing arrangements for new nuclear power plant constructions, the implementation of nuclear waste disposal, and, last but not least, public perception, information and education.

The paper presents an overview of the current worldwide status of nuclear energy situation, a brief overview of reactor technology, and of some non-electric uses of nuclear energy.

DRIVERS FOR NUCLEAR ENERGY USE

It is common understanding that energy is essential for sustainable development. At the same time, it must be recognized that energy consumption has only become noticeable with the advent of the industrial revolution in the second half of the eighteenth century. Thus, even when limiting “mankind history” to just the last 5000 years (i.e. starting with the Egyptian civilization), energy consumption and mankind development have only been related for a very short period of time[1]. However, in these less than three centuries, primary energy consumption, which was, and still is, fossil fuel dominated, reached dramatic growth rates[2], with currently an average *per capita* and per year growth rate of about 2%. The data for 2009 and for estimated primary energy requirements up to the year 2050 [2] indicates an increase from a worldwide total energy requirement of 17.4×10^9 tce[3] in 2009 to 20.8×10^9 tce, 25.8×10^9 tce, and 36.9×10^9 tce in 2020, 2030, and 2050, respectively. Worldwide in 2009, primary energy used for electricity generation was 36.9%, and the share of nuclear was 5.5%. The estimates for 2050 indicate 55% of primary energy used for electricity production, and the share of nuclear at 5 – 10%. For the following discussion it is also worthwhile keeping regional energy consumption data in mind: while, in 2009, the combined primary energy consumption in North America, Western and Eastern Europe, on the one hand side, and that of the whole Asian continent (including the Middle East), on the other, were the same (about 44% of the worldwide consumption), and the respective figures for Latin America and Africa were slightly more and slightly less than 6%, respectively, the estimates for 2050 are indicating a drop for North America to 22%, and increases for all the other regions: 53% for the whole Asian continent (including the Middle East), just over 8% for Latin America, and almost 18% for Africa.

Against this backdrop, there are three major drivers for nuclear energy use: (i) the expected growth of energy demand (due to demographics and economical development goals), stemming mostly from developing countries and nations with emerging economies, and a logical consequence of the marked imbalance in current energy consumption; (ii) security of supply concerns; and (iii) the need to transition to a carbon-free energy supply.

Worldwide demographics and development goals are favoring an increase in nuclear energy use in developing and countries with emerging economies of the Asian–Pacific region. Table 1 summarizes population growth estimates for various regions [2]. This data indicates that by 2050 more than ¾ of the world’s population will be concentrated in Asia and Africa.

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[1] Even more so, when, as one could argue, “mankind history” starts twice as long (10000 years) ago with the transition to sedentary agricultural communities in the Fertile Crescent

[2] The *per capita* energy consumption today is roughly two orders of magnitude higher than in pre-industrial times

[3] 1 tce (ton of coal equivalent) = 29.3×10^9 J

TABLE 1. Population growth estimates (million inhabitants) and growth rate relative to 2009

Region	2009	2020	2030	2050
North America, Western & Eastern Europe	1222	1256 (2.8%)	1275 (4.3%)	1324 (8.4%)
Asia (including Middle East)	3979	4432 (11.4%)	4739 (19.1%)	5081 (27.7%)
Latin America	587	659 (12.3%)	711 (21.1%)	729 (24.2%)
Africa	965	1188 (23.1%)	1398 (44.9%)	1998 (107%)
World total	6753	7535 (11.6%)	8123 (20.3%)	9132 (35.2%)

Energy consumption data for 2009 and projections for 2020, 2030 and 2050 are summarized in Table 2 [2]. The projection figures are arithmetic averages between low and high estimates.

TABLE 2. Energy requirement estimates (10^9 tce), share of electricity generation, and share of nuclear

	2009			2020			2030			2050		
Region	Tot. Prim. Energy	% Elec	% Nucl	Tot. Prim. Energy	% Elec	% Nucl	Tot. Prim. Energy	% Elec	% Nuc	Tot. Prim. Energy	% Elec	% Nuc
North America, Western & Eastern Europe	7.6	38.3	9.7	7.8	41	11.1	7.95	44	13.2	8.16	49	17
Asia (inc. Mid East)	7.7	38.7	2.6	10.1	43	4.6	13.2	50	5.5	19.6	60	6
Latin America	1.1	27.9	1.0	1.4	30	1.35	1.91	35	2.6	2.97	46	3
Africa	1.0	21.7	0.4	1.5	25	0.46	2.7	32	1.2	6.21	55	1
World total	17.4	36.9	5.5	20.8	41	6.5	25.8	45	7.2	36.9	55	7

Because it is given region wise, the data in Table 2 masks, to a certain extent, the existing severe imbalances in current energy consumption, which are also a clear indication of the strong correlation between energy consumption and poverty: In the developed Western world, the *per capita* energy consumption in 2009 ranged between 13100 kW×h in North America and 4300 kW×h in Eastern Europe (with Western Europe at 6300 kW×h, and peak values as high as 16000 kW×h in Sweden), while the average figures for Africa and South Asia were 700 kW×h and 900 kW×h, respectively. However, even these last figures, which are roughly two orders of magnitude lower than average values in the OECD countries, are hiding the fact that in some African countries the yearly *per capita* electricity consumption is in the 70 – 100 kW×h range, meaning, e.g., that the people in a country like Nigeria have, in average, access to 8 W of electricity (a very dim light bulb!) per person. The strong correlation between energy consumption and poverty is striking: based on analyses performed in preparation of the IEA (2010) *World Energy Outlook* by the International Energy Agency (IEA), the United Nations Development Programme (UNDP), and the United Nations Industrial Development Organization (UNIDO) [3], one-fifth of the world population (more than 1.4 billion people) are without electricity, and 40% of the world population (almost 2.7 billion people) are relying almost exclusively on biomass as the principal energy source.

The fact that uranium, unlike petroleum, is distributed much more evenly around the planet explains why concerns linked to security of supply are an important driver for nuclear energy development. While almost two-thirds of the known oil reserves are concentrated in the Middle East, the 5.7×10^6 t of identified conventional uranium[4] resources that are recoverable at a cost of less than US$ 130/kg are distributed rather evenly over the five continents [4]. Australia has the most known uranium resources, followed by Kazakhstan, Canada, Russia, South Africa, Namibia, Brazil and the USA (the resources in these countries add up to about 85% of the known uranium resources). In the OECD/NEA – IAEA publication commonly known as the 'Red Book' [4], the not yet identified conventional uranium resources recoverable at a cost of less than US$ 130/kg are estimated at 6.3×10^6 t. Since all figures for mineral resources are also a function of market prices, extraction costs and intensity of the exploration efforts, the 'Red Book' [4] estimates speculative uranium resources at unspecified extraction costs and/or in areas that have not yet been explored to be 3.8×10^6 t. The security of supply argument is further strengthened if unconventional (e.g. seawater uranium[5]) and thorium is considered (the worldwide thorium resources are estimated at 6.3×10^6 t [4]).

The amount of integrated solar heat that is trapped in the atmosphere when burning fossil fuel is more than two orders of magnitude larger than the released fossil fuel energy. If worldwide energy production continues according to a "business as usual" paradigm, CO_2 doubling in the atmosphere will occur within 50 – 100 years. The possible catastrophic environmental consequences linked to the ensuing global warming of the planet ask for a transition to non-fossil energy production. Nuclear power is essentially carbon-free at the point of generation. When taking into consideration the full electricity generation life cycle, the greenhouse gas emissions from nuclear power production (2.5 – 5.7 g of carbon-equivalent per kW×h) are comparable to wind and biomass (2.5 – 16.6 g of carbon-equivalent per kW×h), lower than most hydroelectric and solar, and orders of magnitude lower than fossil electricity production [5].

WORLDWIDE STATUS AND PROSPECTS OF NUCLEAR ENERGY USE

According to data [1] updated by the IAEA on August 24, 2011, currently there are 439 nuclear power reactors in operation worldwide in 29 countries, totaling a net installed capacity of 374.0 GW_{el}[6]. Five nuclear power reactors are in long-term shutdown (totaling 2.78 GW_{el}), and 66 are under construction (totaling 63.6 GW_{el}) in China (27), Russia (11), India (6), the Republic of Korea (5), Bulgaria, Japan,

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[4] Uranium is a rather common metal in the Earth's crust (as common as zinc or tin). It can be found in most rocks (the average concentration of uranium in the Earth's continental crust is about 2.8 ppm) and also in the seawater (albeit at very low concentrations of about 3.3×10^{-3} ppm)

[5] Given the low concentration of uranium in seawater, producing 1 kg of uranium requires processing 330×10^6 kg of water; Japanese reports about marine extraction experiments indicate the possibility of yearly 1200 t uranium extraction from seawater at an estimated cost of US$ 300/kg [4]

[6] The totals include 6 reactor units with 4.98 GW_{el} in Taiwan, China

Slovakia, and Ukraine (with 2 each), as well as in Argentina, Brazil, Finland, France, Iran, Pakistan, and the USA (with 1 each). Most of the commercial reactors currently in operation are light water moderated and cooled; about 10% are heavy water moderated and cooled, 4% are gas-cooled, and 3% are graphite moderated and water-cooled. There are 2 commercial sodium cooled fast breeder reactors in operation. Table 3 is providing a synthesis of this data.

TABLE 3. Nuclear reactors worldwide (August 24, 2011)

Region	**In Operation**		**Under Construction**		**Electricity Supplied in 2009 [TW×h]**
	Number	Net Capacity [GW_{el}]	Number	Net Capacity [GW_{el}]	
North America	122	113.81	1	1.17	882
Latin America	6	4.12	2	1.94	30
Western Europe	128	122.79	2	3.2	796
Central and Eastern Europe	67	47.45	17	13.74	310
Africa	2	1.8	-	-	13
Middle East & South Asia	23	5.12	8	5.42	17
Far East	91	78.95	36	38.04	510
World total	439	374.04	66	63.51	2558

In 2010, the nuclear share in electricity generation ranged from 74.1% in France, 51.8% in Slovakia, 51.2% in Belgium, and 48.1% in Ukraine to 5.9% in Argentina, 5.2% in South Africa, 3.6% in Mexico, 3.4% in the Netherlands, 3.1% in Brazil, 2.9% in India, 2.6% in Pakistan, and 1.8% in China.

In 2010, there was one final shutdown (the fast breeder reactor Phénix in France), 5 new connections to the grid (Rostov 2 in Russia, Rajasthan 6 in India, Lingao 3 and Qinshan 2-3 in China, and Shin Kori 1 in the Republic of Korea), and 16 construction starts (Ningde 3, Taishan 2, Changjiang 1, Haiyang 2, Fangchenggang 1, Ningde 4, Yangjiang 3, Changjiang 2, Fangchenggang 2 and Fuqing 3 in China, Leningrad 2-2 and Rostov 4 in Russia, Ohma in Japan, Angra 3 in Brazil, as well as Kakrapar 3 and 4 in India).

So far in 2011, Oldbury A2 was shut down in the UK, Fukushima-Daiichi 1, 2, 3 and 4 in Japan were officially declared as permanently shutdown; Kaiga 4 in India, Chasnupp 2 in Pakistan, and Lingao 4 were connected to the grid; and construction of Chasnupp 3 in Pakistan and of Rajasthan 7 in India were officially started.

The nuclear industry is looking back at more than 14000 reactor years of experience, and some interpret the construction starts trend of the last decade (from 1 new construction start in 2001 to 16 in 2010) as the beginning of a "nuclear energy renaissance" (even though the numbers pale when compared with those in the 1970s with an *average* of 25 construction starts *per year*). If so, this renaissance is definitely happening in Asia: 13 of the 16 construction starts in 2010 were in Asia (including Japan), one in South America, and 2 in Russia. Moreover, of the 5 new connections to the grid in 2010, four were in Asia, and of the 66 nuclear power reactors currently under constructions, 44 are in Asia (including Japan). Asia is also the center of both near and long term nuclear energy growth prospects, with China planning to have about 40 GW_{el} installed by 2020 (up from 11.1 GW_{el} now), and India aiming at about 20 GW_{el} and 270 GW_{el} installed capacity by 2020 and 2050, respectively (up from currently 4.4 GW_{el}[7]) [6].

In the rest of the world, the picture is more mixed, with the Fukushima events in the wake of the devastating earthquake and tsunami, and the global financial crises of the last years having major impact on nuclear power projects and development plans. While, in a brutal reversal of recent decisions to extend the lifetime of the country's 17 power reactors, Germany has decided to abandon nuclear energy by 2022, other European countries (e.g. Poland which is reviving its nuclear power program) are adopting a more positive attitude towards the use of nuclear energy. In Spain, the government approved a 10-year license extension for the two-unit Almarez nuclear power plant and for Unit 2 of the Vandellos nuclear power plant. In any case, the financial crises have noticeably influenced short-term nuclear power projects: GDF Suez and RWE withdrew from the Belene project in Bulgaria, Vattenfall is delaying planned nuclear power plant projects in the UK, Russia is reducing the pace of new builds (from 2 to 1 per year), Eskom in South Africa is delaying the schedule of the next two reactors to 2018, and Ontario Power Generation, for the time being, has stopped procurement for two new nuclear power plants at Darlington. In the USA, utilities have asked the NRC to suspend the review of 5 of the 28 reactors for which combined license applications had been submitted, and Exelon, the largest nuclear US utility, is delaying preparatory work on a site near Victoria, Texas. On the other hand, regulatory bodies in Europe, Canada and the USA have granted licenses for power up-rates and lifetime extensions, e.g. a four-year license extension for the Garona nuclear power plant in Spain, five-year license renewals for both Bruce A and B nuclear power plants in Canada, and in the USA, NRC has granted a total of 59 license renewals for up to additional 20 years of lifetime [6].

The list of the mixed signals that the nuclear industry is receiving and that characterize its current worldwide status can be extended: after closing its Ignalina nuclear power plant, Lithuania is considering to construct a new plant over the next decade, and is exploring the possibility of a joint project with other Baltic countries; an industrial consortium involving Samsung, Hyundai and Doosan, as well as Westinghouse, and led by the Korea Electric Power Corporation (KEPCO) was successful with its bid and will install four 1.4 GW_{el} APR-1400 units in the United Arab Emirates (UAE) by 2020; at the 2009 Copenhagen Conference of the Parties to the Kyoto Protocol (COP-15) there was some (very limited) progress towards recognizing the potential of nuclear power in reducing greenhouse gas emissions[8]; and, finally, about 65 countries have expressed interest in embarking into some kind of nuclear program, and the number of IAEA technical cooperation projects in this area has increased considerably.

Based on public statements and presentations at various IAEA conferences, of the 29 countries currently using nuclear power, 13 are having new plants under construction, 5 are supportive of new builds, 4 are considering new builds but do not

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[7] In the case of India, such an ambitious growth scenario has been made possible only after many suppliers have lifted the restrictions on nuclear trade with that country

[8] While far from acknowledging that nuclear power is a practically zero greenhouse gas emitting option, the *Ad Hoc Working Group on Long-term Cooperative Action under the Convention* (AWG-LCA) has removed from its text all references that excluded nuclear power from 'nationally appropriate mitigation actions (NAMAs)'

provide any incentives, 5 are looking at nuclear as a potential option, and 2 are planning to phase out nuclear power.

As for the countries with new or renewed interest in nuclear power, they are at various planning stages of a national power program. Not surprisingly (see discussion above), the geographic distribution is heavily tilted towards Asia and Africa (one-third for each of these regions), and only about one-sixth each of these countries belongs to Latin America and Eastern Europe. Among the roughly 65 countries interested in nuclear power, less than half are actually planning to construct a nuclear power plant, but are rather interested in considering the issues that must be addressed when starting a nuclear power program. Less than one-third of these countries expect to operate their first nuclear power plant before 2030.

Nuclear energy can have a long-term noticeable environmental impact only if its uses are extended to non-electric power applications, e.g. heat and steam markets, seawater desalination, and hydrogen production for the petrochemical sector and for transportation. Many industrial processes can benefit from the coupling of electricity and heat produced in a nuclear power plant. As the reactor outlet temperature (ROT) is increased (e.g. in High Temperature Gas-cooled Reactors, HTGRs), there are more applications that can benefit from such a coupling. Figure 1 shows some of the

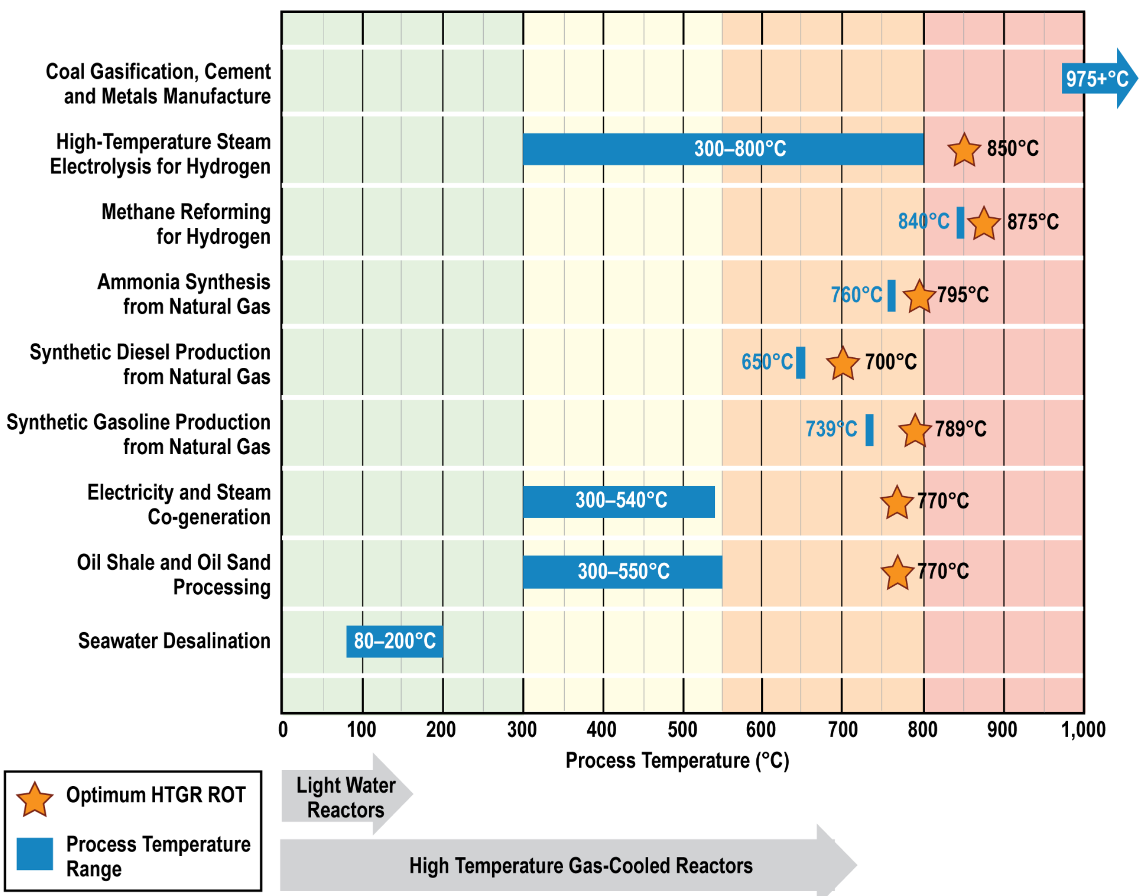

FIGURE 1. Non-Electric Applications of Nuclear Energy: Heat Requirements for Various Processes

processes that are being studied. Most of these processes require hydrogen and are related to synthetic fuel and to unconventional oil production from shale and sands [7].

OVERVIEW OF REACTOR TECHNOLOGY DEVELOPMNT

Since the majority of operating nuclear power plants has thermal reactors, most of the reactor technology development work is concentrating on evolutionary Light and Heavy Water Reactors (LWRs and HWRs, respectively). Evolutionary designs achieve improvements over existing designs through small to moderate modifications. This chapter provides a brief overview of the major current reactor technology development activities worldwide.

The country with the most ambitious nuclear power deployment program and growth plans, China, has already developed and deployed indigenous medium-size PWR designs. The China National Nuclear Corporation (CNNC) has also developed an evolutionary design, the CNP-1000, which has already been deployed at Lingao-1 and 2. The State Nuclear Power Technology Corporation (SNPTC) is developing CAP1400 (a large-scale passive design on the basis of Westinghouse's AP-1000), various small and medium sized reactors (SMRs), and a thermodynamically supercritical water-cooled design.

Advanced boiling water reactor technology developed by General Electric, Hitachi, and Toshiba is employed in the ABWRs for which series deployment was achieved in Japan. Some US utilities are also looking at ABWRs for deployment in the USA.

Two units of the Advanced Pressurized Water Reactor (APWR) developed by Mitsubishi Heavy Industries (MHI) and Westinghouse were deployed in Japan (Tsuruga-3 and 4). MHI has developed a larger APWR version, the APWR+, a European version, the EU-APWR, which is being evaluated by European utilities, and a US version, the US-APWR that was submitted to the NRC for design certification. Japan is also working on high-conversion designs, *viz*. the large Reduced Moderation Resource-Renewable Boiling Water Reactor (Hitachi's RBWR) and the large Reduced Moderation Water Reactor (JAEA's RMWR).

The Republic of Korea is deploying in series the 1000 MW_{el} Korean Standard Nuclear Plant (KSNP). The Korea Hydro and Nuclear Power Company (KHNP, a KEPCO subsidiary) developed an improved KSNP version, the Optimized Power Reactor (OPR-1000). One OPR-1000 (Shin-Kori-1) was connected to the grid in 2010, and 3 are under construction (Shin-Kori-2, Wolsong-1 and 2), with planned connection to the grid in 2011 and 2012. Aiming at improved economics, KHNP has up-rated the KSNP and designed the 1400 MW_{el} Advanced Power Reactor (APR-1400). Two APR-1400 units are under construction (Shin-Kori-3 and 4), and 4 units have been ordered by the UAE.

In Russia, nuclear power plants featuring the 'Water-Water Energetic Reactors' (WWER-1000 and WWER-1200) are in operation and continue to be deployed in and outside (China, India) the country. The Saint-Petersburg Institute 'Atomenergoproekt' has developed an evolutionary WWER-1000 design to be deployed in Belene, Bulgaria (2 units).

Four of AREVA's European Power Reactors (EPRs) are currently under construction, *viz*. Olkiluoto-3 in Finland, Flamanville (Cotentin Peninsula) in France, and Taishan 1 and 2 in China. Moreover, Electricité de France (EdF) is planning to start in 2012 the construction of an EPR at Penly (Normandy), France. AREVA has submitted its US-EPR to the US NRC for design certification, and to the UK Health and Safety Executive for generic design assessment. Finally, AREVA is also working on the development of evolutionary light water cooled reactor designs: a 1100 MW_{el} PWR (called ATMEA-1) developed jointly with MHI, and a 1250 MW_{el} BWR (called KERENA) developed jointly with several European utilities.

The status of reactor technology development in the USA can be summarized as follows: the US NRC has certified two large advanced water-cooled designs, *viz*. Combustion Engineering's Advanced Pressurized Reactor System 80+ APWR, and General Electric's Advanced Boiling Water Reactor ABWR. General Electric is also designing a large evolutionary boiling water reactor based on modular passive system technology, the Economic Simplified Boiling Water Reactor (ESBWR), which is currently under certification review by the US NRC. Westinghouse developed a mid-size advanced pressurized water-cooled reactor with passive safety features, the (Advanced Passive) AP600, which was also certified by the US NRC. Aiming at improving economics, Westinghouse has developed the AP1000 design on the basis of the passive safety features adopted for AP600. The AP1000 was certified in 2006. Various amended applications to the 2006 design certification of AP1000 are currently under review by the US NRC.

Research and technology development activities are also going on for advanced HWRs, mostly in Canada, China and India. The Atomic Energy of Canada Limited (AECL) is developing the Enhanced CANDU 6 (EC6) and the large (1200 MW_{el} class) Advanced CANDU Reactor (ACR-1000). EC6 is an updated version of the two 728 MW_{el} CANDU 6 reactor units built at Qinshan, China. ACR-1000 is an evolutionary design whose salient features are low enriched uranium fuel, heavy water moderator, and water-cooling.

Fast neutron spectrum reactors with fuel recycling significantly enhance nuclear energy's sustainability indices. The fast reactor has the flexibility to operate as breeder to achieve net creation of fissile material; as convertor to balance the transuranics production and consumption; and as transmuter to convert the long-lived minor actinides and other radioisotopes to short-lived ones. This has lead to renewed interest in fast reactor research and technology development:

In 2010, China has commissioned the 25 MW_{el} China Experimental Reactor (CEFR). The conceptual design of the 600 – 900 MW_{el} China Demonstration Fast Reactor (CDFR) is ongoing.

To meet legal obligations[9], the Commissariat à l'Énergie Atomique (CEA) and its industrial partners (EdF and AREVA) are implementing an ambitious research and technology development program aiming at the design and deployment of a sodium cooled fast reactor prototype in the 600 MW_{el} class named ASTRID. Within the framework of Euratom projects, CEA is also pursuing conceptual design studies for a 50-80 MW_{th} gas-cooled experimental prototype fast reactor called ALLEGRO.

[9] Reference is made to two French Parliament Acts, *viz*. the July 13, 2005 Act specifying the energy policy guidelines, and the July 28, 2006 Act outlining policies for sustainable management of radioactive waste, and requesting R&D on innovative nuclear reactors to ensure that, firstly, by 2012 an assessment of the industrial prospects of these reactor types can be made, and, secondly, a prototype reactor is commissioned by 31 December 2020 (with an industrial introduction of this technology in 2040 – 2050).

In India, commissioning of the indigenously designed (by the Indira Gandhi Center for Atomic Research, IGCAR) and constructed (by Bharaiya Nabhikiya Vidyut Nigam Limited, BHAVINI) 500 MW_{el} Prototype Fast Breeder Reactor (PFBR) at Kalpakkam is planned for 2012. The next step foresees the construction and commercial operation by 2023 of 6 additional PFBR-type reactors. Beyond 2020, the Indian fast reactor development plans are centered on high breeding gain sodium-cooled fast reactors in the 1000 MW_{el} class, and on the collocation of multi-unit energy parks with fuel cycle facilities based on pyro-chemical reprocessing technology.

The Japanese fast reactor design and deployment activities are expected to lead to the introduction of a demonstration fast reactor around 2025 and to the commercial operation of fast breeder technology around 2050. These goals will be achieved on the basis of operation experience to be gained with the prototype fast reactor Monju, which was restarted in 2010.

The Russian fast reactor program is based on extensive operational experience with experimental and industrial size sodium cooled fast reactors. Russia has also developed and gained experience with the technology of heavy liquid metal cooled (lead and lead-bismuth eutectic alloy) fast reactors. Russia is currently constructing the 870 MW_{el} sodium cooled BN-800 reactor at the Beloyarsk site with planned commissioning in 2012 – 2013. Russia's fast reactor development program includes life extension of both the experimental reactor BOR-60 and the industrial reactor BN-600, and the design of the new 50 MW_{el} experimental reactor MBIR, planned as replacement of BOR-60. Within the framework of the program, fast reactor technologies based on sodium, lead, and lead-bismuth eutectic alloy coolants (i.e. SFR, BREST-OD-300, and SVBR-100, respectively) will be developed simultaneously, along with the respective fuel cycles. The design of the advanced large-size sodium cooled commercial fast reactor BN-K is also ongoing.

CONCLUSIONS

Given that (i) energy is a necessary (albeit not sufficient) condition for sustainable development, (ii) there are severe imbalances in current energy consumption, (iii) there is a strong correlation between energy consumption and poverty, and (iv) economic and population growth rates in developing countries are high, it must be assumed that the worldwide energy demand will continue to grow. With electricity being arguably the highest-value "energy currency", it must further be assumed that electricity demand growth rates will be even higher than overall primary energy growth rates.

In 2010, nuclear energy's share of the worldwide electricity generation was about 15%. Nuclear power is essentially carbon-free at the point of generation, and does not produce any nitrogen oxides, sulfur dioxide, volatile organic compounds, or particulates. When taking into consideration the full electricity generation life cycle, the greenhouse gas emissions from nuclear power production are 2.5 – 5.7 g of carbon-equivalent per kW×h (about the same as wind and biomass), which is two orders of magnitude lower than for coal, oil, and natural gas. Currently, worldwide and per year, nuclear power avoids the release of approximately 600×10^6 t of carbon (the same as hydropower), which corresponds to 8% of the current worldwide greenhouse gas emissions.

It is reasonable to expect that nuclear will provide vast amounts of energy in both emerging and developed economies and that its utilization will increasingly encompass non-electric applications. However, acceptance of nuclear energy with large scale contributions to the world's energy mix depends on satisfaction of key requirements to enhance sustainability in terms of economy, safety, adequacy of natural resources, waste reduction, and non-proliferation. Achieving these objectives requires continuous innovation that can be ensured only through focused, project driven and result oriented research and technology development, as well as strong international collaboration.

REFERENCES

1. INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), Power Reactor Information System (PRIS), www.iaea.or.at/programmes/a2/.
2. INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), Reference Data Series No. 1 (RDS-1/30), 2010 Edition.
3. INTERNATIONAL ENERGY AGENCY (IEA), UNITED NATIONS DEVELOMENT PROGRAMME (UNDP), UNITED NATIONS INDUSTRIAL DEVELOPMNT ORGANIZATION (UNIDO), Energy Poverty: How to Make Modern Energy Access Universal?, OECD/IEA, Paris, 2010.
4. OECD/NEA – IAEA, Uranium 2009: Resources, Production and Demand, OECD, Paris, 2010.
5. Joseph V. Spadaro, Lucille Langlois, and Bruce Hamilton, "Greenhouse Gas Emissions of electricity Generation Chains: Assessing the Difference", IAEA Bulletin, **42**, 2, Vienna, 2000.
6. INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), Nuclear Technology Review 2010, Vienna, 2010.
7. Steve Herring (private communication).