NUCLEAR POWER AND SUSTAINABLE DEVELOPMENT

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FOREWORD

Any discussion of 21st century energy trends must take into account the global energy imbalance. Roughly 1.6 billion people still lack access to modern energy services, and few aspects of development — whether related to living standards, health care or industrial productivity — can take place without the requisite supply of energy. As we look to the century before us, the growth in energy demand will be substantial, and 'connecting the unconnected' will be a key to progress.

Another challenge will be sustainability. How can we meet these growing energy needs without creating negative side effects that could compromise the living environment of future generations?

Nuclear power is not a 'fix-all' option. It is a choice that has a place among the mix of solutions, and expectations for the expanding use of nuclear power are rising. In addition to the growth in demand, these expectations are driven by energy security concerns, nuclear power's low greenhouse gas emissions, and the sustained strong performance of nuclear plants.

Each country must make its own energy choices; one size does not fit all. But for those countries interested in making nuclear power part of their sustainable development strategies, it is important that the nuclear power option be kept open and accessible.

Mohamed ElBaradei

Director General

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NUCLEAR POWER: STATUS AND TRENDS

As of 1 April 2006, there were 443 nuclear power reactors in operation around the world. They total 370 GW(e) of generating capacity and supply about 16% of the world's electricity. This percentage has been roughly stable since 1986, indicating that nuclear power has grown at the same rate as total global electricity for 20 years. There are also 26 new reactors under construction. Table 1 shows the distribution across countries of both operating reactors and those under construction.

TABLE 1. NUCLEAR POWER REACTORS IN OPERATION AND UNDER CONSTRUCTION IN THE WORLD (AS OF 1 APRIL 2006)

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2004		Total operating experience through 2004	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW·h	% of total	Years	Months
Argentina	2	935	1	692	7.3	8.2	52	7
Armenia	1	376			2.2	38.8	37	3
Belgium	7	5 801			44.9	55.1	198	7
Brazil	2	1 901			11.5	3.0	27	2
Bulgaria	4	2 722	1	953	15.6	41.6	133	2
Canada	18	12 599			85.3	15.0	509	7
China	9	6 572	3	3 000	47.8	2.2	47	11
Czech Republic	6	3 368			24.8	31.9	80	10
Finland	4	2 676	1	1 600	21.8	26.6	103	4
France	59	63 363			426.8	78.1	1 405	2
Germany	17	20 339			158.4	31.8	666	0
Hungary	4	1 755			11.2	33.8	78	2
India	15	3 040	8	3 602	15.0	2.8	237	5
Iran, Islamic Republic of			1	915				
Japan	56	47 839	1	866	273.8	29.3	1 176	4
Korea, Republic of	20	16 810			124.0	38.0	239	8
Lithuania	1	1 185			13.9	72.1	38	6
Mexico	2	1 310			10.6	5.2	25	11
Netherlands	1	449			3.6	3.8	60	0
Pakistan	2	425	1	300	1.9	2.4	37	10
Romania	1	655	1	655	5.1	10.1	8	6
Russian Federation	31	21 743	4	3 775	133.0	15.6	791	5
Slovakia	6	2 442			15.6	55.2	106	6
Slovenia	1	656			5.2	38.9	23	3
South Africa	2	1 800			14.3	6.6	40	3
Spain	9	7 588			60.9	22.9	228	2
Sweden	10	8 910			75.0	51.8	322	1
Switzerland	5	3 220			25.4	40.0	148	10
Ukraine	15	13 107	2	1 900	81.8	51.1	293	6
United Kingdom	23	11 852			73.7	19.4	1 354	8
UnitedStates of America	104	99 210			788.6	20.0	2 975	8
Total[b]	443	369 552	26	20 858	2616.9	16%	11 588	6

[a.] Data are from IAEA (2006).
[b.] The total includes the following data in Taiwan, China:
— 6 units, 4904 MW(e) in operation; 2 units, 2600 MW(e) under construction;
— 37.9 TW·h of nuclear electricity generation, representing 20.9% of the total electricity generated in 2004;
— 146 years, 1 month of total operating experience.

As shown in the table, nuclear power is mainly used in industrialized countries. Of the world's operating reactors, 405 (or 91%) are in either OECD countries or countries with economies in transition. In terms of electrical generating capacity, 350 GW(e) out of 380 GW(e), or 95% of nuclear generating capacity is installed in these countries. In terms of new construction, however, the pattern is reversed. Sixteen of the 26 new reactors under construction (62%), and 11 GW(e) out of 20 GW(e) (53%), are in developing countries.

Current expansion, as well as near term and long term growth prospects, are centred in Asia. Of the 26 reactors under construction worldwide, 16 are in Asia. Twenty-four of the last 34 reactors to have been connected to the grid are in Asia.

Figure 1 shows historical growth in worldwide nuclear generating capacity since 1960 plus high and low projections through 2030 by the IAEA (2005a). The expansion of nuclear power was initially rapid. In the first half of the 1970s, growth averaged 30% per year, and average growth for the full decade was 21% per year. Nuclear power's share of global electricity rose to 16% in 1986.

Near the end of the 1980s, growth slowed substantially. Licensing interventions from growing environmental movements on both sides of the Atlantic often stretched out licensing times and increased costs. The combination of inflation and rising energy costs resulting from the oil shocks of 1973 and 1979 depressed growth in electricity demand and disproportionately raised the cost of capital intensive power plants, like nuclear power plants. Some utilities found the regulatory and transaction costs of nuclear power simply too high to manage cost-effectively. The 1979 Three Mile Island accident severely damaged the reputation of the nuclear power industry in the USA, although it had no off-site impacts, and the Chernobyl accident in 1986, which had substantial off-site impacts, largely stalled the expansion of nuclear power in both Europe and the former Soviet Union. Finally, the price deregulation of electricity markets, particularly in OECD countries, exposed excess capacity, pushed electricity prices lower and made power plant investments more risky. Other things being equal, nuclear power's front-loaded cost structure is a disadvantage in markets that emphasize short term profits and hence value rapid returns.

In the 1990s, growth in nuclear electricity generation exceeded the growth in nuclear capacity as consolidation in the nuclear industry, management efficiencies and technological advances progressively raised the average energy availability of the world's nuclear plants. The energy

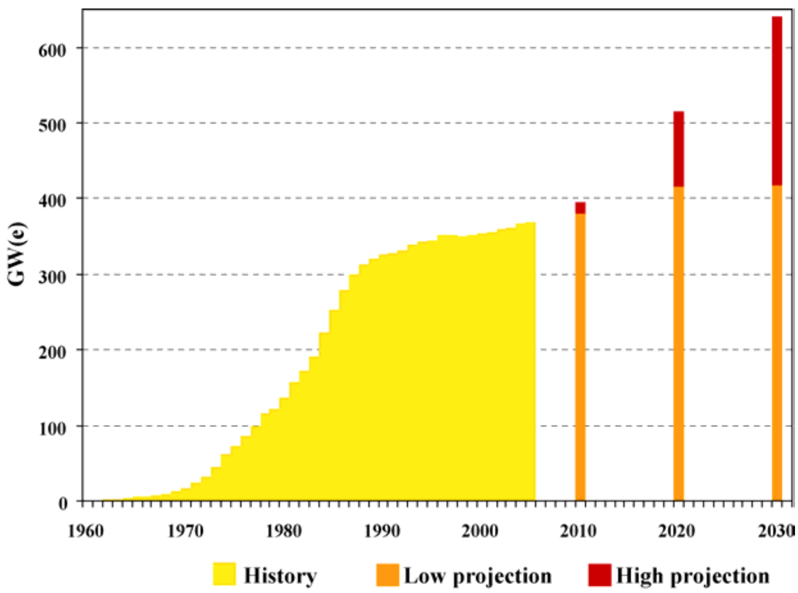

FIG. 1. Installed nuclear power generating capacity worldwide. The yellow bars to the left show historical growth from 1960 through 2005. The bars on the right show the IAEA's latest low and high projections.

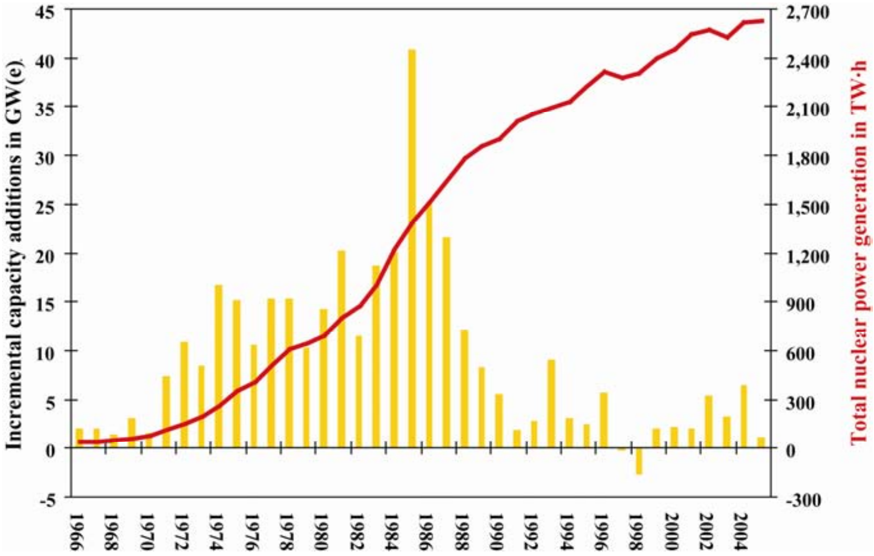

FIG. 2. Nuclear electricity generation and capacity additions since 1966. The orange bars show the new nuclear generating capacity (in GW) that came on line each year from 1966 to 2005. Annual additions peaked in 1985 and have been quite modest since the end of the 1980s. The red line shows annual nuclear electricity generation, in TW·h. As explained in the text, electricity generation has kept increasing, even with only modest capacity additions since 1990 because of continuing increases in the global average energy availability factor for nuclear power reactors.

availability factor measures the percentage of time that a power reactor is available to generate electricity, rather than being shut down for refuelling, maintenance or other reasons. The global average for nuclear power reactors has risen from 73% in 1990 to 83% in 2004. This increase is equivalent to the addition of 33 new 1000 MW reactors. The red line in Fig. 2 shows how electricity generation from the world's nuclear power reactors has continued to climb steadily, although the amount of new nuclear capacity coming on line each year (the orange bars) has dropped substantially since its peak in the 1980s.

Two projections to 2030 published by the IAEA are shown on the right side of Fig. 1. The low projection assumes that no new nuclear power reactors will be built beyond those already under construction or currently planned. Nuclear power capacity grows only slightly in this projection, to 416 GW(e) in 2020, before leveling off. The high projection incorporates nuclear projects proposed beyond those already firmly committed. Global nuclear power capacity in this projection grows steadily to 640 GW(e) in 2030, an average growth rate of slightly over 2% per year.

While both projections show significant differences in different parts of the world, both project greatest growth in the Far East. There is also significant expansion in Eastern Europe in both projections, and for North America in the high projection. In Western Europe, there is a contraction in the low projection as retirements outpace new construction, but substantial growth in the high projection. Growth rates are high in the Middle East and South Asia in both projections, although these regions start from a small 2005 base.

Sustainable Development

Sustainable development was defined in 1987 by the Brundtland Commission, known formally as the World Commission on Environment and Development, as "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987).

This definition does not unambiguously distinguish sustainable development from development that is not sustainable. Rather, it creates a bridge, or framework, to address possible strains between economic development and environmental protection. It emphasizes the importance of economic development to satisfy needs, and the importance of the natural environment as both a resource provider and waste absorber. And it requires that we judge today's options not only by today's immediate political, economic or environmental implications, but also from the perspective of future generations who will benefit from our successes in achieving sustainable development, or suffer from our failures.

Extensive literature on sustainable development has developed since 1987, generally dividing the concept into three areas: economic, environmental and social. A full review of the literature is beyond the scope of this brochure. However, the important steps taken so far in translating the original definition into practical directives relevant to nuclear power can be summarized as follows.

Five years after the Brundtland Commission's report, the United Nations Conference on Environment and Development (UNCED) was held in Rio de Janeiro. Among other things, UNCED produced the UN Framework Convention on Climate Change (UNFCCC) and *Agenda 21*. The latter is a comprehensive action plan for sustainable development. It is effectively UNCED's translation of the Brundtland Commission's definition into more specific policy directions. It has 40 chapters on all aspects of sustainable development and covers energy issues, but has no separate chapter dedicated to energy (UNCED 1992).

To follow up on the implementation of *Agenda 21*, the UN established the Commission on Sustainable Development (CSD). The full commission meets annually to address selected topics covered by *Agenda 21*. Energy was addressed for the first time at the ninth session of the CSD (CSD-9) in 2001. CSD-9's decision on energy (UN 2001) is thus the first dedicated effort by the CSD to further translate the Brundtland Commission's definition of sustainable development into specific policy directions with respect to energy.

Nuclear power was a particularly controversial topic during the extensive preparatory process for CSD-9 and at the two-week meeting. The debate between countries that consider nuclear power an essential component of their sustainable development strategies and those that consider nuclear power fundamentally incompatible with sustainable development was long and thorough. It reached two main conclusions:

(1) Countries agreed to disagree on the role of nuclear power in sustainable development. CSD-9's final text observed that some countries view nuclear power as an important contributor to sustainable development and others do not, and summarized briefly the logic of each perspective.
(2) Countries agreed that "The choice of nuclear energy rests with countries."

The extensive debate at CSD-9 on nuclear power was not repeated the following year at the World Summit on Sustainable Development (WSSD) in Johannesburg. With respect to energy, the WSSD's concluding Johannesburg Plan of Implementation (JPOI) begins with an explicit call to governments, as well as relevant regional and international organizations and other relevant stakeholders, to implement the recommendations and conclusions of CSD-9 (UN 2002). A new feature of the JPOI was the inclusion of a 'positive list' of technologies. The JPOI calls for a series of actions to promote the widespread availability of clean and affordable energy, specifically the promotion of renewable energy resources, efficiency improvements, and advanced energy technologies, including cleaner fossil fuel technologies. Nuclear power is included in the category of advanced energy technologies (UN 2006a).

Energy and nuclear power will next be part of the CSD agenda during its fourteenth and fifteenth sessions in 2006 and 2007 on energy for sustainable development, industrial development, air pollution/atmosphere and climate change. CSD-14, in 2006, is designated a review session; CSD-15, in 2007, is designated a policy session.

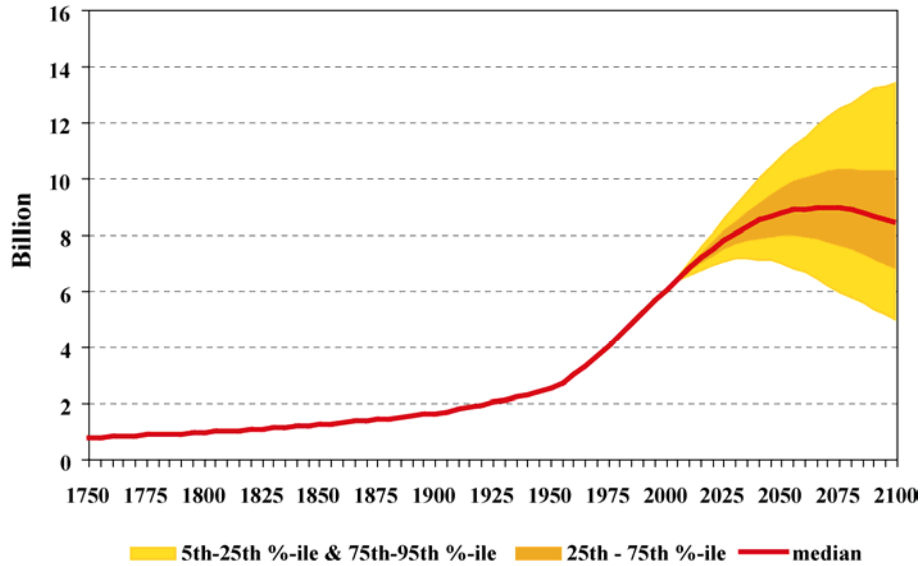

FIG. 3. Probabilistic global population projections to 2100 (adapted from Lutz et al. (2004)).

ENERGY NEEDS

All projections of global energy demand anticipate large increases in the century ahead, although scenarios have also been developed that explore ways in which this growth in demand may be slowed. The principal drivers are global population and economic growth, especially in the developing countries.

Population Growth

The world population is currently about 6.5 billion. The UN projects growth to more than 9 billion by 2050 (UN 2003). Population growth, however, is slowing down as fertility rates drop, particularly in the least developed countries. The International Institute for Applied Systems Analysis (IIASA) estimates an 86% chance (six out of seven) that global population growth will come to an end before 2100 (see Fig. 3), and that the world's population will start to slowly decrease (Lutz et al. 2004).

Nonetheless, the projected population increase of 1.5 billion people between now and 2050 will occur almost entirely in developing countries, and if the world is to meet even a fraction of the economic aspirations of the poor already alive today, plus those still to be born before the population peaks, there must be a substantial increase in energy supplies.

Economic Development

Energy is and will continue to be a primary engine for economic development. The CSD has specifically recognized that, "Energy is central to achieving the goals of sustainable development" (UN 2001). Both quality and quantity are important. Reliance on human power, draft animals and traditional fuels cannot sustain the same level of economic activity as ready access to refined petroleum products and electricity.

Energy systems have grown more complex over time, particularly with urbanization and industrialization. Modern manufacturing and service industries, and today's urban environments, rely especially on electricity — a computer cannot run on coal. All demographic projections anticipate continued urbanization which, together with economic development, will cause electricity needs to grow even faster than energy needs in general.

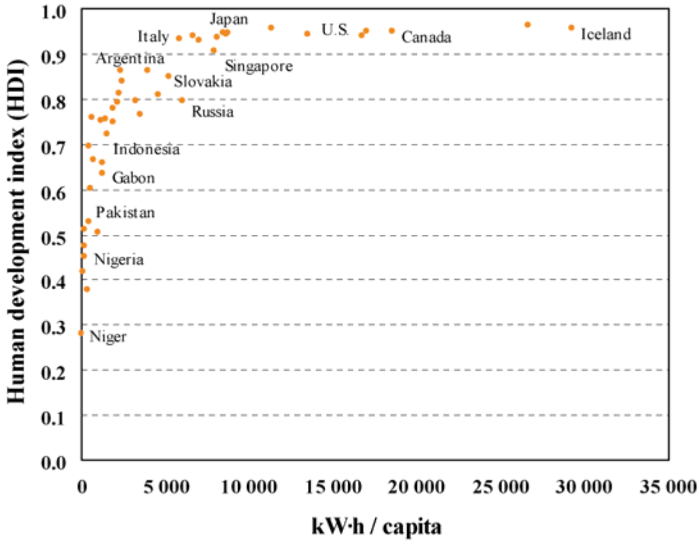

FIG. 4. Human development index and per capita electricity consumption (UNDP (2005)).

The per capita consumption of electricity correlates well with a country's social well-being as measured by the UN Human Development Index (HDI), a composite index based on measures of health, longevity, education, and economic standards of living (UNDP 2005). Figure 4 plots the HDIs of 43 countries against their per capita electricity use. An HDI of 0.8 or higher corresponds to almost 3000 kW·h per capita and an HDI greater than 0.9 to more than 6000 kW·h per capita.

However, Fig. 4 shows only national averages, which hide the reality that an estimated one quarter of the world's population today — 1.6 billion people — have no access to electricity (IEA 2004). Ensuring such access — 'connecting the unconnected' — has been highlighted by the CSD as an essential task for advancing sustainable development. This access has been further emphasized by UN-Energy as a requirement for meeting the Millennium Development Goals (MDGs) (see Box 1). The MDGs were established at the 2000 Millennium Summit to "form a blueprint [for development] agreed to by all the world's countries and all the world's leading development institutions" (UN 2006b). UN-Energy was created after WSSD to coordinate energy related activities throughout the UN system.

Box 1. "Main Messages"

***The Energy Challenge for Achieving the Millennium Development Goals* (UN-Energy 2005)**

- Energy services such as lighting, heating, cooking, motive power, mechanical power, transport and telecommunications are essential for socioeconomic development, since they yield social benefits and support the generation of income and employment.
- The poor obtain energy services by gaining access to modern fuels, electricity and mechanical power. This access is particularly important for women and girls since they are often the most affected by inadequate energy services.
- Reforms to the energy sector should protect the poor, especially the 1.1 billion people who live on less than $1 per day, and should take gender inequalities into account in recognizing that the majority of the poor are women.
- The environmental sustainability of energy supply and consumption should be enhanced to reduce environmental and health hazards. This requires measures that increase energy efficiency, introduce modern technologies for energy production and use, substitute cleaner fuels for polluting fuels, and introduce renewable energy.
- Large amounts of financial resources need to be mobilized for expanding energy investments and services in developing countries. They account for a much larger share of gross domestic product compared with OECD countries. Public sector resources will remain crucial for investing in energy service delivery for the poor due to the private sector's limited appetite for risk in emerging markets.
- The role of energy and the costs of energy services should be factored into overall national economic and social development strategies, including poverty reduction strategies and MDG campaigns, as well as to donor programmes in order to reach development goals. Energy planning must be linked to goals and priorities in other sectors.

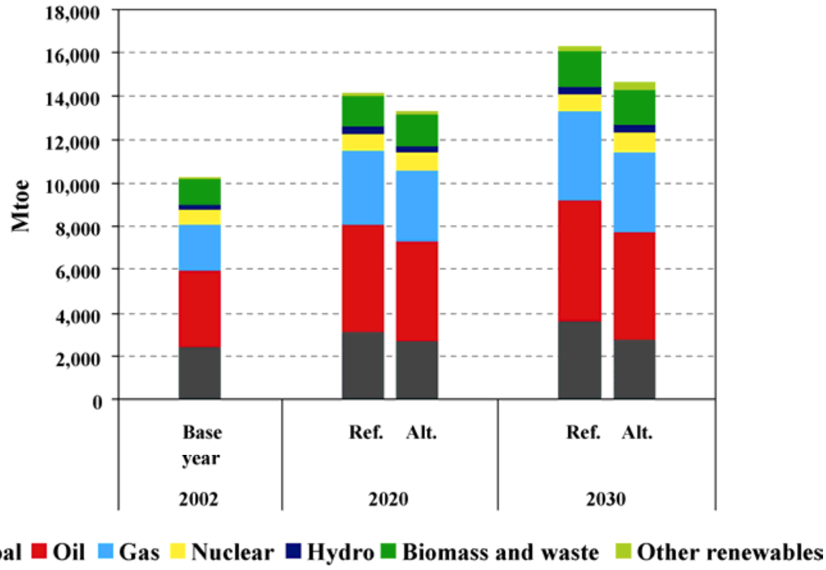

FIG. 5. Projected global primary energy use by fuel through 2030 in two IEA scenarios (ref.: reference scenario; alt.: alternative scenario) (adapted from IEA (2004)).

Energy Use

Large increases in global energy use are consistently projected for the next century. This section summarizes two sets of widely cited future energy scenarios.

The OECD International Energy Agency (IEA) regularly publishes updated intermediate term energy scenarios. Figure 5 shows the IEA results extending to 2030 in terms of total primary energy demand by fuel for both a reference scenario (based on business-as-usual assumptions) and an 'alternative policy scenario' (which assumes faster improvements in energy efficiency, faster reductions in air pollution and greenhouse gas (GHG) emissions, greater use of renewables and nuclear power, and stronger measures to enhance energy security) (IEA 2004). Both scenarios show a continuing projected rise in energy use, and a continued rise in the use of fossil fuels. Two other key conclusions detailed in the report, but not evident in this figure, are that energy growth is faster in developing countries and that electricity use grows even faster than overall energy demand.

Forty longer term scenarios, extending to 2100, have been published by the Intergovernmental Panel on Climate Change (IPCC) in a Special Report on Emissions Scenarios (SRES) (IPCC 2000). These scenarios (Fig. 6) project a continuation of the intermediate term growth in global energy use shown in Fig. 5. They also reflect, in their detailed results, continued faster growth in developing countries and a continuing shift toward electricity. As can be seen from the low end of the ranges in Fig. 6, growth in energy use moderates in the second half of the century in some of the SRES scenarios and actually reverses in a few cases that assume a combination of low population growth, much less energy intensive lifestyles and much more energy efficient technologies. For the SRES scenarios as a whole, however, median primary energy use grows by a factor of 3.5 from 2000 to 2100.

Electricity Demand

In the IEA reference scenario, global electricity demand grows at 2.4% per year. To meet this growth, the world's electricity generating capacity grows from about 3700 GW(e) in 2004 to 7303 GW(e) in 2030. This is roughly a doubling of installed electricity generating capacity between now and 2030. Thus, the equivalent of today's capacity must be newly constructed in the next

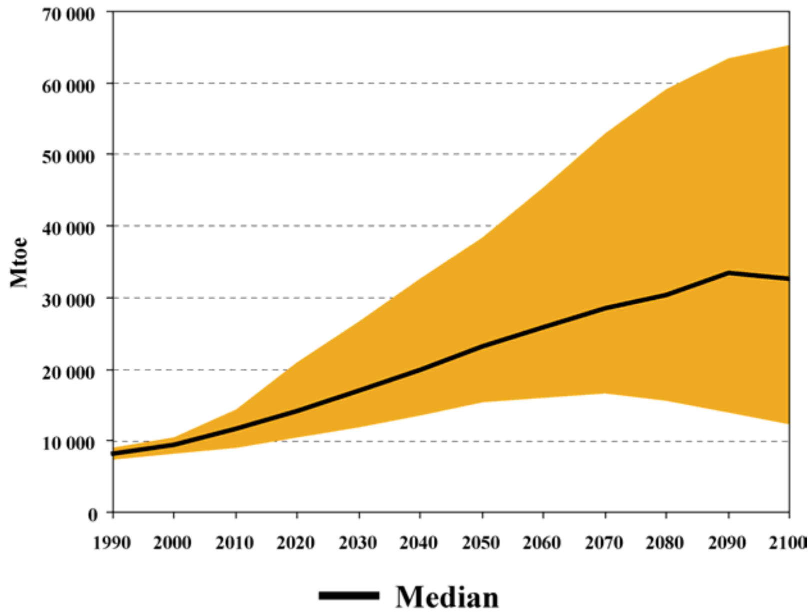

FIG. 6. Projected global primary energy use through 2100 in 40 IPCC SRES scenarios (adapted from IPCC (2000)).

24 years, and additional capacity must also be built to replace many of today's power plants that will be retired during this same period. If half of today's capacity is assumed to require replacement (and the real number will probably be higher), between 4400 and 5400 GW(e) of new generating capacity will need to be built in the next quarter century. Because power plants have useful lifetimes of 30–70 years or more, near term investment choices will largely dictate any future generation supply mix, making these an important component of national sustainable development strategies.

ENERGY SUPPLY

In considering how to meet the world's growing need for energy, it is important to recognize that every country uses a mix of energy supplies, and that all countries are different. Every country uses a mix of energy supplies because:

(1) Different technologies are needed to meet different needs, e.g. for baseload power in contrast to peak power, or for meeting concentrated demand in megacities in contrast to off-grid power for small users in remote areas;
(2) Evolution of the energy supply is uneven, and new technologies replace older ones in fits and starts and with overlaps;
(3) Different investors choose different technologies based on different requirements and perceptions about profitability and risk;
(4) Fast growing countries like China may need to expand all energy sources simultaneously just to keep up with growing demand.

Moreover, the right mix is different for each country. It depends partly on how fast a country's energy demand is growing; on the country's energy resources and alternatives; on the available financing options and whether the investment is in a deregulated market that values rapid returns; and on national preferences and priorities as expressed in national politics. Trade-offs among issues like accident risks, cheap electricity, pollution, jobs, import dependence, and climate change are at least partly a matter of personal and national preference, and thus an area of legitimate disagreement even if everyone were to agree on all the facts.

Economic Characteristics of Nuclear Power and Alternative Generating Technologies

Generation Costs

Well run nuclear power plants are generally a competitive and profitable source of electricity. One reason is that while these plants are relatively expensive to build they are relatively inexpensive to operate. Once a nuclear power plant's construction costs have been fully amortized, it is generally at its most profitable stage. Other things being equal, there is an economic incentive to operate the plant for as long as it is safe to do so, as seen from the continuing pace of licence renewals.

In the USA, as of 1 April 2006, the US Nuclear Regulatory Commission had approved 39 licence renewals of 20 years each, for a total licensed life of 60 years for each reactor. The owners of approximately three-quarters of the USA's 104 operating reactors have either received, applied for, or stated their intention to apply for such licence renewals. The situation is similar in other countries, although licence renewals outside the USA are generally for shorter periods and are more frequent, or take the form of 'rolling renewals'.

For new construction, however, there is no universal answer to the question "Is nuclear power economic?" As noted above, the availability and appropriateness of supply options depend on national circumstances. They also depend on market structure, the regulatory environment and the investment climate in a given country.

Table 2 summarizes new construction cost estimates and levelized production costs from seven studies done in the last few years. For levelized costs, Fig. 7 shows graphically the ranges in Table 2 for different electricity technologies. Except for oil fired generation (estimated in only one of the studies) the high end of each cost range is at least 100% higher than the low end. Some of the variation is due to different technological assumptions across the studies, but much is also due to national factors. These costs are based on compliance with existing regulations. Any regulatory change that effectively imposes more costs would alter the numbers.

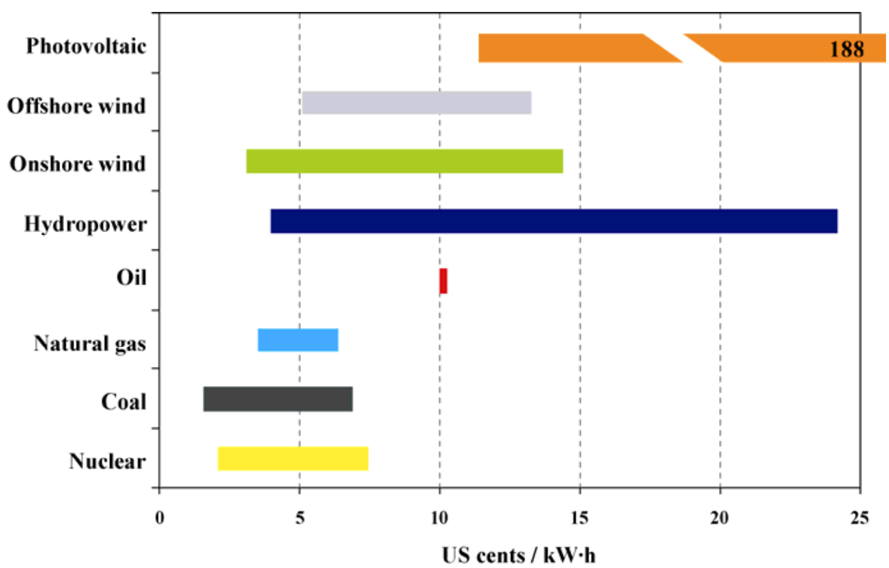

FIG. 7. Ranges of levelized costs associated with new construction as estimated in seven recent studies (see Table 2) for electricity generating technologies in different countries.

TABLE 2 . COMPARATIVE COST ESTIMATES FROM RECENT STUDIES

	MIT[a]	University of Chicago[b]	Royal Academy of Engineering[c]	DGEMP France[d]	METI Japan[e]	CERI Canada[f]	OECD/NEA/IEA[g]
Levelized cost[h]	*US cents/kW·h*	*US cents/kW·h*	*US cents/kW·h[i]*	*US cents/kW·h*	*US cents/kW·h*	*US cents/kW·h*	*US cents/kW·h*
Nuclear	6.7	4.1–7.1	4.2	3.6	5.0	4.4–7.5	2.1–6.9
Coal	4.2	3.3–4.1	4.6–6.4	4.1–4.4	5.3	4.0–4.9	1.6–6.9
Natural gas	3.8–5.6	3.5–4.5	4.1–5.2	4.5	5.8	6.0–6.3	3.8–6.4
Oil					10.0		
Hydropower							4.0–24.2
Poultry litter			12.5				
Onshore wind			6.8–9.9				3.1–14.4
Offshore wind			10.1–13.3				5.2–12.3
Wave/marine			12.2				
Solar PV							12.1–187.6
Overnight cost[j]	*$/kW(e)*	*$/kW(e)*	*$/kW(e)*	*$/kW(e)*	*$/kW(e)*	*$/kW(e)*	*$/kW(e)*
Nuclear	2000	1200–1800	2119	1823	2614	1968–2491	1074–2510
Coal	1300	1182–1460	1345–1511	1290–1419	2548	1341	719–2,347
Natural gas	500	500–700	553	652	1536	596	424–1292
Oil					2520		
Hydropower							1541–6985
Poultry litter			1390				
Onshore wind			1364				976–1634
Offshore wind			1695				1637–2622
Wave/marine			2580				
Solar PV							3363–10 164

[a] MIT (2003).
[b] University of Chicago (2004).
[c] Royal Academy of Engineering (2004).
[d] DGEMP (2003).
[e] METI (2004).
[f] CERI (2004).
[g] OECD/NEA/IEA (2005).
[h] The levelized cost of electricity is the price at the busbar needed to cover the operating plus annualized capital costs of a power plant.
[i] National currencies used in the different studies are converted to US dollars using exchange rates as of 11 November 2004.
[j] The overnight cost is the amount that would be paid out if all capital expenses occurred simultaneously. It includes no interest charges.

Internalizing External Costs

External costs are those that the public suffers (such as health costs due to a highly polluting power plant) but that the beneficiaries of generating the electricity (the plant owner and his or her customers) do not have to pay. Substantial progress has been made in recent decades in internalizing many previously external environmental and health costs through, for example, regulations for pollution control, nuclear safety, mine safety, oil tanker operation and, more recently, new markets in carbon emissions created by the entry into force of the Kyoto Protocol. Once such costs are internalized, they are taken into account in private investment decisions and in consumer choices.

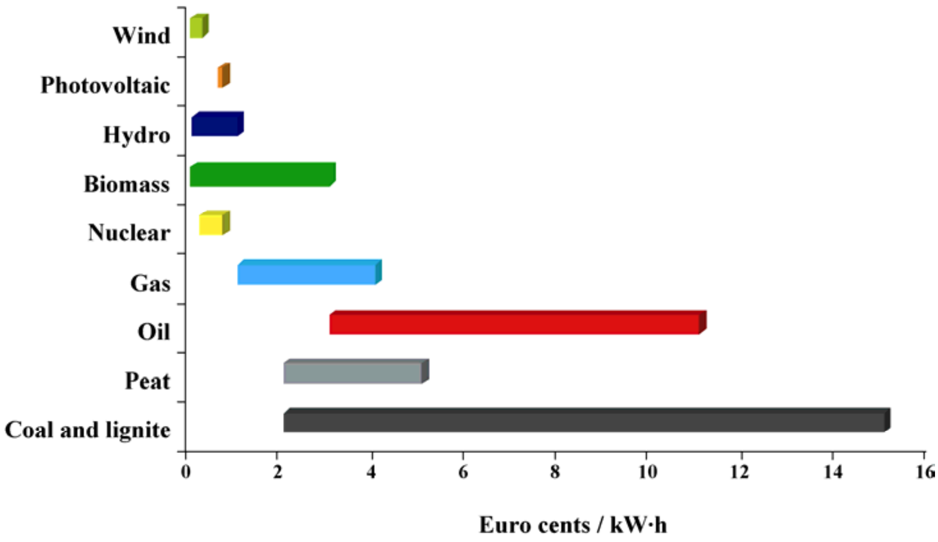

FIG. 8. Summary of external costs taken from ExternE based on technologies available in 1999. Health and environmental costs are included, and are shown in Euro cents/kW·h (European Commission 2003).

Despite the progress just noted, the JPOI calls for additional efforts to internalize externalities to advance sustainable development, and, in the case of GHG emissions, much progress is still needed to meet the UNFCCC goal of stabilizing the atmospheric concentration of GHGs "at a level that would prevent dangerous anthropogenic interference with the climate system".

Although private investors will make their decisions based largely on internalized costs, government investors and policy makers may wish to make decisions based on both internalized plus any remaining external costs. External costs can be difficult to quantify and convert into monetary values, any valuation process remains subjective, and results vary across countries. Despite the uncertainties and national differences in valuation of externalities, however, several major studies have sought to estimate the total internal and external costs associated with different electricity generating technologies. Results of two ExternE related studies are shown in Figs 8 and 9 (PSI 2001; EC 2003; Friedrich 2005). Nuclear power compares well in both cases.

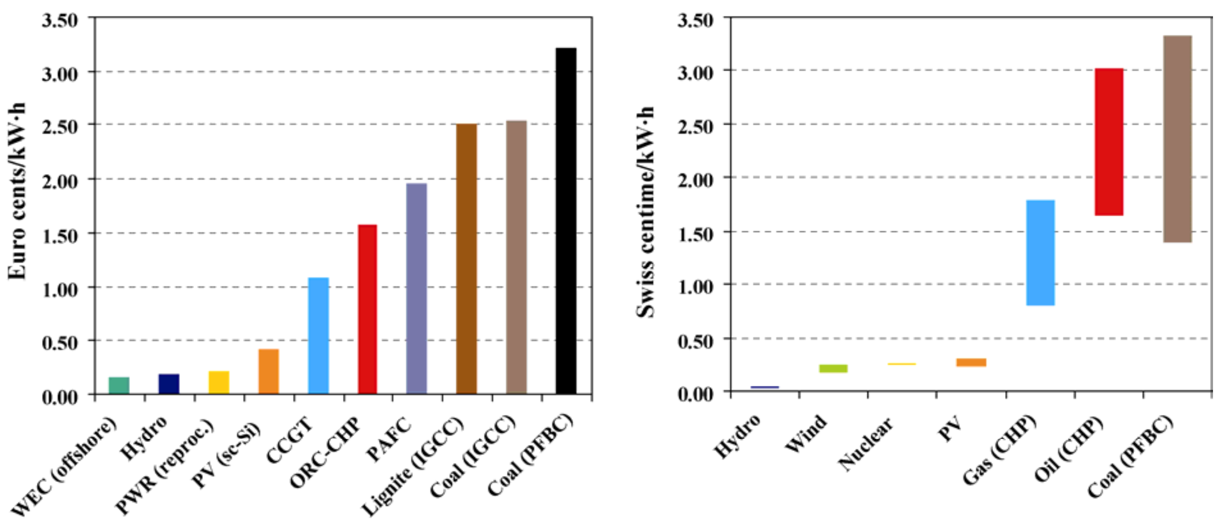

FIG. 9. Summary of external costs for Germany (left chart) based on technologies expected to be available in 2010 (adapted from Friedrich (2005)). Summary of external costs for Switzerland (right chart) based on technologies expected to be available between 2010 and 2020 (adapted from PSI (2001)).

Unpriced environmental impacts are not the only external costs of interest. Current concerns about energy supply security recall similar concerns that were important during the nuclear expansion programmes of France and Japan at the time of the oil shocks in the 1970s. The disadvantages and worries associated with an insecure national energy supply constitute an external cost that is largely invisible to an investor in a liberalized energy market. For most countries, expanding nuclear power would increase the diversity of their energy supplies and thus their energy supply security. Moreover, nuclear power has two features that further increase resiliency. First, nuclear electricity generating costs are less sensitive to changes in fuel prices than are fossil fired electricity generating costs. The recent trebling of uranium prices has resulted in only a 2–3% difference in generating costs for nuclear power. Second, the basic fuel — uranium — is available from a variety of producer countries, and small volumes are required, making it easier to establish strategic inventories. In practice, the trend over the years has been away from strategic stocks toward supply security based on a diverse, well functioning market for uranium and fuel supply services. But the option of relatively low cost strategic inventories remains available for countries that find it important.

Nuclear Fuel Resources

The extent of energy resources is limited partly by nature and partly by human ingenuity and economics. 'Reserves' are the accessible portion of resources at existing prices using existing technology. Reserves therefore depend mainly on how much people are willing to pay for energy services and on the technology available to extract resources and turn them into services. Resources not demanded by the market are just 'neutral stuff'. Thus, reserves are continually replenished not through the creation of new material, but through growing demand and declining production costs that turn 'neutral stuff' into reserves. This is true for both finite and renewable resources, but for finite resources, unlike renewables, there will eventually be a limit.

Nuclear resources include uranium and thorium. Thorium is three times as abundant as uranium, but, as noted above, the reserves, or recoverable quantities, depend on market conditions and technology as well as the geology of different deposits. Currently, uranium is in much greater demand.

All 443 of the world's operating nuclear power reactors use uranium fuel, as will all 26 that are under construction. Identified conventional uranium resources are currently estimated at 4.7 million tonnes of uranium (Mt U) for costs below \$130/kg. For reference, the spot market price of uranium at the end of January 2006 was about \$94/kg. Additional conventional resources beyond those already identified are estimated to add another 10.1 Mt U. Table 3 summarizes how long conventional uranium resources would last at current burnup rates. The top row of numbers assumes that future nuclear power reactors use the same technology as today's reactors, which can only use less than 2% of the energy in natural uranium. The bottom row assumes that, as uranium becomes more expensive, used fuel is eventually recycled, using technologies available today, to extract much more of the available energy. Since all the numbers in the tables are based on current uranium consumption rates, they will all decrease in proportion to any expansion of nuclear power.

Taking unconventional uranium resources into account greatly increases all the numbers in Table 3. Unconventional uranium resources include about 22 Mt U that occur in phosphate deposits and up to 4000 Mt U contained in sea water. The technology to recover uranium from phosphates is mature, although costs are relatively high at \$60–100/kg U. The technology to extract the large dilute uranium resources in sea water has only been demonstrated at the laboratory scale, and extraction costs are currently estimated at about \$300/kg U (UNDP 2000). The impact on nuclear generating costs of any eventual shift to higher cost uranium resources would be limited, given that fuel costs are a smaller part of nuclear electricity generating costs (2%) than they are of fossil fired electricity generating costs (40–70%).

TABLE 3. YEARS OF URANIUM AVAILABILITY FOR NUCLEAR POWER (OECD/NEA–IAEA 2006)

Reactor/fuel cycle	Years of 2004 world nuclear electricity generation with identified conventional resources	Years of 2004 world nuclear electricity generation with total conventional resources
Current once-through fuel cycle with light water reactors	85	270
Pure fast reactor fuel cycle with recycling	5000–6000	16 000–19 000

Table 3 refers only to uranium. Thorium-fuelled reactors were developed in the 1960s and 1970s but never captured a significant share of the market. India, which has far greater thorium than uranium resources, is one country continuing to develop the thorium fuel cycle. Thorium is three times as abundant in the Earth’s crust as uranium. Although existing estimates of thorium reserves plus additional resources total more than 4.5 Mt, such estimates are considered conservative. They do not cover all regions of the world, and the historically weak market demand has limited thorium exploration.

Environmental Characteristics

No form of energy production or use is without environmental impact. This is true for all energy chains: from extracting resources, building facilities and transporting material through the final conversion to useful energy services. The principal environmental impacts associated with nuclear power and sustainable development are radiation, air pollution, GHG emissions and radioactive waste.

Greenhouse Gas Emissions

A major environmental concern for sustainable development is the buildup of carbon dioxide (CO_2) and other GHGs in the atmosphere and the potential for undesirable climate change. The primary GHGs are CO_2, methane and nitrous oxide (N_2O).

All these gases remained at relatively stable concentrations in the atmosphere until the beginning of the Industrial Revolution around 1750, when CO_2 concentrations began to rise dramatically, as shown

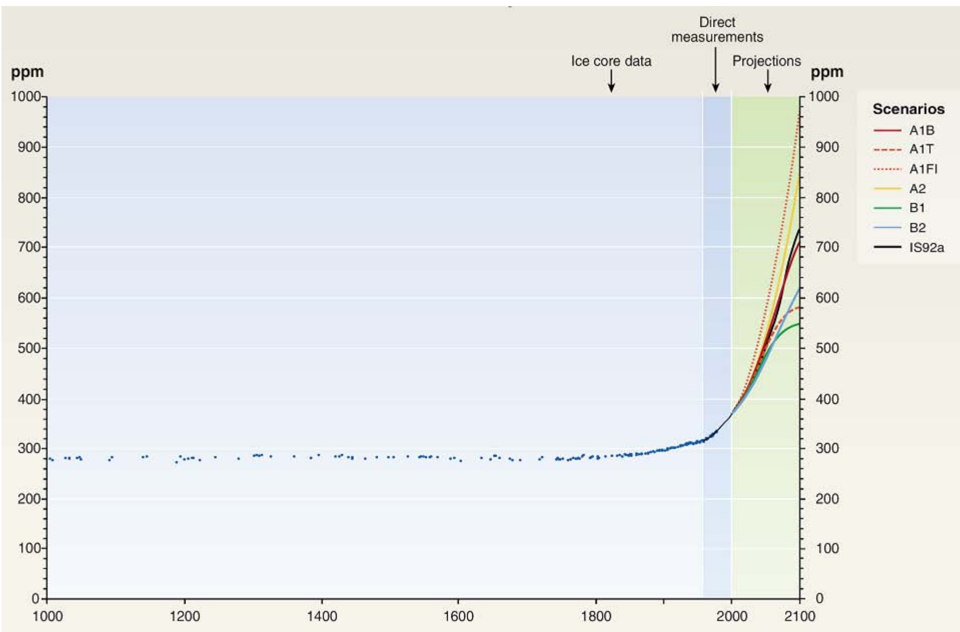

FIG. 10. Atmospheric CO_2 concentrations and projected concentrations (IPCC 2001).

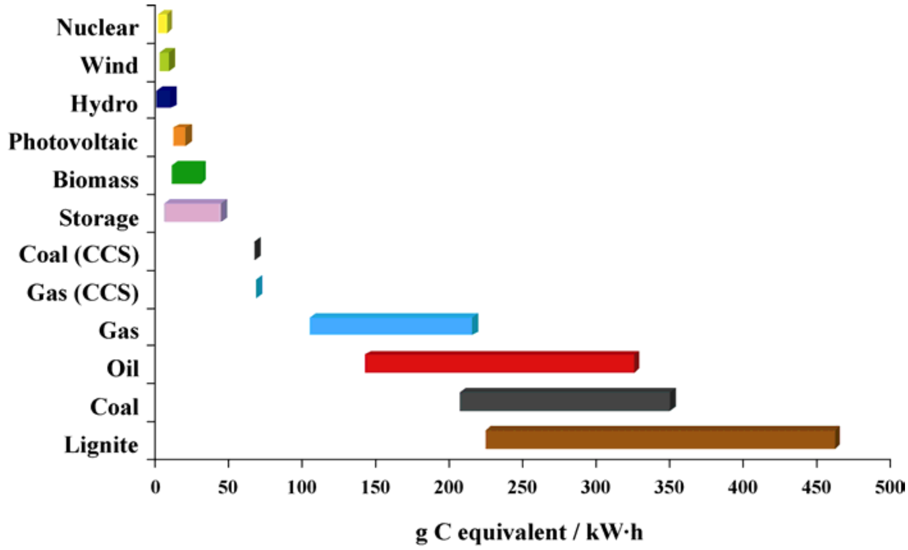

FIG. 11. CO_2 emission rates for electricity generating alternatives (storage: batteries, pumped hydro, compressed air storage; CCS: carbon capture and storage) (Weisser to be published).

in Fig. 10. Current atmospheric concentrations of CO_2 are about 380 parts per million (ppm) and are continuing to rise. The goal of the UNFCCC is to stabilize the concentration of GHGs "at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1992).

Among the alternatives for generating electricity, fossil fuelled technologies (coal, oil and natural gas) have the highest CO_2 emission rates per kW·h (Fig. 11) and create the majority of energy related GHG emissions. The figure shows emission rates for the complete fuel cycle, including facility construction, equipment manufacture, resource extraction, transport, processing and conversion.

The complete nuclear power chain, from resource extraction to waste disposal including reactor and facility construction, emits only 1–6 grams of carbon equivalent per kilowatt-hour (g C_{eq}/kW·h). This is about the same as wind and hydropower, including construction and component manufacturing. All three, together with solar power and biomass, are well below coal, oil and natural gas (60–460 g C_{eq}/kW·h) even taking account of carbon capture and storage.

Figure 11 indicates that stabilizing CO_2 concentrations in the atmosphere will require significant reductions in emissions from fossil fuelled power plants, either by reducing their emissions directly, by more efficient energy use, or by greater use of renewable technologies and nuclear power.

Air Pollution

Nuclear power reactors emit virtually none of the traditional air pollutants associated with fossil fuel combustion, principally sulphur dioxide (SO_2), nitrogen oxides (NO_x) and suspended particulate matter (PM). Nor do they emit trace heavy metals, like arsenic and mercury, associated with coal combustion. SO_2 and NO_x contribute to human morbidity and mortality, reduce crop yields and are the principal cause of acid rain. In turn, acid rain damages forests, broader ecosystems, agricultural crops and building materials. NO_x is a precursor of ground level ozone, which has further adverse health impacts. Particulate matter, which is both emitted directly and formed in the air as the result of SO_2 and NO_x emissions, directly increases human mortality and morbidity.

Emission levels of these pollutants have been reduced in recent decades through technological improvements and by capturing emissions from stack gases. The vertical scale of Fig. 12 presents a qualitative comparison of the various technologies currently used in the European Union.

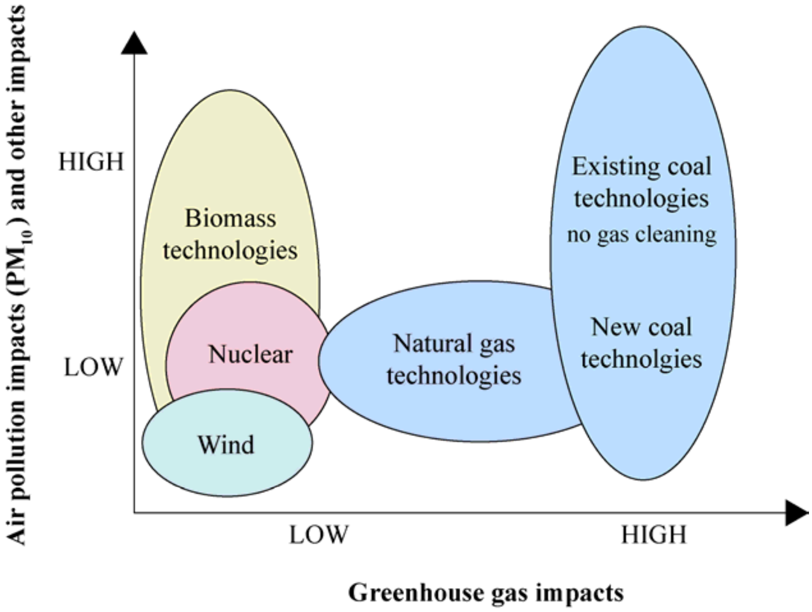

FIG. 12. Relative environmental impacts from emissions of different electricity generating technologies (European Commission 2003).

Radiation

Radiation is relevant for nuclear, coal, oil, gas and geothermal power plants. All bring radioactive material in the Earth's crust to the surface. The US Environmental Protection Agency (EPA) estimates that someone living within 50 miles of a coal fired power plant receives an average dose of 0.3 µSv; someone living within 50 miles of a nuclear power plant receives 0.09 µSv. Both are more than one thousand times less than the average dose received by people in the USA from X rays and other medical procedures, and more than ten thousand times less than their average dose from natural background radiation.

Figure 13 presents a worldwide comparison, based on data from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), showing, on a logarithmic scale, that the average radiation dose from nuclear power production is one ten-thousandth of the dose from natural

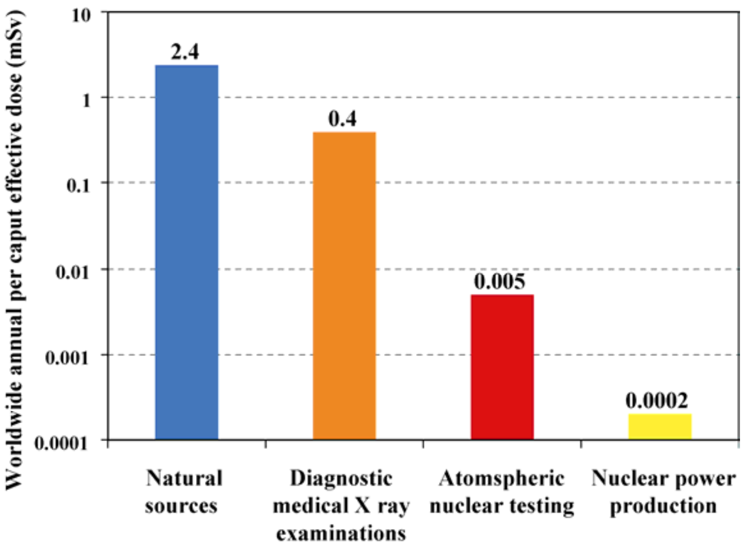

FIG. 13. Worldwide average annual per capita dose from natural and anthropogenic radiation (adapted from UNSCEAR (2000)).

background sources. Background sources include cosmic rays and naturally occurring radioactive substances in the air (mainly radon), in food and water (such as potassium), and in the Earth. Human activities create additional exposure, particularly from medical X rays (as shown in Fig. 13) and nuclear medical procedures. But living in a brick, stone or concrete building; watching television or using a computer terminal; travelling in a jet airplane; and wearing a luminous wristwatch all add to the dose. The incremental dose from a home smoke detector is comparable to that from living within 50 miles of a nuclear power plant.

In some jobs, workers receive additional occupational exposure, for example, in industrial, medical and research jobs where radiation or radioactive material is used, in mining, in nuclear power plant operation and in high altitude jet travel by pilots and flight crews. The average level of occupational exposure in such jobs is normally comparable to the global average level of natural radiation exposure.

Significant health impacts from nuclear power plants thus arise only from major accidents that release radiation, of which there has been one — the 1986 Chernobyl accident. Chernobyl was caused by serious design flaws coupled with serious operator mistakes. It was a catastrophic accident that cost lives and caused widespread suffering. But it also brought about major changes, including the founding of a 'safety culture' of constant improvement, thorough analysis of experience and sharing of best practices. The World Association of Nuclear Operators (WANO) was created in the wake of Chernobyl and the IAEA created the International Nuclear Safety Advisory Group, both of which help spread best practices, tighten safety standards and infuse a safety culture in nuclear power plants around the world. Regular meetings of the IAEA–OECD/NEA Incident Reporting System, where recent incidents are discussed and analysed in detail, are another part of this global exchange process. Also, the Convention on Nuclear Safety brings countries together to report on how they are living up to their safety obligations and to critique each other's reports.

These international exchanges of operating experiences and, in particular, the broad dissemination of 'lessons learned' are essential parts of maintaining and strengthening the safe operation of nuclear power plants. There is strong empirical evidence that learning from nuclear power plant operating experience has led, and continues to lead, to improvements in plant safety. This safety culture has been demonstrating its effectiveness for nearly two decades (see Figs 14 and 15), and it is this safety record that provides the basis for countries now considering constructing new nuclear power plants.

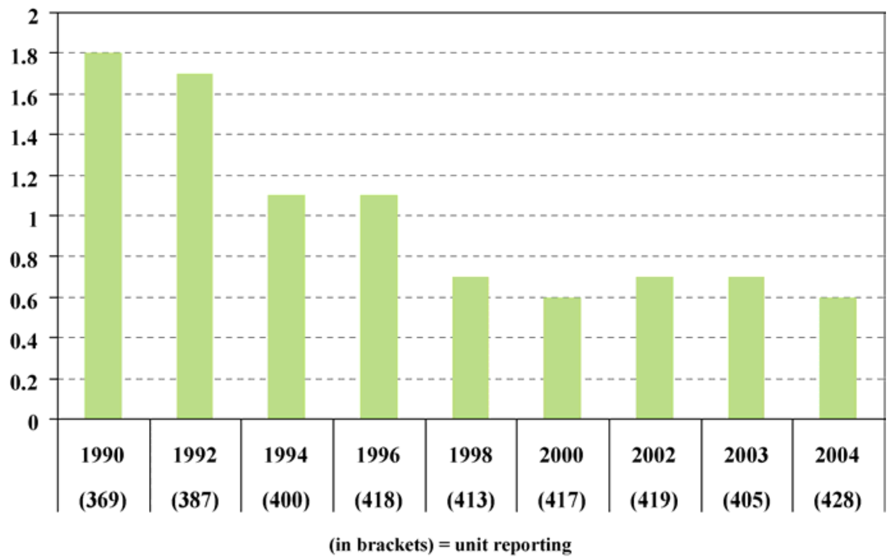

FIG. 14. Unplanned scrams per 7000 hours critical (WANO 2004).

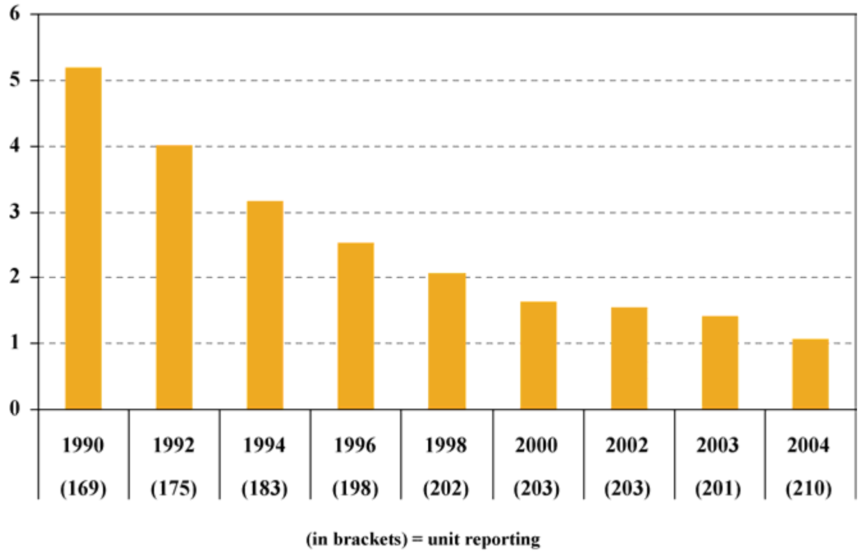

FIG. 15. Industrial accidents at nuclear power plants per 1 000 000 person-hours worked (WANO (2004)).

Long Term Waste Disposal

Final repositories for low level radioactive waste from nuclear power plants and from medical, research, and other applications have been licensed and are in operation in many countries. There is no operating repository for the final disposal of high level waste (HLW) from civilian nuclear power plants, although the scientific and technical communities generally agree that such waste can be disposed of safely in stable geological formations. There is one operating geological repository, for the disposal of long lived transuranic waste generated by research and the production of nuclear weapons, the Waste Isolation Pilot Plant in New Mexico, USA.

Currently, spent fuel generated by operating nuclear power plants is either reprocessed or stored. Reprocessing extracts usable uranium and plutonium from the spent fuel for use in new fuel. What remains is HLW that is currently stored pending final disposal. China, France, India, Japan and the Russian Federation reprocess most of their spent fuel. Canada, Finland, Sweden and the USA have opted for the alternative of direct disposal of spent fuel as HLW, although the USA has recently proposed a third approach in which spent fuel would be recycled not to extract usable uranium and plutonium, but to immediately 'burn' the plutonium and reduce the volume and toxicity of the waste requiring permanent disposal. Countries that have not yet chosen a strategy are currently storing spent fuel and keeping abreast of developments associated with all alternatives.

There is now over half a century of experience with spent fuel storage technology. The amount of spent fuel is relatively small: the spent fuel produced in one year by all the world's operating reactors would cover a soccer field to a depth of about 1.5 metres. And it is relatively easy to add incremental storage capacity. Hence, there is no strong technical reason to expedite creation and operation of a deep geological repository. There may be good political and symbolic reasons to do so, but storage means that politicians and the public have time to exhaustively debate, explore and determine each country's preferred solution. Where politically acceptable, multinational disposal can be considered as a potentially more cost effective option, especially for small countries with small nuclear programmes and limited repository sites.

The Finnish, Swedish and US repository programmes have made the most progress, but none is likely to have a repository in operation much before 2020. All of these programmes are designed to isolate waste from the environment by means of a series of engineered and natural barriers, as

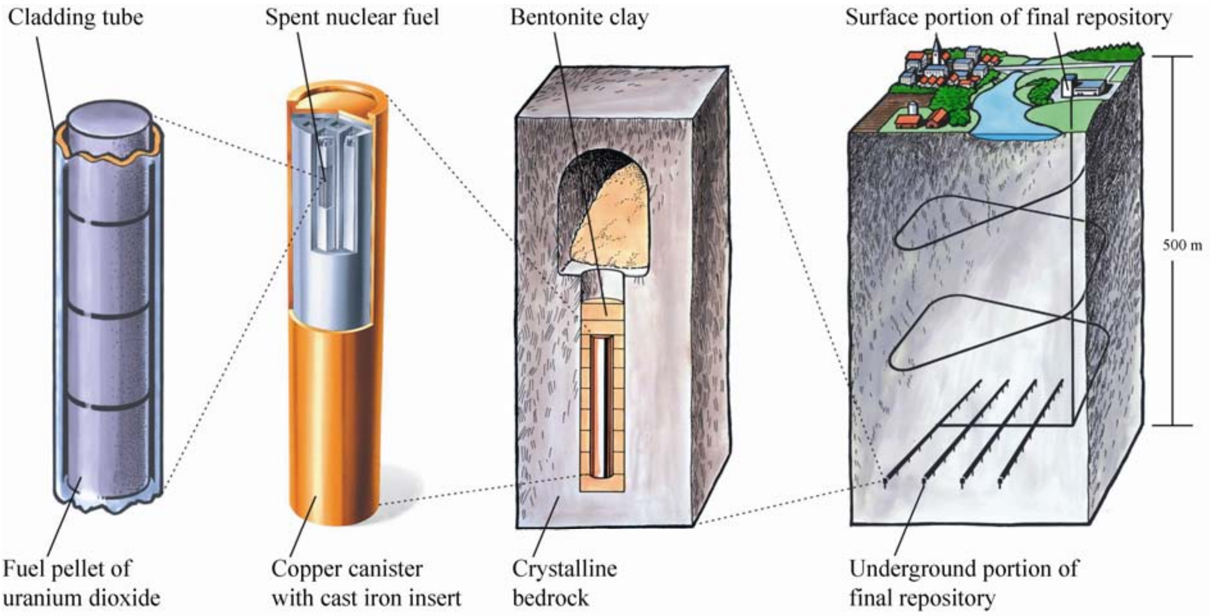

FIG. 16. The Swedish concept for the disposal of spent nuclear fuel as an illustration of the multi-barrier concept.

shown in Fig. 16 for the Swedish programme. The first barrier is the waste matrix and initial waste package (in the Swedish case solid fuel pellets and fuel rod cladding). Second are additional engineered barriers (copper canisters, iron inserts and bentonite clay backfill in the figure). Third is the host geological formation (crystalline bedrock in Sweden) chosen for proven geological stability over hundreds of millions of years, favourable geochemical conditions and limited water movement.

Waste disposal is an area in which nuclear power is generally ahead of alternatives. Nuclear waste is small in volume, well confined and highly monitored, unlike solid and toxic waste produced by other fuel chains. The cost of containing, storing and disposing of nuclear waste is in most countries included in the price of electricity. These internalized expenses include the cost of managing waste, disposing of the waste in long term repositories and decommissioning the plant at the end of its life.

NON-PROLIFERATION AND THE SECURITY OF NUCLEAR MATERIAL

The Nuclear Non-proliferation Regime

Nuclear weapons preceded civilian nuclear power. In 1953, US President Eisenhower therefore proposed an international agency and international assistance to help spread the peaceful applications of nuclear energy so that countries wishing to acquire nuclear expertise for peaceful purposes did not feel compelled to follow the ‘weapons-first’ path of the nuclear pioneers.

Three years later the IAEA was founded “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world”. The IAEA’s Statute also authorizes it to establish safeguards to ensure that material it provides is not used for military purposes. And it allows the IAEA to apply safeguards to nuclear material “at the request of the parties, to any bilateral or multilateral arrangement”. The principal multilateral arrangement for which the IAEA applies safeguards is the 1970 Treaty on the Non-Proliferation of Nuclear Weapons (NPT).

The NPT has to date been remarkably successful in limiting the spread of nuclear weapons and remains at the centre of the global non-proliferation regime, which consists of:

- The NPT, together with comprehensive IAEA safeguards agreements and, since 1997, Protocols Additional to Safeguards Agreements that strengthen IAEA monitoring for possible undeclared nuclear material;
- International verification measures (the IAEA safeguards system plus regional and bilateral agreements);
- Export controls on nuclear materials and specified facilities, equipment and other materials;
- National physical protection measures, and material accounting and control measures.

However, proliferation concerns have gained visibility in the last few years. First, with rising expectations for nuclear power, critics have cited possible increased proliferation risks as a reason to proceed slowly or not at all. Second, revelations in the last few years concerning undeclared activities for uranium enrichment and reprocessing of spent fuel, and the discovery of an international illicit market in sensitive nuclear technologies have heightened awareness of proliferation risks associated particularly with sensitive parts of the nuclear fuel cycle.

At the 2005 NPT Review Conference, the IAEA Director General proposed seven steps to strengthen the non-proliferation regime.[1] Six of the seven do not address nuclear power — it is not a principal source of proliferation risk. The one that does address nuclear power proposes tighter control over proliferation sensitive elements of the nuclear fuel cycle, specifically enrichment and reprocessing, while assuring supply of nuclear fuel for peaceful uses. In 2005, an expert group appointed by the IAEA Director General submitted their report on possible multilateral approaches to proliferation sensitive parts of the nuclear fuel cycle (IAEA 2005b). Possible initiatives are being explored by several governments and organizations.

Thus, despite the success of the NPT and the IAEA's safeguards system, current proliferation risks continue to be serious, and it is imperative that the world take steps, such as those laid out by the IAEA Director General at the 2005 NPT Review Conference, to reduce such risks. It is also essential to recognize that nuclear power is not a principal contributor to proliferation risks, and that halting or reversing the expansion of nuclear power would not appreciably reduce such risks.

Security of Nuclear Material

The September 2001 attacks in the USA and subsequent attacks in Spain, Indonesia, the Russian Federation and elsewhere have driven a dramatic re-evaluation of terrorist risks for all sensitive locations — urban centres, industrial complexes, harbours, oil refineries, air and rail travel and nuclear facilities. They have focused added attention on nuclear security — the ability to control and protect nuclear and other radioactive material, nuclear installations and transports — from terrorist and other illegal activities (IAEA 2004). Assessments of nuclear power plant security note that nuclear plants and other fuel cycle facilities are designed to withstand natural disasters such as earthquakes, floods, tornadoes and hurricanes. Terrorist attacks involving explosions and fire would be analogous to such external events in their implication for damage and the release of radioactivity (MIT 2003). The containment building and other plant buildings are, by design, major hardened obstacles that would be especially resistant to attack. An evaluation by the Electric Power Research Institute in the USA of an aircraft crash into a nuclear power plant concluded that US containments would not be breached by such an attack (NEI 2006a). Switzerland's Nuclear Safety Inspectorate studied a similar scenario and reported in 2003 that the danger of any radiation release would be low for older plants and extremely low for newer ones (UIC 2006).

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[1] The seven proposed steps are: reaffirm the goal of eliminating nuclear weapons; strengthen the IAEA's verification authority; establish better control over proliferation sensitive parts of the fuel cycle; secure and control nuclear material (e.g. strengthen the Convention on the Physical Protection of Nuclear Material and minimize high enriched uranium in civilian use); demonstrate a commitment to nuclear disarmament; strengthen the NPT non-compliance mechanism; and address the real security concerns of States.

Similarly, the construction strength of nuclear facilities, special security to guard against unauthorized or forced entry, and regulatory requirements that plants should be designed to withstand ‘design basis threats’ from sabotage and theft, means that any attack from inside a plant would be very unlikely to result in a significant release of radioactivity. A security exercise conducted in 2002 by the US Center for Strategic International Studies concluded that nuclear power plants are a distinctly less attractive target for terrorists because of the stringent security measures in place (NEI 2006b; NEI 2006c).

POLICY OPTIONS AND TECHNOLOGICAL CHANGE

Policy Options for Stabilizing GHG Concentrations

One concept for systematic thinking on policies to stabilize atmospheric GHG concentrations is that of “stabilization wedges”, as described by Pacala and Socolow (2004) and shown in Fig. 17 and Box 2. The figure shows the difference between rising business-as-usual CO_2 emissions and stabilized emissions as a yellow ‘stabilization triangle’. The triangle is composed of ‘stabilization wedges’, which represent different policies toward the goal of stabilization. This framework emphasizes that stabilization will likely require multiple policies working in combination. No one policy can solve the problem on its own. In practice, the potential ‘size’ of each wedge will depend on local conditions and opportunities — the availability of renewables and nuclear power, opportunities for efficiency improvements and more rational energy use, and carbon capture and storage possibilities.

Box 2 summarizes energy related policies identified by Pacala and Socolow that can contribute to reducing carbon emissions. They can be grouped into three categories: energy efficiency measures to reduce energy use directly; fuel shifts from, particularly, coal to natural gas, nuclear power and renewables; and capturing and storing the carbon currently emitted by today’s fossil fuel technologies. Each of these categories is discussed briefly below.

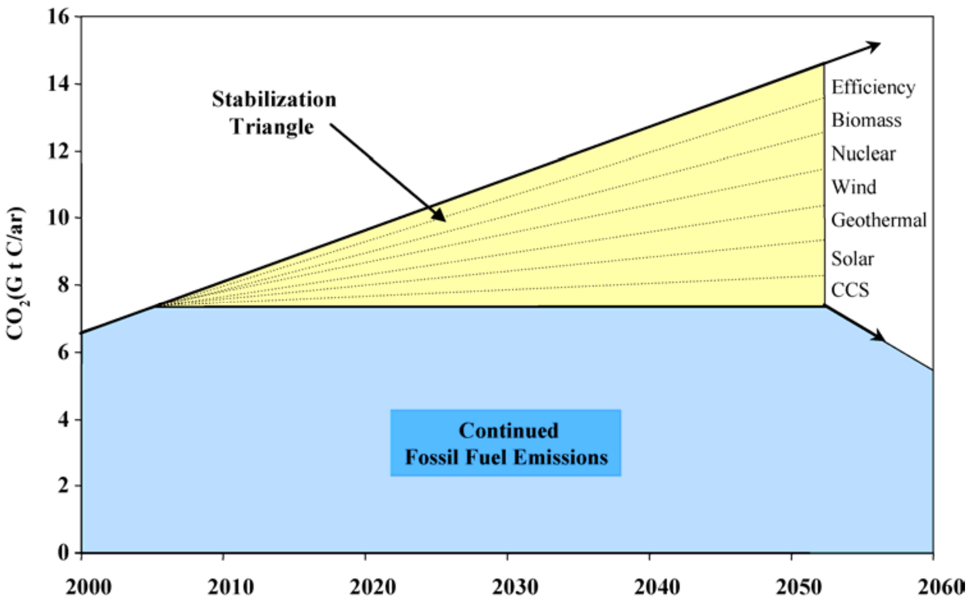

FIG. 17. CO_2 stabilization wedge concept. (Excerpted with permission from Pacala and Socolow (2004). Copyright 2004, AAAS)

Box 2. Potential Options for Carbon Reduction

- ***Energy Efficiency and Rational Energy Use***
  - — Economy-wide, carbon intensity reduction (emissions/GDP).
  - — Efficient vehicles.
  - — Reduced use of vehicles.
  - — Efficient buildings.
  - — Efficient baseload coal plants.

- ***Fuel Shift***
  - — Substitute gas baseload power for coal baseload.

- ***CO_2 Capture and Storage***
  - — Capture CO_2 at baseload power plant.
  - — Capture CO_2 at H_2 plant.
  - — Capture CO_2 at coal-to-synfuels plant.
  - — Geological storage.

- ***Nuclear Fission***
  - — Substitute nuclear power for coal power.

- ***Renewable Electricity and Fuels***
  - — Wind power for coal power.
  - — PV power for coal power.
  - — Wind H_2 in fuel cell car for gasoline in a hybrid car.
  - — Biomass fuel for fossil fuel.

Energy Efficiency and Rational Energy Use

Energy efficiency improvements have contributed substantially to avoiding carbon emissions. The energy intensity of the OECD economies has declined from 0.31 tonnes of oil equivalent (toe)/1000 $(2000) in 1973 to 0.20 toe/1000 $(2000) in 2003. Some of this is due to economic restructuring, (shifting from manufacturing to less energy intensive services), but a great deal is due to efficiency improvements in the wake of the oil shocks of the 1970s. Globally, energy intensity is higher than in the OECD, but it also has dropped since the 1980s, as shown in Fig. 18. Nonetheless, there remain substantial opportunities for further energy efficiency improvements to help reduce future GHG emissions, and the JPOI stresses the importance of additional improvements for sustainable development.

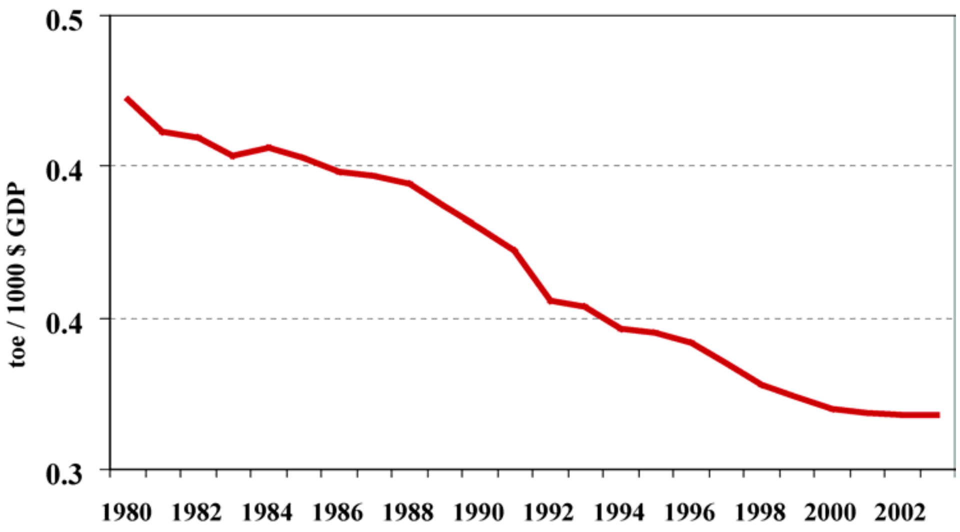

FIG. 18. Energy intensity of global GDP, 1980–2003 (adapted from EIA (2003)).

However, efficiency improvements have limited potential for those in 'energy poverty'. They cannot use less electricity if they have nothing to start with. And 'connecting the unconnected', a recognized priority for sustainable development as noted above, will necessarily increase their energy use. Hopefully, development can take advantage of technology leap-frogging opportunities (a non-energy example is cellular phone networks) such that developing countries can skip many of the less efficient technological stages experienced by today's industrialized countries, and take immediate advantage of modern efficient technologies, designs and possibilities for community and workplace planning.

Shifting the Energy Mix to Less Carbon Intensive Fuels

Faster growth in less carbon intensive fuels has also helped avoid carbon emissions. Some of this is due to fuel switching, such as the significant shift in the United Kingdom in the 1990s from coal to natural gas. However, much of the faster growth in less carbon intensive fuels is due to new investments in that direction. Nonetheless, the overall global trend is slow, and it is not consistent across different regions of the world. In the OECD, the carbon intensity of primary energy decreased 16% from 1971 to 2002, an average decrease of just 0.56% per year (IEA 2004). In countries with economies in transition, it decreased 14% over the same time period, but in developing countries it *increased* by 32%. Because the industrialized countries account for the bulk of the world's energy use, the overall global change between 1971 and 2002 was still a decrease. But it totalled only 10%, or an average of just 0.33% per year. Many opportunities still exist for fuel switching and for promoting faster growth in the use of low carbon technologies such as renewables and nuclear power. One important constraint, however, will be the transport sector, which is expected to grow particularly fast in large developing countries like China and India. Currently, hydro, wind, solar and nuclear power produce only electricity, and electricity accounts for less than 1% of the world's transport sector (EIA 2005). For these technologies to contribute substantially to reducing future carbon emissions from the transport sector, significant advances will be needed either in electric and hybrid vehicles, or in fuel cell vehicles using hydrogen and other low carbon synthetic fuels produced by renewables and nuclear power.

Carbon Capture and Storage

A *Special Report on Carbon Dioxide Capture and Storage* (IPCC 2005) concluded that this option could contribute substantially to reducing carbon emissions. Pre-combustion and post-combustion technologies to capture CO_2 are already economically feasible under specific conditions and are already in use. Storage of CO_2 in deep oil and gas fields and saline formations is economically feasible under certain conditions. On the other hand, ocean storage and its ecological impacts are still in the research phase, as is storage through reacting CO_2 with metal oxides to produce stable disposable carbonates.

The major opportunity for carbon capture and storage to contribute to climate change mitigation would be in the electricity sector, and the studies assessed in the IPCC report suggest that CO_2 prices of approximately \$25–30/t CO_2 would create incentives for significant deployment. Worldwide, the technical potential for carbon storage is estimated to be at least 2000 Gt CO_2 (545 Gt C) of storage capacity in geological formations. This compares with current global energy related emissions of approximate 6.4 Gt C per year in total, about 2.9 Gt C of which are associated with electricity generation. The economic potential is necessarily less than the technical potential, among other reasons because of environmental considerations, inconveniently located storage opportunities and the practical difficulty of capturing carbon from many sources — for example, automobile tail pipes. Nevertheless, in most scenarios for the stabilization of atmospheric GHG concentrations that were reviewed for the IPCC report, including the option of carbon capture and storage in a mitigation portfolio reduced the costs of stabilizing CO_2 concentrations by 30% or more over the course of the century.

Technological Change

The 21st century promises the most open, competitive, globalized markets in human history, and the most rapid pace of technological change ever. If a technology is to survive and flourish in this century, continual innovation is essential. Energy supply technologies (from oil exploration to solar cells), energy distribution technologies and energy end use technologies can all be expected to improve substantially.

In the near term, most new nuclear reactors will likely be evolutionary improvements on existing designs. In the longer term, more innovative designs that incorporate radical changes and promise significantly shorter construction times and lower capital costs could help to promote a new era of nuclear power. Several innovative designs are in the small (< 300 MW(e)) to medium (300–700 MW(e)) size range. As noted below, such designs could be attractive for the introduction of nuclear power in developing countries and for remote locations.

Advanced designs seek improvements in three principal areas: cost reductions, safety enhancements, and proliferation resistance:

(1) With regard to cost reductions, some designs emphasize the further development of proven strategies, i.e. achieving economies of scale through larger units, shorter construction schedules through modular systems and addressing licensing issues early, standardization and construction in series, multiple unit construction, and enhancing local participation. Other designs emphasize new cost reduction strategies, including economies of series production, enhancing the accuracy of codes and databases to eliminate overdesign, developing 'smart' components to detect incipient failures and reduce dependence on costly redundancy and diversity, making greater use of passive safety systems, further developing probabilistic safety analysis to support plant simplification and risk informed regulatory decision making, using fewer components that require nuclear grade standards, and achieving higher thermal efficiencies.

(2) Safety enhancements include larger water inventories (in the case of water cooled reactors), lower power densities, larger negative reactivity coefficients, redundant and diverse safety systems with proven high reliability, and passive cooling and condensing systems.

(3) Proliferation resistance covers intrinsic measures incorporated into various advanced designs concerning the chemical form of nuclear material — its mass and bulk, radiation field, heat generation and spontaneous neutron generation rate, the complexity of modifications necessary to use a civilian facility and material for weapons production, and design features that limit access to nuclear material.

Important design efforts on large, advanced light water reactors are under way in Argentina, China, the European Union, France, Germany, Japan, the Republic of Korea, the Russian Federation and the USA. Both Canada and India are working on advanced heavy water reactor designs, and advanced gas cooled reactor designs are being developed in China, France, Japan, the Republic of Korea, the Russian Federation, South Africa and the USA. The design and safety review of a demonstration unit of the 165 MW(e) pebble bed modular high temperature reactor (PBMR) in South Africa has been completed and a licensing review is under way. Development work on liquid metal cooled fast reactors is under way in China, France, India, Japan, the Republic of Korea and the Russian Federation.

Complementing these initiatives are two major international efforts to promote innovation. The first is the Generation IV International Forum, and the other is the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles.

Research is also continuing on increasing the proliferation resistance of some fuel cycles while decreasing the volume and potential toxicity of the eventual waste. Such fuel cycles would eliminate any separation of plutonium, and would ‘burn’ plutonium and other actinides to eliminate them from the resulting waste.

A number of developing countries are particularly interested in the development of commercial reactor designs that are smaller than those currently offered on the market. Smaller reactors would reduce the required initial investment and associated infrastructure costs, and they would be better suited to the small electrical grids of many developing countries. There are many designs in different stages of development. The Korean Atomic Energy Research Institute has applied for a construction permit for a one-fifth scale, 65 MW(th) prototype of a system integrated modular advanced reactor (SMART) which ‘cogenerates’ electricity while desalinating sea water. In the Russian Federation, a barge mounted floating 300 MW(th) KLT-40S cogeneration plant has been licensed for construction in Severodvinsk in 2007. The 165 MW(e) South African PBMR is planned for demonstration at full size by 2012.

A number of the small and medium size reactor (SMR) designs are in the category of ‘reactors without on-site refuelling’. These are reactors designed for infrequent replacement (every 5–25 years) of well contained fuel cassettes in a manner that impedes the clandestine diversion of nuclear fuel material. This category includes factory fabricated and fuelled reactors, and the general expectation is that the supplier country would retain all back end responsibilities for spent fuel and waste. The potential benefits include: possibly lower construction costs in a dedicated facility in the supplier country; lower investment costs and risks for the purchaser, especially if the reactor is leased rather than bought; reduced obligations for spent fuel and waste management; and possibly a higher level of assurance of non-proliferation to the international community.

Research and development efforts are also focused on two non-electric uses of nuclear power of particular relevance to sustainable development: desalination of sea water and hydrogen production.

An estimated 1.1 billion people currently lack access to clean water, and it is projected that by 2025 about 1.8 billion people worldwide will live in regions experiencing serious water scarcity (UNCSD 2005). Better water conservation, water management, pollution control and water reclamation are all part of the solution to projected water stress, as are new sources of fresh water, including the desalination of sea water. Desalination technologies have been well established since the mid-20th century and have been widely deployed in the Middle East and North Africa. The operating capacity of desalination plants has increased steadily since 1965 and was over 25 million m^3/d worldwide as of July 2004. Although less than 0.1% of this capacity is nuclear powered, Japan has accumulated over 143 reactor-years of desalination experience and Kazakhstan accumulated 26 reactor-years before retiring the Aktau fast reactor in 1999.

A number of countries with nuclear expertise, coastal sites, limited freshwater supplies, growing populations and/or limited fossil fuels are active in developing nuclear desalination. India, for example, is proceeding with full commissioning of its nuclear desalination demonstration plant at Kalpakkam, Tamil Nadu, where desalination using reverse osmosis has been in operation for several years and desalination using the multi-stage flash process is scheduled to start in 2006. In 2004, India commissioned a low temperature evaporation plant at the CIRUS heavy water research reactor at Trombay utilizing its moderator waste heat for producing high quality water from sea water. The Korean Atomic Energy Research Institute has finalized the design for a pilot SMART reactor with a desalination unit and in 2005 applied for a construction permit. Pakistan has begun construction on coupling a multi-stage distillation plant with the existing pressurized heavy water reactor at the Karachi nuclear power plant for demonstration purposes. In China, a test system is being set up in the Institute of Nuclear and New Energy Technology for validating the thermal-hydraulic parameters of a multi-effect distillation process. In Egypt, construction of the pre-heat reverse osmosis test facility is scheduled for completion in 2006.

The second non-electric research focus is hydrogen production. To the extent that fuel cells using hydrogen become widely used in the transport sector — and in other applications ranging from mobile telephones to large stand-alone power plants — hydrogen production would allow nuclear energy to meet a much greater share of the world's energy needs than it now can through electricity generation alone. Compared with today's dominant method of hydrogen production, steam reforming of natural gas, nuclear generated hydrogen would also both reduce GHG emissions and conserve natural gas for other priority uses.

Nuclear hydrogen production could take two routes: electrolysis and thermo-chemical water splitting. Electrolysis uses electricity to split water into hydrogen and oxygen. It is the more straightforward route, and commercially available electrolysis technology currently exists.

The second route — thermo-chemical water splitting — has yet to be demonstrated on a commercial scale. It combines heat from a high temperature nuclear reactor with chemical catalysts to more efficiently separate water into hydrogen and oxygen. Currently, a cycle based on sulphur and iodine is considered the leading contender among the numerous thermo-chemical cycles that have been studied over the past twenty years. It is under development at the Italian National Agency for New Technologies, Energy and the Environment (ENEA), the Japan Atomic Energy Agency (JAEA) and elsewhere.

The thermo-chemical cycles being studied require temperatures between 700 and 950˚C, well above those associated with commercially available nuclear reactors. A number of reactor designs that could produce process heat in this range are included in the research cited above, including the PBMR in South Africa, the very high temperature reactor, the molten salt reactor and the gas cooled fast reactor.

CONCLUSION

A major goal of sustainable development is bringing energy, especially electricity, to the quarter of the world's population now without it. Much of the emphasis on energy in the context of CSD-9 and the JPOI has been on expanding energy access and energy supplies in developing countries, i.e. 'connecting the unconnected,' particularly through rural electrification. For some rural poor, the best promise may be that offered by off-grid renewables, and additional efforts are essential to realize that promise as quickly and broadly as possible. For others, and for the urban poor and the needs of growing megacities, the mix must include large centralized power generation to match large centralized power demand. Nuclear power can make a substantial contribution.

Sustainable development is about growing assets and opening options — not foreclosing them. Given the *Agenda 21* principle of differentiated responsibilities, those countries that are able and willing have a particularly important role to play in keeping the nuclear power option open.

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