SUSTAINABLE DEVELOPMENT AND NUCLEAR POWER

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Abstract

The substantial increase in global energy consumption in coming decades will be driven principally by the developing world. Although there is some awareness on both the technical and political levels of the advantages of nuclear power, it is not a globally favored option in a sustainable energy future. This paper, after discussion of rising energy consumption, concentrates on a comparison of the environmental impacts of the available energy options.

1. INTRODUCTION

With projections of sharply rising energy consumption and continuing global dependence on fossil fuel sources, environmental pollution and greenhouse gas emissions could reach severely damaging levels. The global challenge is to develop strategies that foster a sustainable energy future less dependent on fossil fuels. Low environmental impacts and a vast fuel resource potential should allow nuclear power to have a meaningful role in the supply of energy during the next century.

Although there is some awareness on both the technical and political level of the advantages of nuclear power, it is not a globally favored option in a sustainable energy future. A sizeable sector of the public remains hesitant or opposed to its increased use, some even to continuation at present levels. This paper, after discussion of rising energy consumption, concentrates on a comparison of the environmental impacts of the available energy options.

2. RISING ENERGY CONSUMPTION

The substantial increase in global energy consumption in coming decades will be driven principally by the developing world. Today's developing countries, with some three-quarters of the world's inhabitants, consume only one-fourth of global energy. Current annual per capita energy consumption differs markedly by country and region. Canada in the high energy use region of North America has a per capita consumption close to 8 tons of oil equivalent (toe), eight times greater than Brazil where consumption is fifteen times more than in Tanzania or in Bangladesh.

Strong economic growth in many developing countries is already leading to sharp increases in per capita energy consumption. Consumption will continue to rise driven also by the projected two fold expansion in world population during the 21st century that will occur overwhelmingly in the developing world. Although progress is evident in restraining global population growth, currently at 80 million per year, the medium projection from the UN *World Population Prospects: 1996 Revision* forecasts a 50% increase by the middle of the next century with India likely exceeding China's projected more than 1.5 billion population and populations greater than 250 million inhabiting Brazil, Indonesia, Nigeria and Pakistan. Half of the world's people now live in intensive energy consuming urban areas and this percentage will increase as urbanization in some regions expands to include 80% of the population.

A 1995 study by the World Energy Council (WEC) - a leading non-governmental voice in energy matters - and the International Institute for Applied Systems Analysis (IIASA) considered three global energy scenarios for the next century - a high, middle and ecologically driven low economic growth scenario. The study projects by mid-century a range of energy demand increase of some 50% for the low economic growth case to more than 150% for the high growth case, with the latter showing a 50% increase before 2020.

The United States Department of Energy (DOE) in its recently released *International Energy Outlook 1997* projects a 54% increase in global energy demand as early as 2015 - less than 18 years from now - some half of this increase due to rising demand in the newly emerging Asian economies, including China and India. It warns that if the transport sector demand in China follows that seen in Thailand and the Republic of Korea, energy demand could be dramatically underestimated.

2.1. A shift from fossils

To limit environmental pollution and to slow the rate of increase of CO_2 concentration, responsive long-term energy strategies exploiting the maximum potential of non-greenhouse gas emitting energy sources need to be developed and implemented as rapidly as possible. The future energy mix that evolves will depend not only on environmental considerations, but also on economic, technological, supply and political factors. It is generally accepted that for many decades fossil fuels will continue to be the major energy source with natural gas, the lowest fossil fuel greenhouse gas emitter, likely becoming the major component. Countries having or exporting fossil fuels cannot easily turn away from their use and likewise, the economically dynamic countries of Asia cannot easily turn from fossil fuels toward uncertain and costly renewables for growing baseload power needs.

The 1995 WEC and IIASA middle economic growth Case B Scenario projects at mid-century more than a two-fold increase in fossil fuel consumption and a continuing fossil dominance with a two-thirds share of global energy - some 20% less than today. Nuclear power and renewables including hydroelectric each will more than double their current 6% shares.

National and regional factors govern the energy mix in each country. They differ considerably today and they will in the future. Today, China is 98% dependent on fossil fuels while France and Sweden have reduced their dependence to some 50% and 35% respectively through use of nuclear and hydroelectric power.

On the global level, difficult policy decisions lie ahead to foster a shift away from fossil fuel dominance. There is little consensus on how to proceed. There is general support for *cost-effective* energy efficiency techniques to somewhat slow demand, and on the supply side, an endorsement of increased use of renewables. Both efforts are necessary, but with limited potential over the near term. In the developed countries, the significant energy efficiency gains seen over the past two decades, such as in the industrial and residential sectors, will not likely be seen in the decades to come.

The supply potential of renewables is difficult to assess since they are only emerging technologies and currently unsuitable for meeting large baseload energy demand. With differing relevance for the various renewables, technological improvements are needed and basic challenges exist in reducing costs, improving efficiency and reliability, solving energy storage problems and integrating the technologies into existing energy systems.

2.2. The prospects of renewables

Both the WEC and the International Energy Agency (IEA) of the Organization for Economic Cooperation and Development (OECD) predict that non-hydroelectric renewables will not be economically competitive for large scale production in the foreseeable future and that they will play only a limited role in the decades to come. The WEC *Message for 1997* indicates that even with adequate support and subsidies, the share of renewables could reach only 5% to 8% of primary energy supply by 2020, this figure including a 2% non-commercial energy share. Hydroelectric has already been extensively developed in Europe and North America - some 50% of the estimated maximum economic potential. Its greatest potential lies primarily in Asia, South America and Africa where the trend will likely be towards small capacity units as concerns grow about the damaging environmental and social impacts of large dams. The hydroelectric share is forecast to remain around the current 6% level.

The ecologically driven low economic Case C scenario in the 1995 WEC and IIASA study, which focuses on a shift away from fossil fuels, considers a major share of energy supply from renewables, in one variant some 39% by 2050 and as much as 81% by 2100. A second variant assumes a somewhat smaller renewable contribution with nuclear power assisting the shift away from fossil fuels through a 33% contribution to global electricity needs by 2050 and some 38% by 2100. However, the ecologically driven scenario - as with any scenario that assumes a huge shift away from fossil fuels principally through renewables and an excessively low energy demand - requires an unlikely rapidly reoriented global energy system focused explicitly on the environment and on developing countries.

2.3. The nuclear power potential

The 6% contribution of nuclear power to global primary energy supply is almost entirely in the rapidly increasing electricity sector where 17% of global electricity is generated by 442 nuclear power reactors in 32 countries. There are 36 units currently under construction in 14 countries. The first commercial nuclear power reactor began operation some 40 years ago with a rapid expansion in reactor units taking place during the 1970s and early 1980s. Today, nuclear power is a mature and highly developed technology.

In terms of the total quantity of nuclear electricity generated, the five largest producers are the United States, France, Japan, Germany and Russia. Globally, the nuclear share of electricity is more than 20% in 19 countries. Regionally, in 1996 Western Europe with a 33% share had the highest percentage of nuclear electricity - the nuclear share in France, Belgium and Sweden being 77%, 57% and 52% respectively. Two large nuclear power units in Lithuania supplied almost 85% of the country's electricity requirements.

With a continuation of the current trend, the next century will see global electricity demand grow faster than overall energy demand as it provides the greatest flexibility in use at the point of consumption. Already Turkey, an example of a rapidly industrializing developing country, has seen its electricity capacity increase 10 times in the past 25 years from some 2,200 megawatts electric (MW(e)) to 21,000 MW(e). The 1997 DOE energy outlook report projects a possible 75% global increase in electricity demand from 1995 to 2015 - equivalent to 1500 new 1000 MW(e) plants.

Although nuclear power is currently a significant source of global electricity supply, there is no consensus concerning its future role. While nuclear power stagnates in much of Europe and in North America, it continues as a strong option in a number of Asian countries. Economy and security of supply have been principal considerations in the choice of nuclear power along with an awareness of its environmental benefits - from mining to waste disposal and decommissioning, it produces remarkably little environmental pollution and greenhouse gas emissions. These three factors - economics, security of supply and the environment will determine the long-term role of nuclear power in a sustainable energy future.

All three energy scenarios of the 1995 WEC and IIASA study - as well as those developed by the IPCC for its climate change studies - assume a significant nuclear power contribution over the next several decades, but the assumptions for nuclear power after 2020 vary considerably due to uncertainty about its future. For the six variants in the study, the range of the nuclear power contribution varies from some twenty-fold increase to a total phase out by the end of the next century.

3. COMPARATIVE ASSESSMENTS

To assist energy planners, over the years the IAEA has carried out comparative assessments of the alternative energy sources. Full energy chain analyses that consider elements beyond the direct power generation stage reveal a wide variety of significant environmental issues and impacts linked to energy options.

Emissions to the environment are commonly the principal focus of energy impact studies. Other significant environmental impacts such as land disturbance and population displacement together with their economic and social implications are less emphasized. Major impacts such as depletion of natural resources and large fuel and transport requirements that influence a wide range of areas, including occupational and public safety as well as national transport systems, are mostly ignored.

In general, *fossil fuels* can have significant damaging impacts locally, regionally and globally through,

- Global climate change
- Air quality degradation (coal, oil)
- Lake acidification and forest damage (coal, oil)
- Toxic waste contamination (coal ash and slag, abatement residues)
- Groundwater contamination
- Marine and coastal pollution (oil)
- Land disturbance
- Large fuel and transport requirements
- Resource depletion.

Hydroelectric while relatively kind to the atmosphere can be much less considerate to the earth and its inhabitants both locally and regionally through,

- Population displacement
- Land loss and change in use
- Ecosystem changes and health effects
- Loss of bio-diversity
- Dam failure
- Decommissioning.

Renewables (solar, wind, geothermal, biomass) are not without their impact although they are more local in nature such as through,

- Air quality degradation (geothermal, biomass)
- Extensive land use
- Ecosystem changes
- Fabrication impact (solar photovoltaic cells)
- Noise pollution (wind).

Nuclear power under normal operation is benign to the atmosphere and to the earth and its inhabitants locally, regionally and globally. As discussed subsequently, due principally to small nuclear fuel requirements there are limited environmental impacts for the full energy chain from mining to waste disposal and decommissioning. A significant environmental impact arises only from *potential* abnormal events such as through,

- Severe reactor accident impact
- Waste repository impact.

3.1. Fuel and land requirements

Generally, the quantity of fuel used to produce a given amount of energy - the energy density - determines in a large measure the magnitude of environmental impacts as it influences the fuel extraction activities, transport requirements, and the quantities of environmental releases and waste. The extraordinarily high energy density of nuclear fuel comparated to fossil fuels is an advantageous physical characteristic.

One kilogram (kg) of firewood can generate 1 kilowatt-hour (KW(h)) of electricity. The values for the other solid fossil fuels and for nuclear power are:

1 kg coal	-	3 KW(h)
1 kg oil	-	4 KW(h)
1 kg uranium	-	50,000 KW(h) (4,000,000 KW(h) if reprocessed)

Consequently, a 1000 MW(e) plant requires the following tonnes (t) of fuel annually:

2,600,000 t coal	-	2000 train cars (1300 t each)
2,000,000 t oil	-	10 supertankers
30 t uranium	-	α of a reactor core (10 cubic meters)

The energy density of fossil and of nuclear fuel allows relatively small power plant areas of some several square kilometers (km^2). The low energy density of renewables, measured by land requirements per unit of energy produced, is demonstrated by the large land areas required for a 1000 MW(e) system with values determined by local requirements and climate conditions (solar and wind availability factors ranging from 20% to 40%):

Fossil and nuclear *sites*	-	1 to 4 km^2
Solar thermal or PV *parks*	-	20 to 50 km^2 (a small city)
Wind *fields*	-	50 to 150 km^2
Biomass *plantations*	-	4,000 to 6,000 km^2 (a province)

3.2. Environmental pollutants

Due to the vast fuel requirements, the quantity of toxic pollutants and waste generated from fossil fuel plants dwarfs the quantities from other energy options. In general, pollution depends on the fuel's impurity level, with natural gas cleaner than oil and oil cleaner than coal. A 1000 MW(e) coal plant without abatement technology produces an annual average of 44,000 t of sulfur oxides and 22,000 t of nitrous oxides that are dispersed into the atmosphere. Additionally, there are 320,000 t of ash containing 400 t of heavy metals - arsenic, cadmium, cobalt, lead, mercury, nickel and vanadium - these quantities without considering energy chain activities such as mining and transportation.

Fossil fuel plants using modern abatement technology can decrease noxious gas releases as much as ten-fold, but significant quantities of solid waste are produced in the process. Depending on sulphur content, solid waste from sulphur abatement procedures for a 1000 MW(e) plant are as much as 500,000 t annually from coal, more than 300,000 t from oil and some 200,000 t from natural gas sweetening procedures. The waste, containing small quantities of toxic substances, is commonly stored in ponds or used for landfill or other purposes. Regulatory bodies increasingly categorize such waste as hazardous.

A 1000 MW(e) nuclear power plant does not release noxious gases or other pollutants and produces only some 30 t of discharged high level radioactive spent fuel annually, along with 800 t of low and intermediate level radioactive waste. In the United States, low-level solid waste from nuclear power plants has been reduced tenfold over the past decade through compaction to 30 cubic meters of waste per plant annually - a total of some 3000 cubic meters from all operating plants. For perspective, industrial operations in the United States are estimated to produce more than 50,000,000 cubic meters of solid toxic waste annually.

3.3. Confinement vs. dispersion of waste

There is continuous public concern that nuclear waste cannot be safely managed. However, nuclear waste has distinct advantages as quantities are remarkably small relative to the energy produced. The small quantities permit a *confinement* strategy with the radioactive material beginning with the nuclear fission process through waste disposal essentially isolated from the environment. Disposal techniques exist and the hazard decreases with time due to radioactive decay. The main disposal options are simple near surface, engineered structures, mined cavities, and deep geological repositories. Some thirty countries currently operate licensed depositories for low and intermediate level radioactive waste.

In sharp contrast, disposal of the large quantities of fossil fuel waste follows an alternative *dispersion* strategy. Most of the waste (noxious gases and many toxic pollutants) is dispersed directly into the atmosphere, while some solid waste containing toxic pollutants is buried in shallow ground, there being no practical alternative. The waste is dispersed or buried at concentrations considered unharmful. While the resulting impact can be small, the accumulation over many years from a large number of waste producing activities can easily overburden the natural environment, locally as well as globally.

Confinement is preferable to dispersion, but is economically feasible only when waste volumes are small and arise under easily controlled conditions. Most nuclear waste consists of relatively short lived low and intermediate level waste, annually some 450 and 350 t respectively from a 1000 MW(e) plant. Low level waste, consisting largely of minimally contaminated clothing, machine parts and industrial resins, can be placed in containers with disposal in trenches covered by soil. Intermediate level waste, including reactor parts and contaminated equipment, is packaged in cement inside steel drums. Similar to low-level waste, it can be safely disposed of in near surface facilities.

3.4. High level waste

High level waste consists of liquid from reprocessing after recovering uranium and plutonium or spent fuel for ultimate disposal, if it is not to be reprocessed. The spent fuel, some 12,000 t annually from all operating plants, can be readily stored above or below ground awaiting decisions on long-term disposal. An interim storage period is necessary to allow the residual heat generated in the spent fuel to decrease, disposal being more practical after several decades. The volume of high level liquid waste from reprocessing 30 t of spent fuel released annually from a 1000 MW(e) plant, containing more than 99% of the radioactivity, is some 10 cubic meters. The waste can be vitrified to a glass solid and stored awaiting long term disposal.

To date, no long term disposal site has been licensed in any country. Deep underground geologic formations undisturbed for many millions and even billions of years are being considered. Solid salt domes or granite tunnels several hundred meters below the surface are impervious to water ingress, which is the potential mechanism for material transport to the surface. A number of barriers would prevent the release and transport of disposed radioactive material; the canisters containing the vitrified waste, a surrounding absorbent clay backfill and the solid host material. A number of countries are developing repository concepts to handle vitrified waste as well as spent fuel. Startup times for repositories are likely at least a decade away. Disposal is blocked not by technical, but by political obstacles.

A common apprehension about radioactive waste concerns its long lived nature. Waste from reprocessing facilities, where much of the very long lived materials such as plutonium are removed, would decay to radioactive levels below that of natural uranium ore in less than one thousand years compared to more than ten thousand years without reprocessing. Waste pollutants from coal such as cadmium, lead or mercury - much of which are dispersed or disposed of in near surface facilities - remain toxic indefinitely. There is a growing recognition that management of indefinitely toxic waste and radioactive waste warrant a harmonized approach. However, managing toxic wastes from fossil fuels to standards proposed for high level radioactive wastes is not economically feasible.

Indicators to compare radioactive waste hazards with fossil fuel waste hazards have been developed. One such indicator is based on admissible concentrations of radioactive and toxic pollutants in water. For similar amounts of energy generated, in some one hundred years the amount of water necessary to dilute reprocessed radioactive waste to admissible concentrations would be less than the amount to dilute lignite waste to admissible concentrations - the reason being the relatively small quantity of radioactive material and the relatively rapid decay of reprocessing waste due to the removal of long lived elements.

3.5. Greenhouse gas emissions

Turning now to greenhouse gas emissions, a single 1000 MW(e) coal plant emits some 6,000,000 tons of CO_2 annually. There is no economically viable technology to abate or segregate the large quantities emitted. Segregation and storage underground are theoretically possible, but technologies are only in very early stages of study. Some may require high energy input and environmental impacts have not been assessed.

Countries with significant nuclear power and hydroelectric capacity have markedly lower CO_2 emissions per unit of energy produced than countries with high fossil fuel shares. Through a rapid expansion in nuclear power, France has lowered its CO_2 emissions by more than 80 %over the past 30 years. In contrast, countries that have rejected or sharply curtailed nuclear power programmes have increased greenhouse gas emissions by turning to fossil fuels. Globally, the use of nuclear power and hydroelectric as an alternative to fossil fuels has helped restrain CO_2 emissions over the past several decades. Today nuclear power and hydroelectric each avoid some 8% of global CO_2 emissions annually from energy production.

Efforts to reduce greenhouse gas emissions require attention to the full energy chain emissions as significant fuel extraction, transport, manufacturing and construction activities can be involved. Full chain analyses require identifying all emission sources. Burning natural gas with a low carbon content produces less CO_2 than burning coal or oil. But leakage's during extraction and pipeline transport, which are more than 5% in some areas, can offset much of this advantage since the escaping methane is a more effective greenhouse gas. In terms of equivalent grams of carbon per KW(h), a quantity used for comparative purposes, some natural gas chains can have emissions similar to coal energy chains.

Full chain hydroelectric assessments generally show comparatively low greenhouse emissions despite massive construction activities. However, if methane gas released from decomposition of inundated organic material at the bottom of some water reservoirs is included, emissions could approach natural gas values. Nuclear power and wind are on the low side of full chain emissions with solar photovoltaic releases higher due to various greenhouse gases released during silicon chip manufacturing. Although biomass can be low in emissions, full chain analyses can be extremely complex and currently provide uncertain results as they involve non-energy byproducts as well as growth and harvesting time periods.

3.6. Natural resources

Depletion of natural resources is an environmental issue. There are proven reserves of coal sufficient for more than 200 years, of natural gas for 60 years and of oil for 40 years at current levels of use. Efforts are underway to increase oil and gas resources through improved recovery techniques and oil-shale and tar-sand processing that are estimated to be capable of at least doubling the resource base. Depending on their specific economics, new technologies to further increase fossil fuel extraction could be developed. But, financing investments and price volatility could then become leading concerns.

Known uranium reserves with reactors operating primarily on a once through cycle without reprocessing spent fuel, assure a sufficient fuel supply for at least 50 years at current levels of use, the same order of magnitude as today's proven resources of natural gas and oil.

Estimates of additional undiscovered (speculative) resources could add more than 100 years. Unconventional uranium resources are also available such as the uranium contained in sea water and phosphates that could increase resources by many multiples of current reserves, but as with speculative fossil reserves, it would not necessarily be an economic energy resource.

Over the long term, recycling plutonium from reprocessed spent fuel in thermal reactors as mixed oxide fuel and introduction of fast breeder reactors also to convert non-fissionable uranium into plutonium would increase the energy potential of today's known uranium reserves by up to 70 times, enough for more than 3,000 years at today's usage. Uranium used in a complete fuel cycle not only maintains, but also significantly increases the resource base.

Additionally, thorium, which like uranium has no significant use other than as a reactor fuel, is another energy resource although it does not contain a fissionable isotope as does uranium. It can be used in a breeding fuel cycle with either fissionable uranium or plutonium and converted to a fissionable isotope of uranium. Indigenous thorium in a number of countries with limited uranium deposits could make this an attractive option.

3.7. External costs

While environmental and energy supply considerations show significant advantages to nuclear power, economic justification is a central factor. As a capital intensive undertaking with relatively long construction periods, the competitiveness of nuclear power depends on investment conditions, particularly interest and payback period of loans. In today's liberalized electricity markets and radically changing financial environment, initial capital investments involving high discount rates must be recovered in excessively short time periods. For discount rates in the order of 5%, nuclear power is competitive with fossil fuels. At higher rates it is difficult to be competitive with gas - particularly with combined cycle - and at 10% not with coal. The economic competitiveness of large hydroelectric projects and capital intensive renewables such as solar have also been adversely affected.

In the long term, nuclear power's economic competitiveness could significantly increase if *externalities* - the considerable indirect and external environmental costs of energy generation and use not usually included in the market price of energy - were weighed. Indirect costs, such as for waste management and decommissioning are already components of nuclear generation costs. For fossil fuels, these costs are not yet fully included and could become significant under more stringent environmental policies.

There would be even greater impact if external costs for local and regional health and environmental impacts were included, perhaps through more stringent regulations or the ecological surcharges some countries already use in the transport and industrial sectors. For nuclear power, most environmental externalities have essentially been internalized in the generating costs by the imposition of numerous costly systems that prevent virtually all radioactive material including waste from entering the environment.

3.8. Carbon tax

With international commitments in place to reduce global greenhouse gas emissions, economic instruments could be considered. Such instruments could include so called carbon trading that in essence allows emission reductions to be accomplished by a third party at a price - a difficult mechanism at the global level - or a more direct carbon value tax.

A carbon value would favor less carbon intensive fossil fuels, particularly natural gas but nuclear, hydroelectric and some renewable systems would be unaffected. To illustrate, if coal generated electricity were 20% cheaper than nuclear, addition of a carbon value of $30 per ton to a coal price of $60 would eliminate the advantage. If natural gas generated electricity were 40% cheaper than nuclear, a carbon value of $200 per ton would make nuclear power competitive.

3.9. Environmental costs

The assessment of environmental externalities must include the entire fuel chain and consider occupational as well as public effects on a local, regional and global scale. For equivalent amounts of energy generation, coal and oil plants, due to greater emissions and fuel and transport requirements, have the highest external costs and equivalent lives lost. The external costs are some ten times higher than for the nuclear power plant and can be a significant fraction of generation costs.

For nuclear power, the impact of routine radioactive releases is negligible and occupational exposures are very low due to small mining requirements. Severe accident impact could be expected to have a great effect on externalities. However, an infrequent event has a small impact per unit of energy generated as its consequences are proportionate to the total amount of energy generated during a period without a severe accident. For example, the Chernobyl accident's projected consequences of 3,500 cancer deaths late in life must be apportioned to the 442 reactors that have operated to date, on average for 20 years each.

4. CONCLUSION

For over 40 years nuclear power has contributed significantly to world energy needs, by providing more than 6% of primary energy and 17% of global electricity. Low environmental impacts and a vast fuel resource potential should allow it to contribute substantially to meeting the sustainable energy challenge. But today's energy planners are confronted by public apprehension about nuclear power and unrealistic expectations for new energy sources. Will future generations applaud us for retarding and perhaps even abandoning nuclear power, or will they condemn us for not fully utilizing it? Clearly, in view of nuclear power's contribution to date and its significant potential, it should be fully considered. Comparative assessments of energy options will help to clarify the issues limiting its full use.