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Nuclear Energy Risks and Benefits in Perspective

1. Background Issues of World Energy Demand

World energy demand continues to increase in an apparently inexorable manner. The OECD International Energy Agency's *World Energy Outlook 2006* [1] shows that demand increased from around 5500 Mtoe (million tons of oil equivalent) in 1970 to around 11 200 Mtoe in 2005, i.e. more than doubled (*Figure 1.1*). It also predicts that, on current world governments' policies, it will continue to increase, reaching about 17 400 Mtoe by 2030, a further increase of 65% over 2005 levels and a factor of more than 3 above the 1970 levels. Looking further ahead, the OECD IEA's *Energy Technology Perspectives 2006* [2] predicts that world energy demand will have doubled again, above 2005 levels, by 2050.

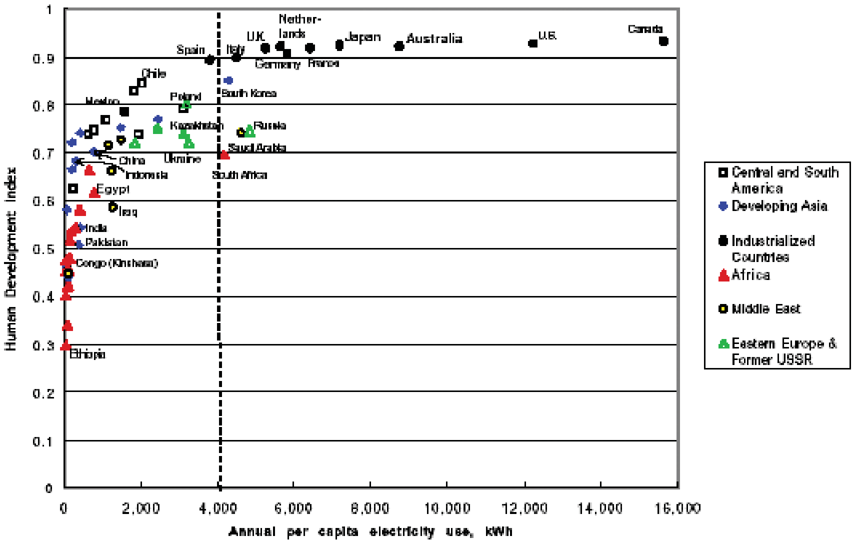
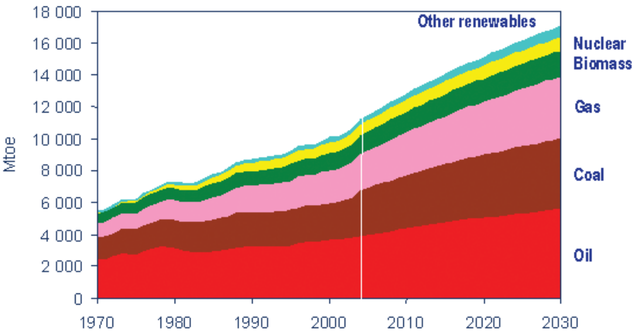


Figure 1.3 - Correlation between electricity use and HDI (Pasternak, 2000)*
Source: In [3] taken from Pasternak, A. D. (2000), *Global Energy Futures and Human Development: A Framework for Analysis*, Lawrence Livermore National Laboratory Report UCRL-ID-140773, Los Alamos, United States.
* The UN Development Index (UNDP, 2000) combines measures of infant mortality, life expectancy, food supply, literacy rate, educational opportunities and political freedom.

Electricity demand, as a component of the overall demand, is continuing to grow at an even faster rate, as the world's economies continue to progress their level of development. The *World Energy Outlook 2006* predicts that electricity demand will have increased by 100% by 2030 and the *Energy Technology Perspectives* publication, that it will have reached 260% of the 2005 value by 2050.



Global demand grows by more than half over the next quarter of a century, with coal use rising most in absolute terms
Figure 1.1 - Reference scenario: World primary energy demand [1]

Why is this happening? Fortunately, the world is becoming a better place in which to live for most communities (*Figure 1.2*). World income has been rising steadily. Despite an increasing world population, income per capita has also been rising steadily and, not surprisingly, this is closely related to the total primary energy supply. While the energy intensity of global production has fallen significantly, it has only been enough to offset the increase in income per capita.

As for electricity use, as the IPCC study says, "Electricity is the highest value energy carrier because it is clean at the point of use, and can be used in so many end-use applications to enhance personal and economic productivity." Increased availability of electricity has a strong impact on the quality of life in developing countries (*Figure 1.3*).

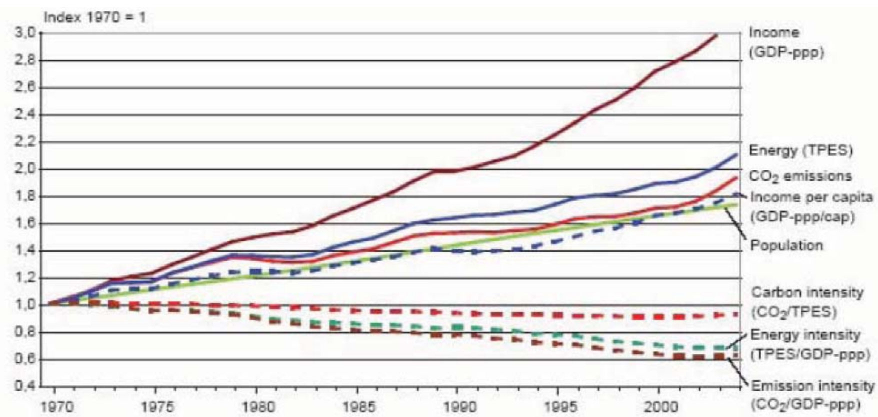


Figure 1.2 - Intensities of energy use and CO_2 emissions, 1970-2004
Source: IPCC Working Group III Fourth Assessment Report, Chapter 1 - taken from IEA data

Furthermore, there is no real evidence that the growth in electricity demand will slow down as economies become more developed (*Figure 1.4*).

Figure 1.2 also shows what has been happening to CO_2 emissions. While the

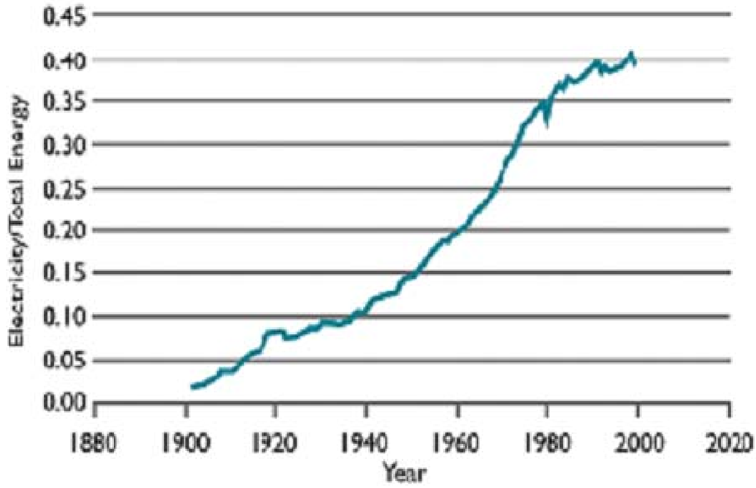


Figure 1.4 - Ratio of electricity to total primary energy in the US since 1900

Source: IPCC Working Group III Fourth Assessment Report, Chapter 4 [taken from EPRI 2003]

carbon intensity of Total Primary Energy Supply (TPES) has improved a little, and emission intensity of Gross Domestic Product (GDP) has fallen more, CO_2 emissions have followed closely in line with population, GDP/capita and TPES. *Figure 1.5* enables this to be seen in terms of the various forms of energy use. For energy related emissions, it is abundantly clear that electricity generating plants are by far the biggest culprit in terms of emissions growth. They are twice the next largest energy contributor, and are growing much faster. Road transport, which has attracted a great deal of media and political attention, is only half the size and is growing more slowly, though it is the second fastest growth area. International transport, including aviation, which has also attracted a great deal of attention, seems in reality to be one of the lesser concerns on a global scale.

Power plants are clearly **THE** big issue. This is not to say, of course, that the other sectors do not merit attention, but it would seem that unless the emissions from power plants are addressed, we cannot really hope to have a significant impact on emissions reduction. Nuclear power can clearly have a role here, but it remains a relatively minor player at present, contributing 16% (25% in the more developed economies of the OECD) of world electricity production and only 6% of TPES. Its growth has been curtailed by its contentious nature with politicians and their publics. In this respect, the OECD Nuclear Energy Agency (NEA) recently published a significant study to assist policy makers by providing tools and data to achieve a balanced perspective [3]. Much of the remainder of this paper will refer to studies collected in that publication.

2. Implications of climate policy and the role of carbon-free technologies

Recently a goal has been proposed by the European Union to set a limit to global warming at plus two degrees Celsius as compared to pre-industrial conditions. Such an increase, which is considered acceptable from a climate change view point, would require a reduction of CO_2 emissions by 50% to 80% compared to the level expected at 2020, when it is hoped that carbon emissions can be made to peak and then turn down. Such reductions should be implemented by 2050.

The Kaya equation provides a simple relation between CO_2 emissions, population (N), production per capita (GDP/N),

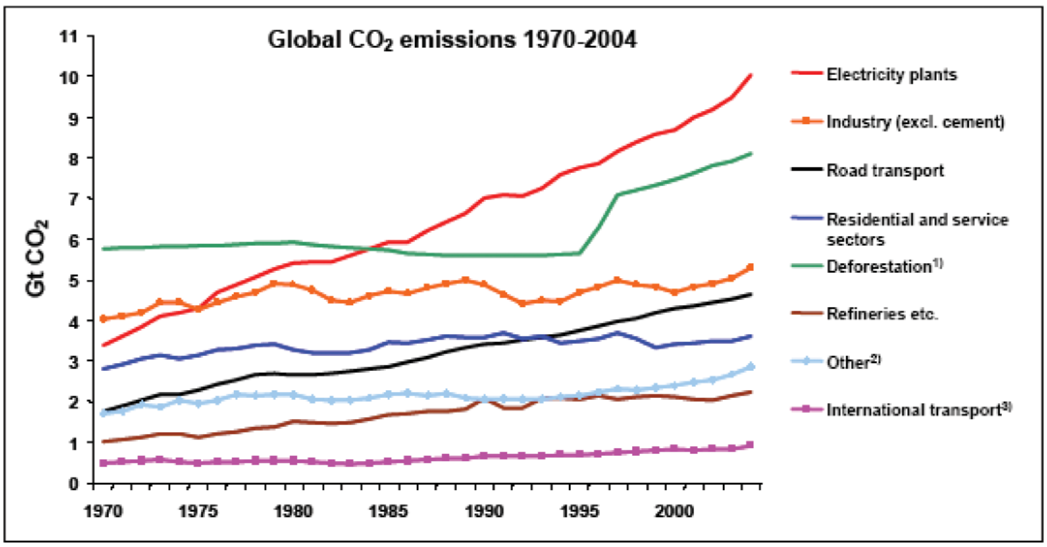


Figure 1.5 - Sources of global CO_2 emissions, 1974-2004 (only direct emissions by sector)

Source: IPCC Working Group III Fourth Assessment Report, Chapter 1.

1. Including fuel wood at 10% net contribution. For large-scale biomass burning averaged data for 1997-2002 are based on Global Fire Emissions Database satellite data (van der Werf et al, 2003). Including decomposition and peat fires (Hooijer et al, 2006). Excluding fossil fuel fires.
2. Other domestic surface transport, non-energetic use of fuels, cement production, and venting/flaring of gas from oil production.
3. Including aviation and marine transport.

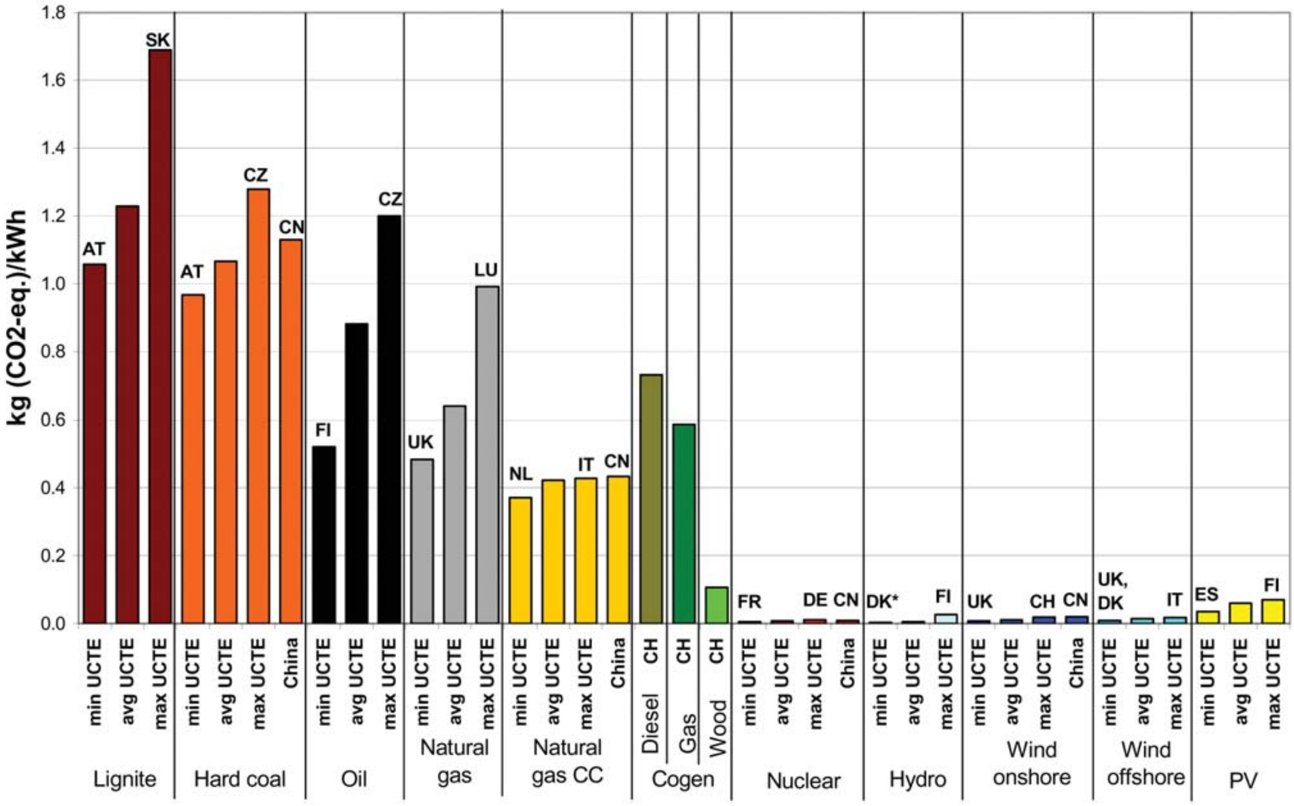


Figure 3.1 - Greenhouse gas emissions of selected energy chains

energy intensity of the economy (E/GDP) and carbon content of energy (C/E):

CO_2 emissions = N x (GDP/N) x (E/GDP) x (C/E)

Assuming that a reduction by 50% of CO_2 emissions would be adequate and considering the individual terms in the Kaya equation the following findings may be highlighted:

• Population is projected to grow by a factor of 1.5 (IPCC, 2000). This means that, to reach the goal, the product of the remaining three terms needs to be reduced by a factor of three.

• The world GDP per capita may be assumed to grow by 1% per year (this is an extremely modest growth having in mind the historical developments, and in particular trends in countries with the largest populations i.e. China and India). As a result of such growth, the product of the two remaining terms needs now to be reduced by a factor of five in order to reach the goal.

• Energy intensity may be assumed, rather optimistically to fall by 1.8% per year. This corresponds to the overall term reduction by a factor of 2.5. Thus, the remaining term needs now to be reduced by a factor of two.

• Reducing carbon intensity of the world energy system by a factor of two is a tremendously ambitious undertaking. Under less optimistic assumptions the reduction of carbon content would have to be even more drastic. Under all circumstances, moving towards the postulated goal would require an expansion of the nearly carbon-free technologies, i.e. renewable sources and nuclear.

Much is made in government policies and in the literature of the need for energy efficiency. Like motherhood and apple pie, one cannot argue that energy efficiency is not important; it clearly is and we must clearly do all that we reasonably can to improve it. However, it is often presented as a solution to the problem. This is an artefact of looking at what can be done at fixed points in time (e.g. 2030, 2050 etc.). Unless one believes (and can prove!) that world energy demand will cap out somewhere, energy efficiency, worthwhile though it is, only buys us time to find a real solution, almost certainly technological.

Assume that, overnight, we could make an energy efficiency saving of 10%. TPES is growing by around 1.9% p.a. In less than 6 years we would be back to the same level. Be more ambitious and improve overnight by 20%; in less than 12 years we would be back to the same level. This is not to say that we should not seek such improvements; we should. It is to say that we should use the time gained to seek the technology developments needed to provide the real answers. If we delude ourselves into believing it provides an answer in itself, we will waste the time benefit that we have gained.

3. Greenhouse gas emissions

Now let us move on to greenhouse gas (GHG) emissions. *Figure 3.1* shows the analysis reported in [3] for full life cycle emissions from various means of generating electricity. The vertical axis is expressed in normalised kg CO_2 equivalent, taking into account the warming potential of each gas. All figures shown refer to the member countries of UCTE (Union for the Co-ordination of Transmission of Electricity the association of transmission system operators in

Table 1 - Lifetime of uranium resources (years)

Technology	Identified ** resources ~4.7 MtU	Total** conventional resources ~14.8 MtU	Total conventional resources plus phosphates ~36.8 MtU
LWRs once through	85	270	675
Progressive introduction of FBRs*	4 250	13 500	33 750

* Here it is assumed that the progressive introduction of fast breeder reactors (FBRs) multiplies by 50 the amount of electricity generated by 1 tonne of uranium.

** See reference [4] for an explanation of Identified Resources, Total Conventional Resources, etc.

continental Europe) in year 2000, namely: Austria, Belgium, Bosnia-Herzegovina, Croatia, Denmark (associated member), France, Germany, Greece, Italy, Luxembourg, Former Yugoslav Republic of Macedonia, the Netherlands, Portugal, Slovenia, Spain, Switzerland, and Serbia and Montenegro. (The CENTREL countries - Czech Republic, Hungary, Poland and Slovak Republic - officially joined UCTE in 2001). GHG emissions of nuclear and renewable energy are between one and two orders of magnitude below emissions from fossil generation chains. UCTE averages are about 5g CO_2 eq./kWh for hydro and 8g for nuclear, 11g for onshore wind, 14g for offshore, 60g for photovoltaics and 100g for wood co-generation.

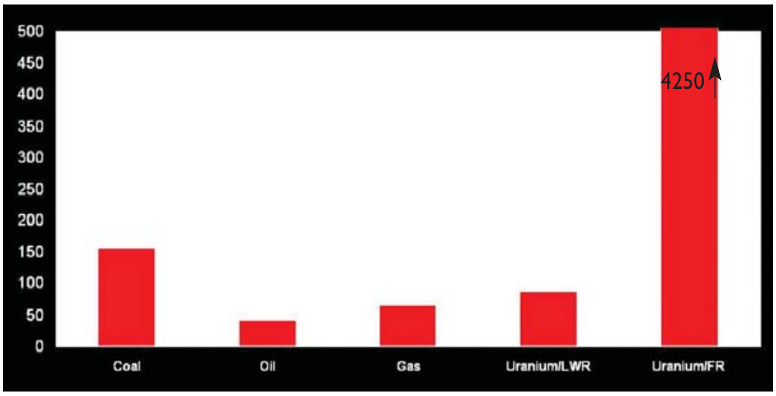


Figure 3.3 - Lifetime of fuel resources (years)*

* Identified resources i.e. these resources for which there is already confidence that they are exploitable at reasonable price.

Those in the nuclear community might believe that this benefit of nuclear power is well known to all. In fact, the recent Eurobarometer study shows that some 40% of the EU population still do not appreciate this, with non-nuclear countries having higher percentages (*Figure 3.2*).

Some anti-nuclear commentators suggest that we will soon run out of high-grade uranium ores and that the life cycle emissions advantages of nuclear will then disappear as uranium extraction becomes much more energy intensive. There is no evidence that we will do so [4]. *Figure 3.3*, taken from data in [3], shows that the reserves-to-production ratio for uranium is significantly larger than for oil or gas. In all cases, industry does not dissipate significant exploration expenditures too far in advance of need.

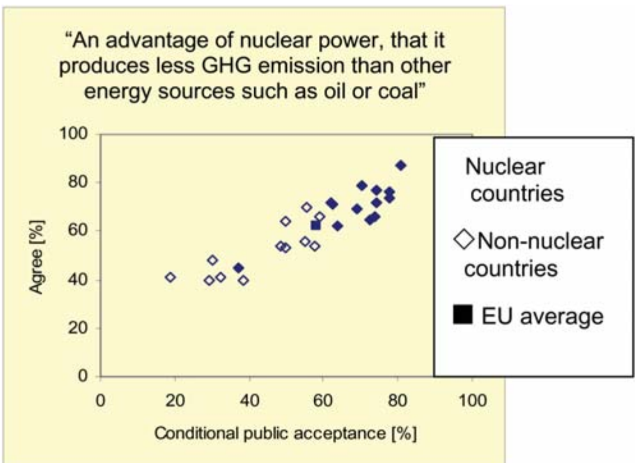


Figure 3.2 - Public knowledge on the CO_2 free nature of nuclear energy

Note: Conditional Public Acceptance is the percentage of the population which would support nuclear power if they considered the waste disposal issue resolved.

Further, in the event of a significant expansion of nuclear power, *Table 1* shows that progressive introduction of FBRs, multiplying the energy extractable from a given quantity of uranium by a factor of 50 or more, expands the energy availability dramatically. Given that nuclear power contributes currently 6% of TPES, the uranium already known to exist in conventional and phosphate resources can quickly be shown to have the energy equivalent of 2000 years of current TPES, largely CO_2-free.

Indeed, the spot price of uranium has risen from the historic lows of the last two decades to a point where commercial extraction of the very small amounts of uranium residing in coal ash is under serious consideration. If the extracted uranium were to be used in fast reactors, it would produce more energy than the coal from which it was derived. A thorium fuel cycle is also possible, but has not been commercially developed thus far. Thorium is some three times more abundant in the earth's crust than uranium.

There does not appear to be any shortage of virtually CO_2-free energy, should we choose to use it.

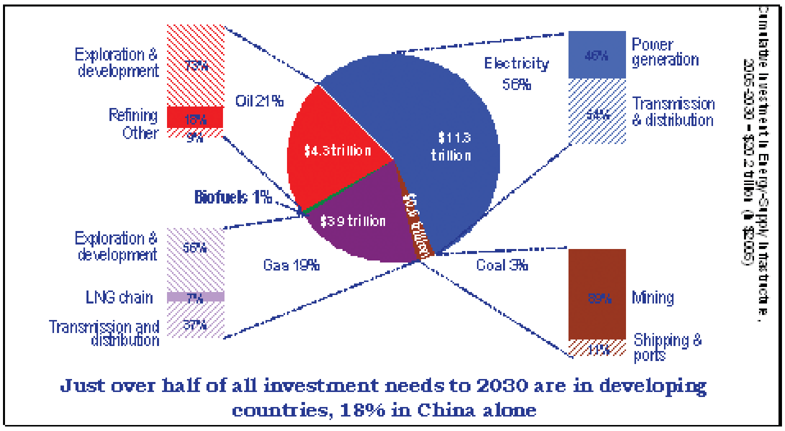
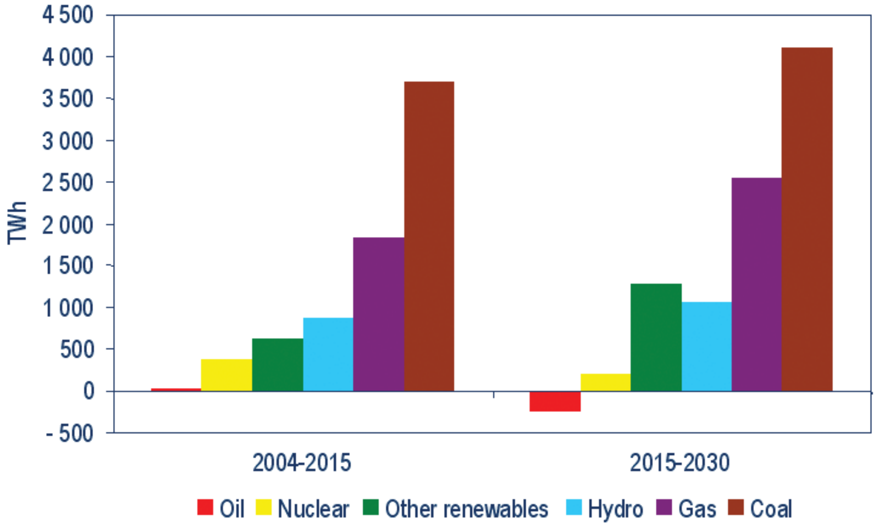


Figure 4.1 - Investment needs in energy systems up to 2030



Most of the additional demand for electricity is expected to be met by coal, which remains the world's largest source of electricity to 2030.

Figure 4.2 - IEA Reference Scenario: World incremental electricity generation by fuel

4. The need for new power plants - an opportunity and a threat

The *World Energy Outlook* [1] explored the need for investments in the energy sector up to 2030 (*Figure 4.1*).

Some US$5 trillion will need to be invested in power plants over that period. Given that such investments have typical economic lives of 40 years or so, their normal turnover rate is very low. Here then, is a major opportunity to invest in low emissions plants for the future. Alternatively, if fossil fuel plants are constructed, they will lock the world community into their continuing emissions up to 2050 and possibly well beyond (it is possible that carbon capture and storage (CCS) could alleviate this if the technology is developed and demonstrated at commercial scale and fossil plants are built as "CCS ready" for future back fitting). On current government policies, *Figure 4.2* shows that the vast majority of new power plants will be fossil fuel based. Clearly, this will not achieve the desired outcome if climate change objectives are to be met, and government policies will need to change quickly in order to do so.

5. Risks and benefits of nuclear generation - some examples

The recent NEA publication [3] has the objective of providing policy makers with authoritative information in support of their decision making. It covers quantitative and qualitative aspects of risks and benefits of nuclear energy encompassing economic, social and environmental aspects. It includes a significant number of illustrative comparisons of nuclear and other options for electricity generation and it examines techniques by which a wide range of such factors can be weighed and balanced in an overall assessment.

In the space of this paper, it is not possible to illustrate all areas and only a small selection will be provided here. The benefits in terms of GHG emissions reduction have already been explored in section 3 above. Reference [3] also deals with the costs of nuclear generation, more fully explored in [5]. Suffice it to say that nuclear is cost competitive in many countries without an effective cost for carbon releases, and is therefore even more so when and where a carbon change is levied.

5.1 ACCIDENT RISKS

A continuing concern for the public and politicians is the safety of nuclear generation. Reference [3] uses data from ENSAD (Energy-related Severe Accident Database) established by the Paul Scherrer Institute in Switzerland, to explore this concern. ENSAD contains data on over 18 400 accidents, mainly from 1969-2000, of which 35% are energy related, 3117 of which are rated as severe (with 5 or more prompt fatalities). *Figure 5.1* shows frequency/consequence curves for this data, for OECD countries. The data for LPG, coal, oil and natural gas are data from real accidents, for full life cycle analysis. During this period there has only been 1 severe hydro power accident in OECD countries, resulting in 14 prompt fatalities. There have been no OECD nuclear accidents in this "severe" classification.

To enable some comparison, *Figure 5.1* also shows the probabilistic safety analysis (PSA) for a Swiss nuclear power plant. Note that this line is not directly comparable, in that it is for the latent deaths (cf. prompt deaths for other data) from theoretically possible releases (not actual releases or accidents). From this Figure, it is clear that nuclear energy is

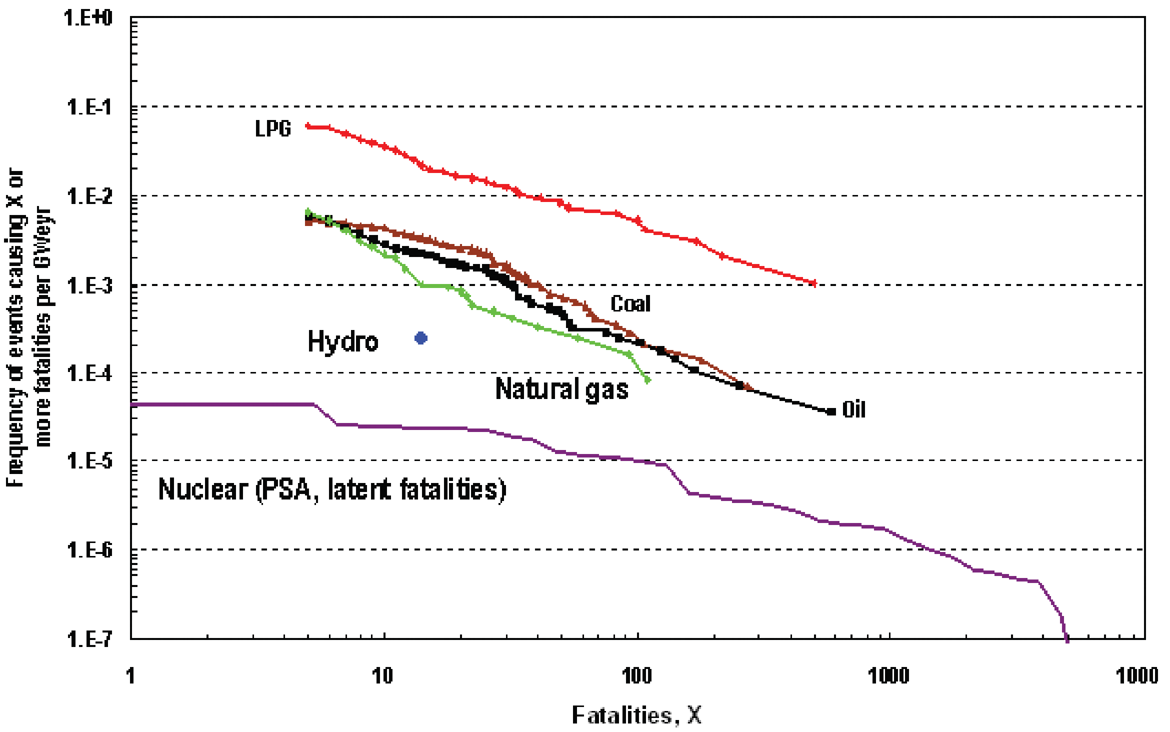


Figure 5.1 - Comparison of frequency-consequence curves for full energy chains in OECD countries for the period 1969-2000

much safer, in comparison with other energy sources, than the public would believe. In OECD countries, both hydro and nuclear are much safer than other sources.

This particular plot could be subject to criticism from a number of positions. In choosing OECD countries, it ignores Chernobyl; but Chernobyl, severe as it was, only caused 40 or so prompt deaths. The biggest energy related accidents elsewhere were caused by oil (Philippines, 1987 - 3000 fatalities; Afghanistan 1982 - 2700 fatalities), hydro (India, 1980 - 1000 fatalities) and LPG (Russia, 1989 - 600 fatalities). It could be criticised for ignoring the latent death estimates from Chernobyl; but in that case it should also include latent deaths from both operation and accidents, and fossil technologies come out quite badly (see section 5.2).

Why then, does nuclear seem to hold a unique fear on safety in the public mind? This is not the place to conduct a detailed consideration, and neither do I have the competence to do so, but it must be some combination of the association with nuclear weapons, the fear of very low probability, but very large, accidents, the fact that latent deaths are associated with cancer, a disease much feared in its own right (and cancer can affect "me"; whereas oil and gas accidents generally impact those working with the industry, except for the huge accidents), and the publicity that nuclear attracts because of these factors. Almost everyone remembers Chernobyl and even Three Mile Island (no prompt fatalities). Who remembers (or ever heard of) the oil, hydro and LPG accidents listed above, which occurred around the same time and directly killed thousands?

5.2 HUMAN HEALTH IMPACTS FROM NORMAL OPERATION

Human health impacts due to normal operation may be represented by "mortality", defined by reduced life expectancy calculated in terms of Years of Lost Life (YOLL). (Morbidity can also be assessed, but presents much greater difficulties in objective assessment). Reference [3] shows, by way of example, an analysis of mortality resulting from the emissions of major pollutants specific to German energy chains, as shown in *Figure 5.2*. Nuclear, wind and hydro have very low mortality due to normal operation. Mortality for natural gas and solar PV are somewhat higher and similar, and other fossil systems are significantly higher. It is worthwhile noting that, for all chains, mortality due to accidents (discussed in 5.1 above) is practically negligible compared with the corresponding effects of normal operation. Again this does not seem to be widely understood by the public and by decision makers.

5.3 DECISION MAKING AIDS

Two decision aiding techniques are explored in [3]: internalisation of external costs and multi-attribute decision analysis. An eternality exists when some negative or positive impact is generated by an economic activity and imposed on third parties without being priced by the market [6]. If the inventory of externalities could be exhaustive and if their value could be estimated in an accurate and reliable manner, the internalisation of external costs would lead to the best choice. Unfortunately, those two conditions can seldom be fully met. Nevertheless, the technique is of value if it can capture reasonably reliable key components.

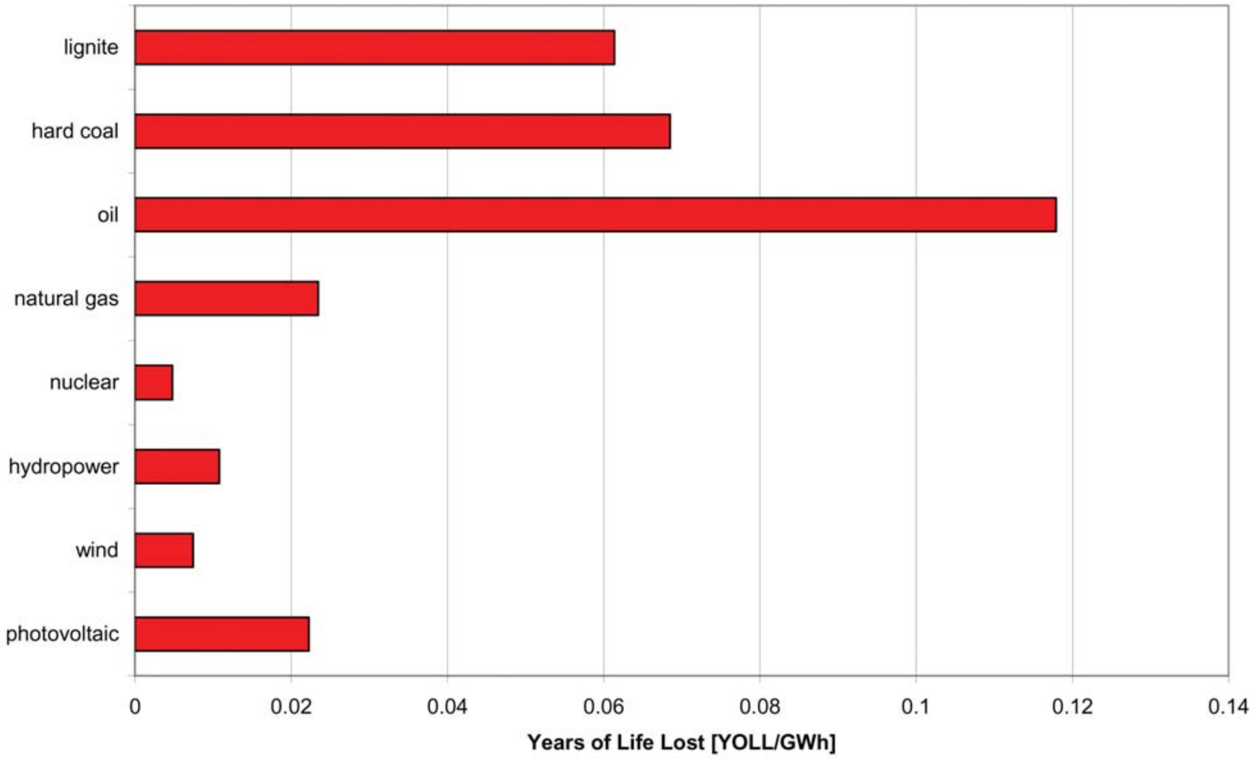


Figure 5.2 - Mortality associated with normal operation of German energy chains in the year 2000

Figure 5.3, taken from [3], shows an analysis of total (i.e. internal and external) costs for electricity generation in a province of China. All results in the figure include the contributions from the entire energy chains. Nuclear has the lowest total cost. It is interesting to note that conventional coal without flue gas desulphurisation (FGD), which corresponds to the current situation, has a rather low internal cost but the highest total cost.

Multi-criteria decision analysis can be used as a separate decision aid, or as a complementary technique. It enables a more extensive representation of social criteria, but these are the most difficult to define, select and measure and are therefore the most controversial. Examples are discussed using three branches of impact factors (those factors which are evaluated and weighed against each other), economic, environment and social factors. In general, only if very high

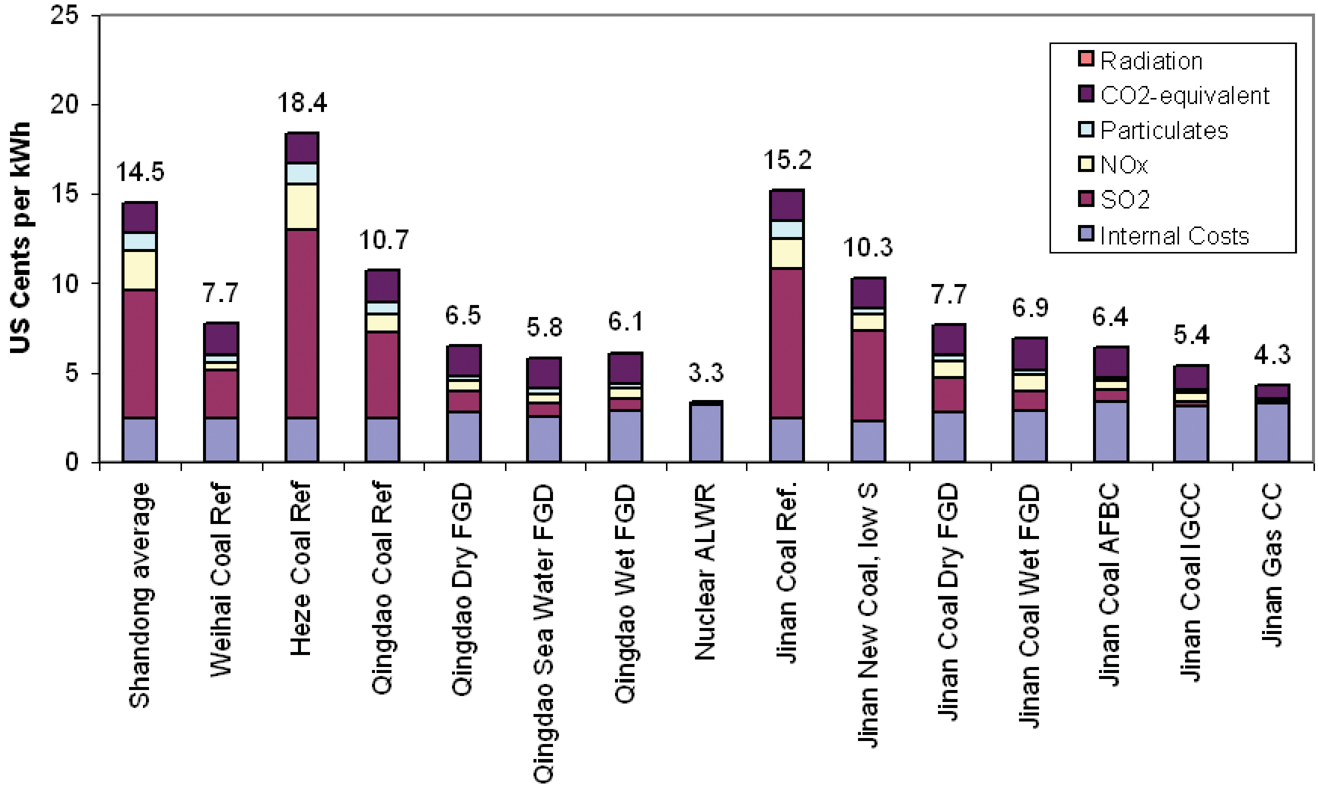


Figure 5.3 - Total costs of electricity generation in Shandong Province of China

weight is given to social factors (e.g. aversion towards hypothetical severe accidents) does the analysis show that nuclear power is not in the group of the most advantageous generating technologies. Many of these social issues remain controversial and, depending on the socio-political perspective of those involved, can be of paramount importance. Otherwise, with balanced weightings or with heavy emphasis on environmental or economic issues, nuclear power regularly ranks amongst the best generating technologies available.

Conclusions

• The world's energy problems are serious. Power plants are the biggest and fastest growing contributors to GHG releases. They are already twice the size of the next largest sector for energy consumption.

• Due to the rapid growth in energy demand in developing countries, and the need to replace the ageing stock of power plants in developed economies, some US$5 trillion will need to be spent over the coming two decades. This provides an excellent opportunity to invest in largely GHG-free generating capacity. Governments must act decisively if this opportunity is not to be missed.

• Nuclear electricity is virtually CO_2 free and, in principle at least, there are vast amounts of energy available if the nations of the world decide to use it. We already know of available uranium which has the energy equivalent of 2000 years worth of the current global total primary energy supply.

• However, nuclear energy remains contentious in many countries. The OECD NEA has recently published a study, *Risks and Benefits of Nuclear Energy* [3], with the objective of providing policy makers with authoritative information in support of their decision making. Examples from this work have been presented in this paper.

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