Nuclear issues evaluation based on rational risk-benefit consideration

UJITA Hiroshi[1]

1. The Canon Institute for Global Studies, 11F, Shin-Marunouchi Bldg., 5-1 Marunouchi 1-chome, Chiyoda-ku, Tokyo, 100-6511, JAPAN (ujita.hiroshi@canon-igs.org)

Abstract: When looking at the discussion after the Fukushima accident, there has been wide discussion of the dichotomy of promotion or abolition of nuclear power plants. However, it is important that such discussion be based on a rational risk and benefit comparison. Both the environmental risk (CO_2, dust, SO_x, NO_x) and the accident risk of nuclear power are low compared with those of other energy industries. On the other hand, benefits are comparatively high: effective mitigation of global warming due to no CO_2 emissions, effective improvement of energy security due to domestic and stable power supply, and the high economic benefit because of the high energy density. Breeder reactors with plutonium 239 usage are expected to have 100 times longer life than the 100-years of resource available with only uranium 235 as used in current light water reactors. Thus, breeder reactors will be able to secure the energy resources of more than 10,000 years, and it is such drastic measures that are needed for long-term global warming mitigation and energy resource issues from the viewpoint of intergenerational equity or the precautionary principle.

Keyword: nuclear safety concept; probabilistic risk assessment; risk benefit analysis; long-term asset

1 Introduction

In any engineering system, problems should be evaluated and debated on the basis of the reasonable risks and benefits associated with technologies or actions. Rather than the discussion of the risks and benefits of a single technical system, it is effective to mutually compare the risks and benefits of many alternative technical systems in the same industry. For example, as shown in this paper, the risk of nuclear power is low compared to other energy industries, and has high benefits, while social acceptability is low.

Critical infrastructure, such as the energy supply system, must be considered as a grand plan for the long‐term future of the nation, and therefore a rational risk benefit assessment is required. However, it is widely acknowledged that just presenting statistical or scientific evidence does not necessarily convince the public – particularly on issues as emotive as nuclear power, where the presentation of positive statistics can be received skeptically by the public. Here, the three broad kinds of primary energy are discussed - comparing renewable energy, fossil energy and nuclear energy – in an effort to present some of the important data that can support such public debate.

First, the problems in the nuclear field are discussed in Chapter 2, Risk-Benefit Comparison is described in Chapter 3, the discussion is then extended to Long-term asset evaluation of energy systems in Chapter 4, and then Discussions and Conclusions follow.

2 Nuclear policy in Japan

After March 11, 2011 and the subsequent Fukushima Daiichi Nuclear Power Plant Accident, long term nuclear policy is still undetermined, and the following problems have arisen:

(i) CO_2 emissions from energy have increased, and the energy security decreased due to the reduction in the quasi-domestic power generation rate with thermal power stations substituted for nuclear,

(ii) The outflow of national wealth, technology industry force degradation, and the electricity prices increasing, and

(iii) The continued evacuation from contaminated areas.

In 2012, the Nuclear Regulation Authority was established to reinforce nuclear safety regulations for all nuclear facilities in Japan. And the new nuclear

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regulatory body has issued strengthened nuclear safety standards in order to permit the restart of existing light water reactor plants in Japan. In response to the new safety standard, power companies have been implementing a variety of measures, but it is still unclear whether the installed new measures will really be effective or on the contrary, whether some measures are in excess of actual requirements. Therefore, rational and quantitative risk evaluation is required in the consideration of this problem.

Safety philosophy is composed of a number of major components: safety assumptions (definition of the event), safety design (hardware), safety operation (software), and safety social system (system design). Reflecting on an accident, it is desirable to comprehensively reconstruct the safety philosophy using quantitative and rational thinking. What is needed now is to put priority on clarifying the policy of nuclear power`s position in the energy system. In the nuclear field, based on the lessons learned from the accident, it is necessary to rebuild the safety concept including a more resilient system, and also to clarify once more the nature of the nuclear industry.

The dichotomy of abolition versus promotion of nuclear power plants is often heard among people in the street, but fundamentally such discussion should be included in energy policy based on reasonable risk and benefit discussion. In general, it is said that three aspects of usefulness, safety and security are necessary for the acceptance of the technical systems. This means that there are a trade-off of benefits and risks. However, this is often difficult to assess and convey to the public or policy makers in a manner that enables rational consideration – and indeed the emotional impact of certain technologies may be more important in general public opinion, regardless of the information at hand.

3 Risk-benefit comparison

3.1 Primary energy source

Three broad categories of primary energy are considered, with their origins as follows [(2)]:

(1) Fossil fuels such as Coal, Oil, Natural gas, which originated as plants, algae *etc.* hundreds of millions of years ago. These plants were in turn originally produced by solar energy that was incident on Earth and was originally generated from nuclear fusion occurring in the sun.
(2) Nuclear fuel, originally a geologically-derived element of the Earth, based on fission process providing energy in proportionality through Einstein`s equation, $E=mc^2$.
(3) Renewable (natural) energy, basically originating from solar energy and converted through physical or biological processes.

The first two of these are categorized as stock type primary energy, while the third (renewable) energy is flow type. Every primary energy source can be eventually traced-back to the Big Bang or Supernova explosion in the Cosmos. The first and third are derived from solar fusion energy, while the second is from fission energy on Earth.

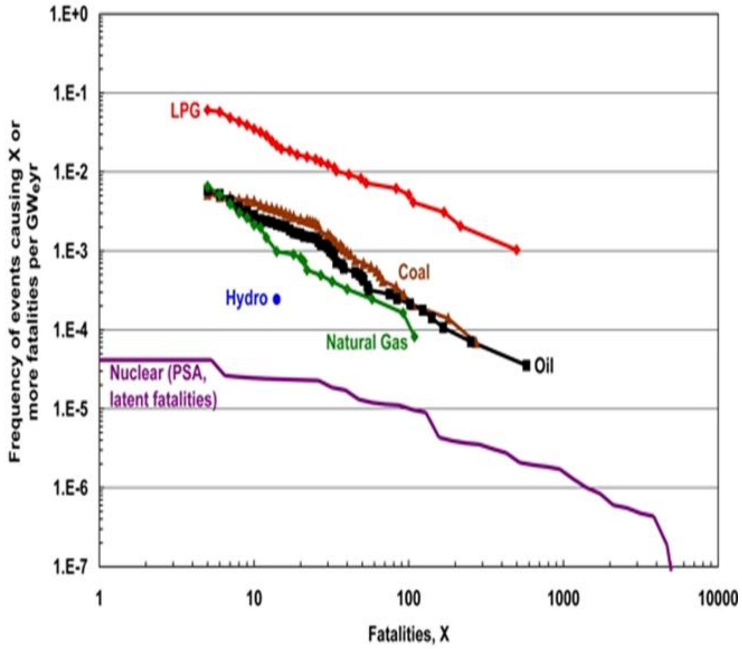
3.2 Risks and benefits

When looking at the discussion after the Fukushima accident, there is much use of the dichotomy of promotion-abolition of nuclear power plants, although ultimately it can be argued that the decision should be made based on the rational comparison of risks and benefits. Both environmental risks (CO_2, dust, SO_x, NO_x) and the accident risk of nuclear are also low compared with those of other energy industries. On the other hand, benefits are comparatively high: it is effective against global warming due to no CO_2 emissions, effective for energy security due to the associated domestic and stable power supply, and high economy also because of its large energy density [(3-4)].

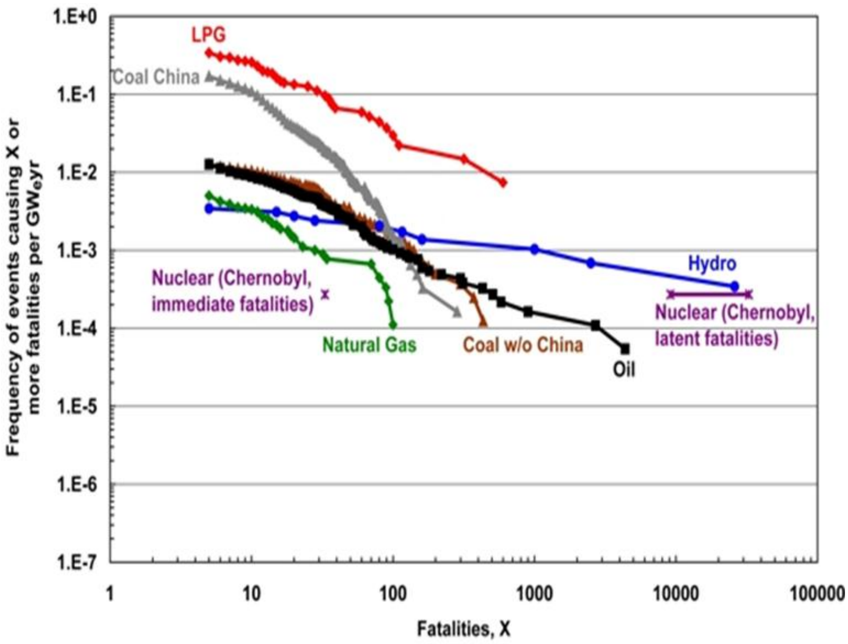
Other energy sources also have both risks and benefits. Therefore, we should evaluate energy sources role by examining various indices of risk and benefit. The following sections provide comparisons of risks and benefits among energy resources.

3.3 Risk

The risks associated with energy sources can be categorized as environmental and human (health and safety). According to a comparison reported in the literature [5], the waste generated in the use of fossil energy from coal, oil, natural gas, and wood is 0.5, 0.27, 0.21, and 0.1 million tonnes per GWe yearly, respectively. On the other hand, the wastes generated by nuclear energy and solar energy are only around 0.01 million tonnes per GWe yearly, respectively (solar is slightly lower, and the waste is actually likely to be generated in the construction phase rather than the operations phase, making the comparison not strictly valid). The amount of waste from fossil fuel is overwhelmingly high due to flue gas desulphurization, ash, or gas sweetening. The literature [5] also reports the environmental risks for fossil energy and nuclear energy.



OECD countries



non-OECD countries

Fig.1 Frequency-Consequence curves for severe accidents in various energy chains OECD: 1969-2001 [6].

The health risks for coal, oil, and gas are 0.37, 0.22, 0.09 YOLL/GWh (years of life lost) due to the high risk associated with emissions of NOx or SOx. The risk estimated for nuclear energy is 0.02 YOLL/GWh, and is associated with cancer risk. In this case, operational activities are only considered, and there are no considerations of the full supply chain. The risk of accidents from the operation of different power plants are compared in Fig. 1, which shows the frequency of fatalities (6) averaged and expressed per year of operation of 1GWe capacity. All figures except for nuclear power in OECD countries are based on the actual values. If we look only at the OECD countries, it is not possible to draw a risk curve for nuclear power because deaths have not occurred in these countries. Nuclear is the only industry forced to perform the safety evaluation by using a probabilistic risk assessment method. Acute deaths due to the Chernobyl accident is point data, but the actual mortality estimates by late-onset cancer which cannot be identified are also shown in the figure. Looking at the non-OECD countries, as well as in consideration of the Chernobyl accident, it can be seen that the nuclear accident risk is lower than other energy industries. Because the data of China's coal mine accidents have been abnormally high, these are then separated out.

Despite being statistically safer, nuclear public acceptance is low, as there is a cognitive bias with humans against such rare extreme or intangible risks (7), for instance radiation or O157 has been widely reported by the media, causing public panic. In fact, the psychological risk due to evacuation is considered to be much larger than radiation risk, according to the lessons learnt from Chernobyl Accident (1). On the other hand large suicide and traffic accident risks which present a more imminent and tangible threat, should be of more concern, but perhaps are too commonplace to warrant it.

3.4 Benefit

Compared with the impacts, nuclear power benefits are overwhelmingly high compared to other industries as follows:

(1) <u>Global warming</u>: In the literature (8), the CO_2 emission intensities for various electric energy sources are compared. The emission intensities of coal-fired, oil-fired, LNG, and LNG combined cycle electricity generation are 975, 742, 608, and 519 g-CO_2/kWh respectively. On the other hand, the CO_2 emission intensities of renewable energy sources are smaller than 53 g-CO_2/kWh which is mostly associated with construction of facilities and maintenance operations. The intensities of PWR and BWR plants are reported as 25 and 22 g-CO_2/kWh for their facilities and operations. (Although it should be noted that such figures are contested.) Since nuclear power generation in principle is a largely carbon-free power generation technology, CO_2 emission reductions by replacing fossil fuels can also be considered a benefit. If electricity and hydrogen are introduced as transport energy, nuclear power is also a favorite for carbon-free energy carrier supply.

(2) <u>Energy profit ratio</u>: Energy resources require the energy to be extracted in order to utilize it. The ratio between energy output and input is called the EPR, energy profit ratio (9). Most of renewable energy sources have an EPR below 5 although hydro and geothermal have high EPR of 15.3 and 6.80, respectively. On the other hand, fossil fuels have EPR of 6.55, 7.90, and 2.14 for coal, oil, and LNG, respectively. A ratio of 5-10 is posited as the lower limit for utilization as an energy source, while for nuclear the EPR is around 17.40 (9).

(3) <u>Energy intensity</u>: Fuel transport and fuel savings are easier (10) for nuclear because of the very large energy density as shown in Table 1, and hence nuclear power is considered quasi-domestic.

(4) <u>Energy security</u>: The IEA reports that the Japanese energy self-sufficiency ratio was only 4%, or 16% accounting for nuclear power as a domestic source in national policy (11) comparing poorly with the ratios of Canada, UK, and USA which exceed 60%. Moreover, since power generation from nuclear fuel is large, it is possible to provide a stable supply of power.

(5) <u>Economic efficiency</u>: Because of the large amount of power generation and the high energy density, fuel costs are cheap, and economy is also high.

Table 1 Power density for each electric power source [10]

Candidate	Power density per square meters [kWh/(m^2 year)]	Remarks
Electrical needs in house	35	Detached house (160 sq.m. 40A)
Electrical needs in office	400	Eight-story (architectural area 3,000 sq.m.)
Biomass power	2	Polar plantation (6 years-cycle) Generating efficiency 34%
Wind power	21	Tehachapi (U.S.A.) Capacity factor 20%
Solar power	24	Roof of every detached house (160 sq.m. 3 kW, equipment availability 15%)
Hydro power	100	Average of 100 hydro power plants in Japan
Coal-fired power	9,560	Hekinan coal-fired power plant (2.1 million kW)
Nuclear power	12,400	Kashiwazaki-Kariha nuclear power plant (8.212 million kW)

3.5 Characteristics of primary energy

Professor Emeritus Yasui of Tokyo University has commented on the following three types of primary energy sources, in the "Environmental studies guide for citizens" [2]:

(i) Fossil fuel looks like a normal human being, but is actually a devil destroying the earth,

(ii) Nuclear seems like a charming person, but shows the nature and violence of a dangerous person, and

Natural energy pretends to be good, but in fact a whimsical spender.

Since all have advantages and disadvantages, by the trade-off of risk-benefit, it is important to take an appropriate combination of all of them for sustainable development.

4 Long-term asset evaluation

4.1 Precautionary principle and inter-generational ethics

In the global warming problem, equity is often discussed primarily with a focus on the current generation. Discussion of Inter-Generational Ethics remains as a future problem, although somewhat implicit in the targets of mitigating climate change. In any case, the impact of irreversible global warming levels cannot be avoided if we do not take measures now. The "precautionary principle" should be the main basis for actions that include responsibility for future generations.

The precautionary principle states that when human activities may lead to morally unacceptable harm that is scientifically plausible but uncertain, actions shall be taken to avoid or diminish that harm[1]. Morally unacceptable harm refers to harm to humans or the environment that is,

(i) threatening to human life or health, or

(ii) serious and effectively irreversible, or

(iii) inequitable to present or future generations, or

(iv) being imposed without adequate consideration of the human rights of those affected.

The present generation should take responsibility for the survival potential of future generations, from the viewpoint of the Inter-Generational Ethics problem. To destroy the environment and deplete resources places the present generation in the role of assailant, while future generations become the victim. Therefore, the environmental problem cannot be solved if Inter-Generational Ethics are not considered. This approach gives choices for future generations through, (i) leaving the ability for research & development and its results, and (ii) leaving various types of social and natural capital in a good state (public goods, clean atmosphere and permanent energy sources).

For the problem of global warming, the following ethics should be considered:

(i) Reasonable reserves should be retained for future generations, through minimizing over consumption of the present generation ,

(ii) Donate the new innovation technology through research and development, and

(iii) Secure long-term energy sources such as atomic energy and renewable energy (as mentioned in following section).

Figure 2 shows long-term characteristics of the global warming problem [12]. The essence of the global environmental problem is the time delay of the environmental impact. Even if CO_2 emissions can be reduced in the next 100 years and ultimately significantly reduced permanently, the various associated environmental impacts have long lag times to reach equilibrium. It may take 100-300 years to stabilize the CO_2 concentrations and thereby the global average temperature. Sea level rise due to thermal expansion can take several hundred years to thousands of years to stabilize, while the sea level rise due to ice melting may take a few thousand years. Clean, large scale, and long-term energy is required as essential countermeasures.

4.2 Energy resource problems

Next we consider the resource problem. From the viewpoint of the history of mankind, the current age is a fleeting moment of consuming fossil fuels with enormous energy density, called the fossil fuel era [13]. More than 50 x 10^{12} kWh/year is currently generated from fossil fuels [13] compared to only a small amount used before the Renaissance. Hereafter, it is necessary to develop an essentially new energy source or cover requirements with energy from fission or fusion. Discovery, production, and projections of oil, gas and coal with CO_2 emissions for 400 years are shown in Fig. 3 (14). The discovery of new oil fields shows an already declining trend, and the natural gas peak of supply is also expected to appear soon. This figure does not include more recent advances in shale oil, methane hydrate and other unconventional resources, but it is anticipated that largely the same trends will occur, at a delayed rate.

Next, uranium resources will be considered [15]. Figure 4 shows the simulation results of utilization of uranium resources by light water reactors, when the CO_2 concentration is constrained to 550ppm [3-4]. Uranium will be largely consumed - initially by developed countries, with rapidly increasing consumption of developing countries after 2020, and therefore uranium resources are depleted during the 21st century. Using enriched uranium, in current light water reactor systems that do not reuse the U and Pu in spent fuel, it is not possible to satisfy the demand with confirmed resources.

Fast Breeder Reactors are therefore expected to be introduced to replace the light-water reactor in the second half of 21^{st} century [3-4]. The depletion of uranium 235 to be used in the reactors (abundance ratio of 0.7%), will be mitigated by using the remaining 99.3% through converting to plutonium 239 generated from uranium-238. Breeder reactors can use the plutonium 239 which is expected to have 100 times longer life than the 100-years using uranium 235 only. Thus, Fast Breeder Reactors will be able to secure energy resources of more than 10,000 years, as shown in Table 2 [15], and are one of the long-term assets that can help curb long-term global warming and energy security issues. Such technology is required from the viewpoint of intergenerational ethics or the precautionary principle.

Table 2 Uranium resource amount and its available years [15]

	Resource Amount	Available Years (At Usage of 2012)	
		LWR Once-Through	FBR Fuel Cycle (100 times)
Identified Conventional Resources	7640 kt-U	142 years	14,200 years
Total Conventional Resources	15,330 kt-U	288 years	28,800 years

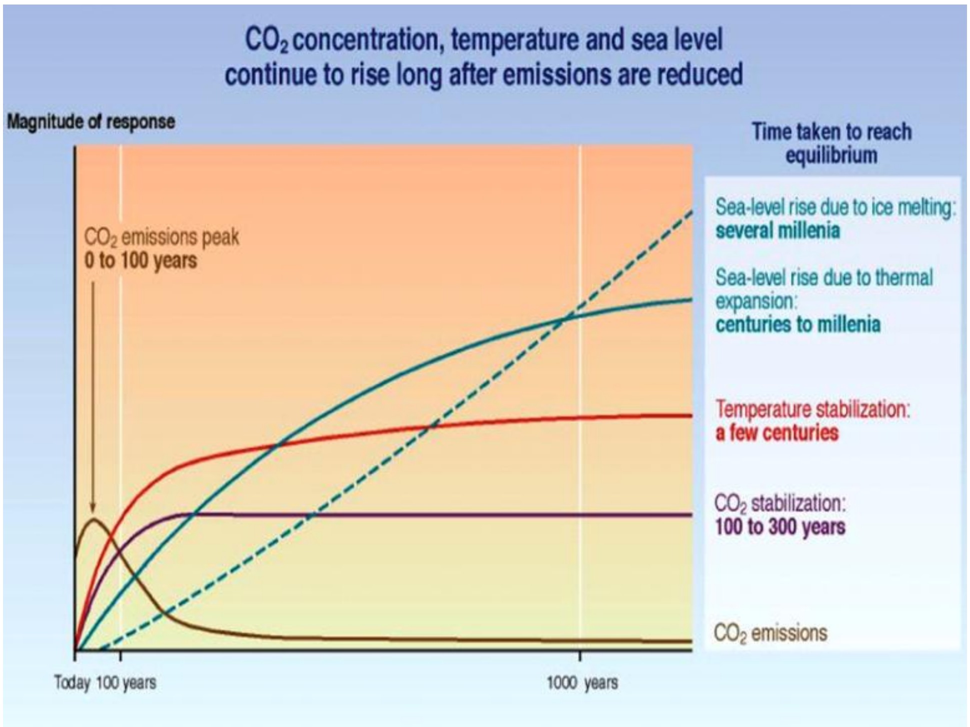


Fig.2 Long-term characteristics of global warming problem (12)

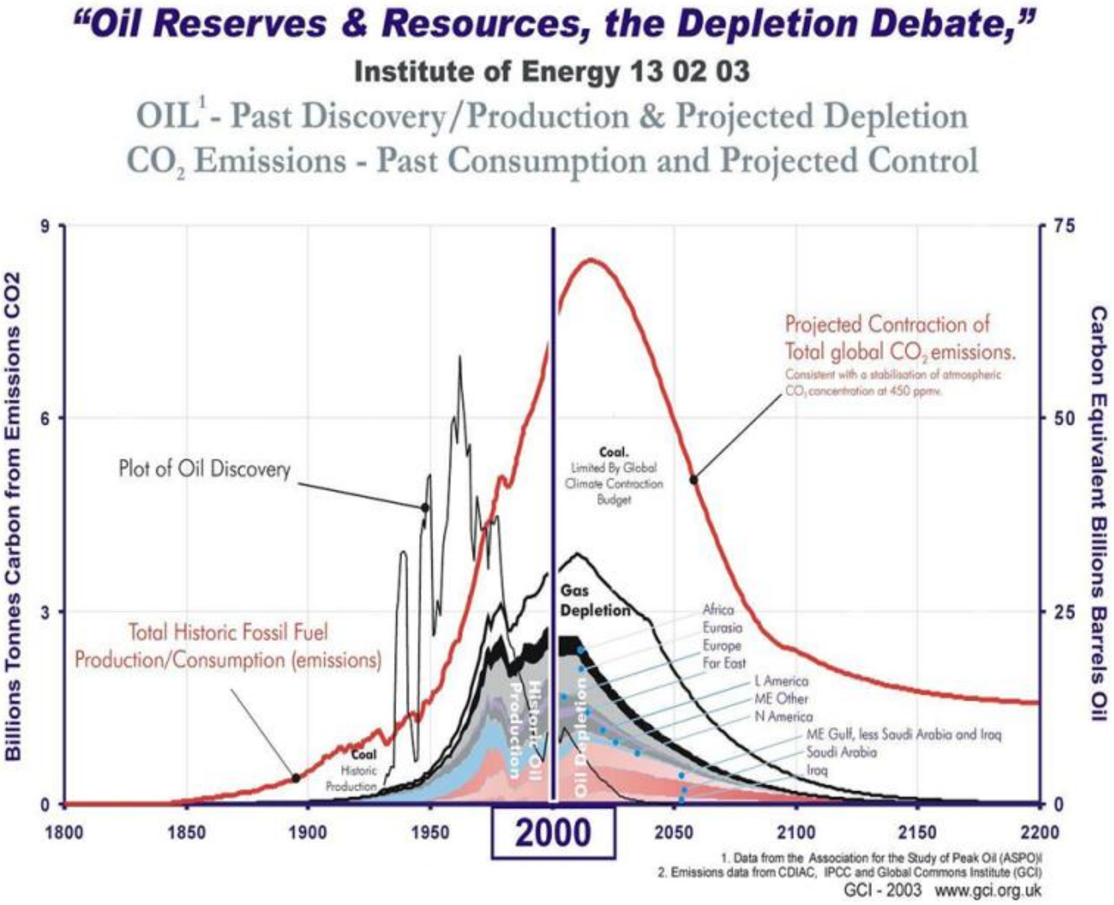


Fig.3 Discovery, production, and projection of oil and gas with CO2 emission (14).

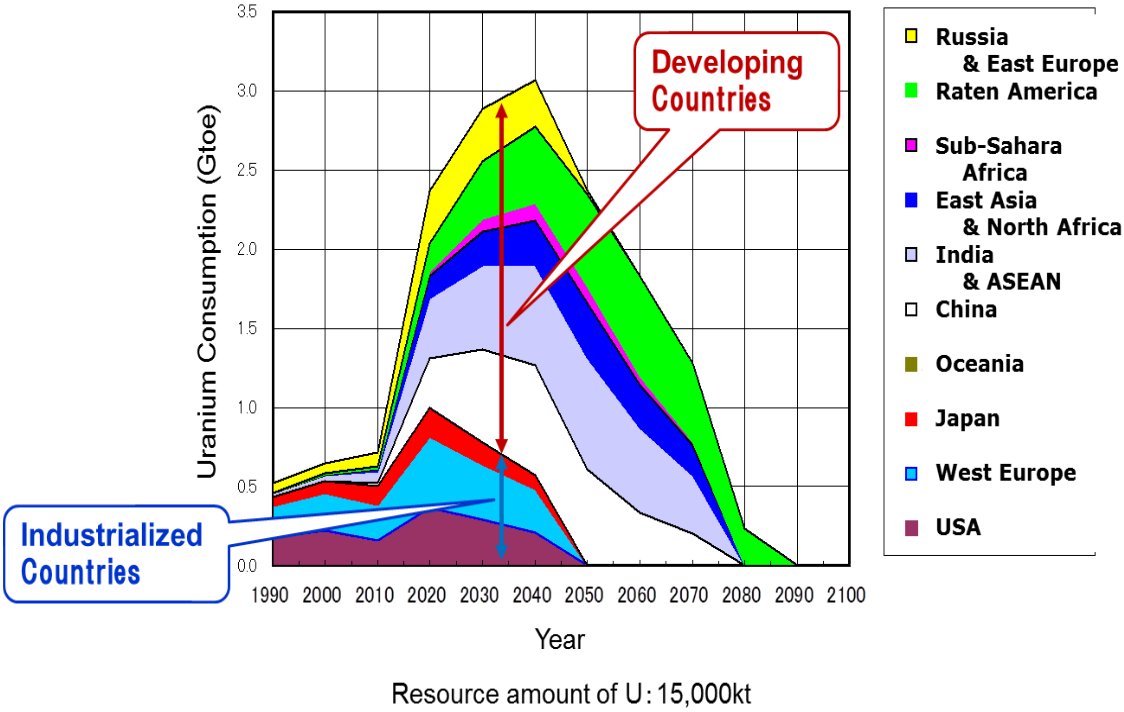


Fig.4 Uranium Consumption with CO2 constraint [3].

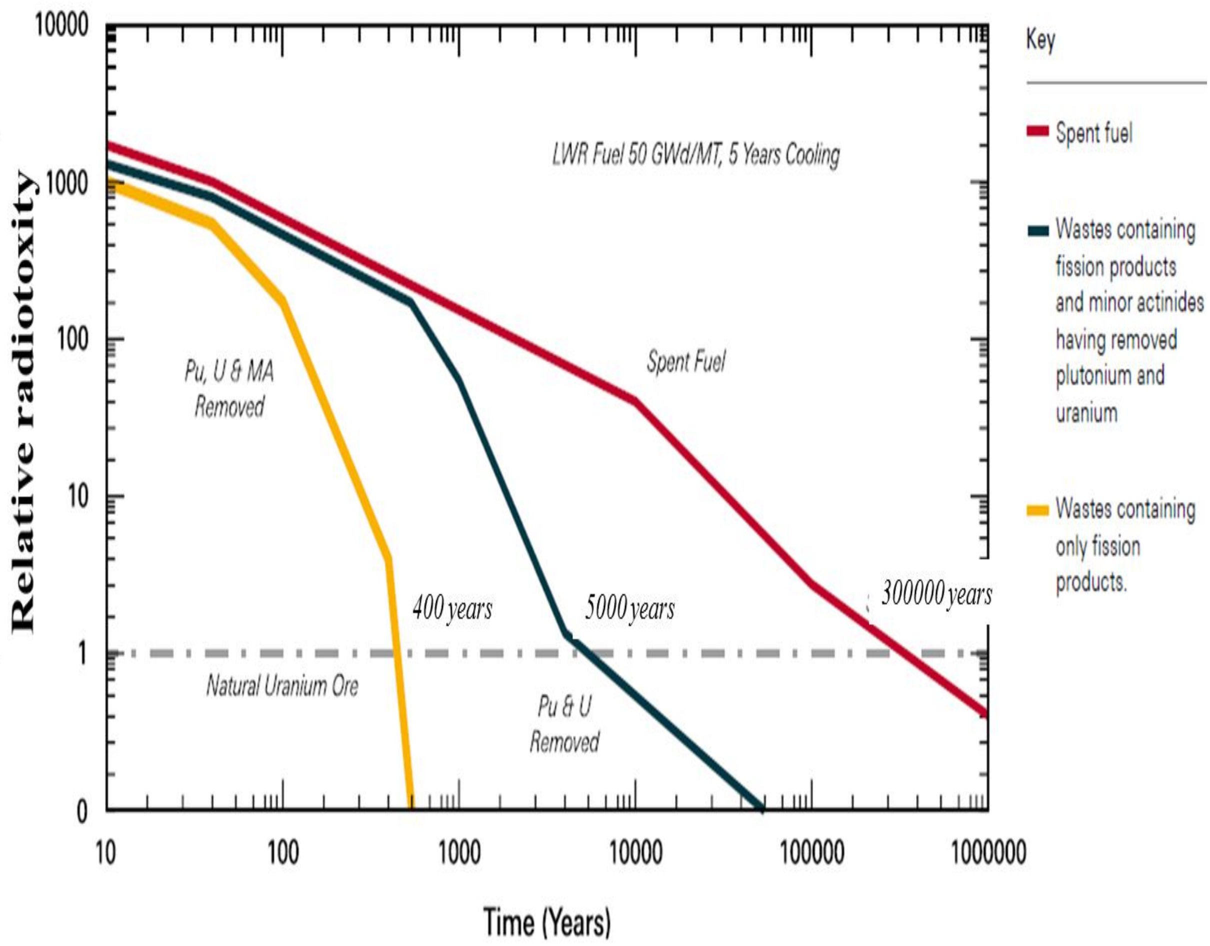


Fig.5 Relative radioactive decay of spent fuel (16).

Table 3 Risk-benefit comparison and long-term asset evaluation

Index		Fossil Energy	Nuclear Energy	Renewable Energy
Risk and Benefit	Generated Waste	×× Flue Gas, Ash	◎ Radioactive	◎ Toxic
	Environment Risk	×× SOx, NOx, Particle	◎ Cancer	—
	Accident Risk	× (××@LPG)	◎	—
	CO2 Emission	×× Fuel (○with CCS) Facility/Operation	◎ Facility/Operation	◎ Facility/Operation
	Energy Intensity	◎ Two order higher than demand	◎ Two order higher than demand	×× Less than demand
	EPR (Energy Profit Ratio)	○	○	×
	Energy Self Sufficient Ratio	× Import	○ Quasi-domestic	○ Domestic, Low contribution
Long-term Asset	Resource	× Consumption	◎ U; Consumption Pu; Extend to 1M years	○ Forever, Low contribution
	CO2	×× Global warming	◎	◎
	Waste	×× Environmental problem	○ Several hundred years by transmutation	◎

* Comparison on indices among three energy resources by author
◎ : Superior, ○ : Good, − : N.A., × : Poor, ×× : Inferior

4.3 Transmutation

Transmutation of Minor Actinides in Fission Products is an important technology for radioactive waste reduction, and Fast Breeder Reactors are an effective means to do so. Transmutation processing is also possible with an Accelerator-Driven System. Figure 5 shows the significance of the transmutation process in the nuclear fuel cycle [16]. Relative radioactive decay of spent fuel is shown, compared with wastes containing fission products and minor actinides with plutonium and uranium removed, and then wastes containing only fission products with removed minor actinides. When compared to the direct disposal of LWR waste (for example), the amount of waste and radioactivity can be reduced by about three orders of magnitude. That is, while LWR direct waste disposal takes tens of thousands of years, it is possible to reduce this to a few hundred years, to reach the radiation level of natural uranium.

5 Discussions

The risk-benefit comparison and long-term asset evaluation are summarized in Table 3. For future energy, fossil energy will eventually not be used due to global warming and environmental problems. Renewable Energy has low energy density, and therefore is likely to be used for distributed power, while nuclear energy has high density and is therefore expected to be used for the most centralized power.

The premise here is that "Global warming and energy security are invariant problems." Taking the effort for emissions reduction as a major premise, CCS (Carbon Capture and Storage) for fossil fuel, renewable energy and nuclear energy should be developed in parallel, which means the energy best mix is required to be achieved, under a CO_2 constraint for sustainable development.

In the near term, an important goal for energy policy is to clarify nuclear positioning in the energy mix. For the nuclear industry, resilient systems should be constructed based on the lessons learned from the Fukushima accident, including rebuilding the safety concept. Clarification of the fatalistically critical nature of the nuclear industry, such as the following, is also required.

(1) Promotion vs. regulation, national liability, regional agreements, the nature of external monitoring
(2) Safety design by manufacturers, safe operation by utilities, clarification of the government responsibility on the safety social system

An important point to note is that, for Japan in particular, the energy situation has largely not changed since before the Fukushima accident – the self-sufficiency ratio of fossil fuels is low and the entrance of renewables has not yet had a major impact. Significant policy shifts could bring a different balance to the situation – for example, further strengthening of feed-in-tariffs or greater purchasing of non-domestic solar cells which have greatly come down in price internationally – however, the risks and benefits of the energy technologies are relatively static.

While the nuclear power generation is shown in the data to have many benefits greater than competing energies, there is a need for further measures to assuage the concerns of a skeptical public. Thus the system should be further augmented by the reconstruction of the safety concept. Innovative research and development is under progress, such as new reactor concepts for safety and usability improvements, or waste reduction.

6 Conclusions

This paper has compared a number of indicators for alternative energy technologies. While this is incomplete, it is hoped that the data presented here can help in developing rational discussions on the risks and benefits of alternative energy sources. Considering the energy system as a whole, the level of reasonable safety measures should be identified by using a risk-benefit analysis method which can rationally evaluate the energy system. In addition, based on the analysis results, individual system acceptance or energy system configuration should be determined on the basis of risk communication.

Nuclear power, especially breeder reactors are arguably indispensable energy sources for global warming and energy security problems, which therefore can be considered as long-term assets. For future generations, energy saving, nuclear power, renewable energy, and carbon capture and storage for fossil fuels will likely be required together.

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