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# Strategic environments for nuclear energy innovation in the next half century

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**Abstract**

In prospecting the role of nuclear energy in a future society, this article attempts to foresee the changes of the socio-economic environment including social attitudes, the economy and the environment, and to analyze their interactions with the exploitation of nuclear energy itself. With this perception, the so-called SWOT analysis is employed to identify the internal strengths (S) and/or weaknesses (W) of nuclear energy when compared with other energy competitors on the basis of an evaluation of the external factors which are likely to play the roles of opportunities (O) for and/or threats (T) against the technological changes in nuclear energy. Out of the external environmental factors, electrification, the regulations for the global environments and the limited availability of fossil fuels are analyzed to provide an opportunity for the nuclear energy innovation in the future. The changes of consumption behavior and the liberation of the marketplace are classified as threat factors. But urbanization, an accelerated technological development and an increased attention to the environment are expected to work either as opportunity factors or threat factors while depending on the innovations of nuclear technology. Such internal factors as the recycling ability of nuclear fuels, high energy density and little emission of greenhouse gases are counted as the strengths of nuclear power, while some weak points for its role in a future society are found both in its social situations such as the management of radioactive waste, safety and nuclear proliferation and in its structure of high capital costs.


*Keywords:* Nuclear energy; Technological innovation; SWOT analysis

## 1. Introduction

The role of nuclear power in a future energy system is very likely to depend on how it will adapt itself to the changing environments of a future society. From a perspective of a global challenge, this article analyses the strategic environments of a nuclear energy development for the next 50 years while integrating the external socio-economic environments with internal competences. The so-called SWOT analysis is employed to identify the internal strengths (S) and/or weaknesses (W) of nuclear energy when compared with other energy alternatives and to evaluate the external factors which are likely to play the roles of opportunities (O) for and/or threats (T) against the technological changes in nuclear energy.

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So far as the external factors are concerned, this article focuses on the changes of the social and economic environments, ecological and environmental concerns, the supply constraints and the sustainability of the energy resources. Initially the changes of the social and economic environments involve the changes of the consumer's behavior for energy products and the production processes, the expansion of electrification and urbanization, and the progress of a technology-based economy. In examining the impact of the social concerns on nuclear energy as well as the general environmental problems, this article reviews the controversial aspects of the environmental affiliations of nuclear energy and the international regulations on global climate change. This article also investigates how the limitations of the fossil energy reserves and the widespread understanding of a sustainability affects the direction of the technological changes for nuclear energy. Internal strengths and weaknesses from the intrinsic characteristics of nuclear energy are reviewed in terms of the long-term stability of an energy supply, greenhouse effect, radioactivity, proliferation risk and the cost structure of an energy production.

## 2. The changes of the socio-economic environment

### 2.1. Consumer behavior

Consumer behavior is very likely to influence the role of nuclear energy as follows. First, a households' preference for energy affects the government's or the utilities' decision on the energy sources and their production methods. Consumer's choice will exert a direct influence on deciding whether or not nuclear power should be included in their energy resources and, if then, how much of a percentage it should be. Second, there has been a change in the behavior of energy consumption which has reduced the number of centralized electricity supply networks. With an attempt to expand a rather decentralized and independent energy, developed countries show an ongoing trend for an autonomous choice of energy and a self-supporting behavior. Households in those countries sometimes make direct choices for the method of electricity production. For example, they set up photo-voltaic panels on the roofs of their houses, and wind-power turbines in their backyards. With the increasing preferences for these methods of a decentralized electricity production, the existing nuclear power system will suffer comparatively unfavorable competition. It is because the present technology of nuclear power is known to be economical within a certain scale of a large capacity above 600 MWe. As such, a centralized management is more appropriate for this kind of large capacity than a scattered one. Accordingly, the large-scale and centralized system of a nuclear power production is not suitable for small cities as well as for a household's independent source of electricity (NEA, 2002).

### 2.2. Electrification and urbanization

Urbanization and electrification will continuously affect the behavior of energy consumption and its consequent system of energy production and distribution. They will also affect the social recognition of the role of alternative energy sources including nuclear power. The share of electricity with regard to the total energy demands and supplies in OECD countries has increased according to their industrial developments and welfare promotions. Developing countries, showing similar trends, have rapidly increased their consumption of electricity. Urbanization, or the increase of metropolises with densely populated areas, has a great influence on the total size and the type of energy demands. This will result in an increase for large-scale power plants and a stabilization of the electricity networks. The increase of an electrification and urbanization will create a high social recognition for the need for a stabilization of electricity supply which provides the opportunity for nuclear power as a source of a centralized energy supply for a base load. Nuclear energy, an enriched energy source, could possibly cope with the concentrated demand of energy in a metropolis. It also has a strong advantage in its much lower rate of land occupation when compared with most other sources of recycling energy.

Nuclear energy, however, may play a limited role in densely populated urban areas, because of the social concern about the problems of radioactive waste. Without solving the problems of radioactive waste and securing the safety of a nuclear energy system, the prospects for this situation are not so promising for attracting nuclear power plants near to metropolises with a large population and high energy consumption, even when they have strong merits in their low rate of land occupation and their appropriateness to large cities with a high energy density. Accordingly, an advancing urbanization will work for the development of nuclear power as an opportunity or a threat factor as well.

### 2.3. The acceleration of technological innovation

It is said that new technologies such as IT (information and communication technology), BT (bio-technology) and NT (nano-technology) will lead the civilization of the 21st century. Together with the development of IT, in particular, the interdisciplinary interactions of sciences and technologies will be increased to speed up the technological changes and to accelerate the transition from a resource-based to a knowledge-based society. As for nuclear energy, computerized devices are largely applied in the nuclear industry. Computers and computing networks, through their simulation and automatic supervision as well as their visualization capacity, have improved the safety and operation efficiency of nuclear power plants and nuclear fuel cycle facilities.

As new technological innovations get into their stride, the global competitiveness will be determined by the innovation capability of the promising technologies. The progress of energy technologies is influenced by these external developments of sciences and technologies which can promote the development of a bio-cell, fuel cell, a new energy carrier like hydrogen, micro-power networks and a new generation's solar technology, etc. With the positive uses of the external innovations as a final resort, it is desirable to raise the effectiveness and efficiency of the innovations of nuclear technology. If the outside innovations from nuclear sector promote the development of competitors or alternative energy technologies rather than contributing to nuclear power, they may turn out to be the threat factors for the future development of nuclear energy (Shell International, 2001).

### 2.4. The deregulations in the energy and electricity market

In the summer of 1992, there was a change in the monopoly structure of American electricity utilities when President Bush signed a new energy policy bill. This bill worked to reorganize the wholesale market system of electricity. In a few years, almost a half of the states including Pennsylvania, California and New York began to alleviate the regulations for electricity sales at the level of the retail markets (McNeill, 2001).

The alleviation of regulations in the energy and electricity markets has affected the choice of energy resources and techniques for producing electricity. The purpose of alleviating the regulations lies in securing, for consumers, the greatest advantages of the market mechanism through free competition. The deregulation of the markets in the area of the electricity industry may have a great influence on investors and operators. The economic danger, resulting from the preceding investment in electric plants and equipment, is an increase in the concern regarding uncertain future demands without regulated tariffs. This market deregulation works as a threat factor for a capital-concentrated technology such as a nuclear energy system.

## 3. The social attitudes toward the eco-environment

### 3.1. Controversies over the environment-friendliness of nuclear energy

In the 1980s, there appeared to be a rising recognition for global environmental damage such as acid rain, the destruction of the ozone layer and the greenhouse effects caused by the use of fossil fuels. Nuclear power is evaluated as being able to make a considerable contribution to solving these global environmental problems, but until now it has not really gained much sympathy for the following reasons (Williams, 2001). First, with all nuclear power's strengths in preventing climate changes and air pollution, its environmental burden is still controversial because of the possible danger of radioactive waste and nuclear accidents. Under the context that it is difficult to make a direct comparison between nuclear power's function to reduce carbon dioxide emissions and its burden on health and the environment, the society's general consciousness of the dangers becomes a crucial factor in evaluating the environmental advantage of nuclear power. Presently in OECD countries the possible dangers of nuclear power are largely recognized more than its strengths in coping with climate changes (NEA, 2002). Second, even when it is admitted that nuclear power has the advantage to reduce the effect of climate change, there still remains controversies over its practical effects. The role of nuclear power in easing climate changes is evaluated through the reduced amount of carbon dioxide emissions. For nuclear power to make a practical contribution to the global society, there should be a great number of nuclear power plants in operation for a long term. For example, in the case of a 10-fold increase in the installed capacity of nuclear power plants by 2100, it is possible to reduce cumulatively at most about 15% of the amount of carbon emissions by the end of the 21st century. Even with the acknowledgement of nuclear power's capability to alleviate the global climate changes, it will not be practically easy to increase the installed capacity of nuclear power plants to that extent (NEA, 2002).

### 3.2. The intensification of the global environmental regulations

The future competitiveness of nuclear power is partly dependent on how the environmental externalities of the energy resources are internalized into the cost of energy. The nuclear industry has by now internalized in its cost much more external effects than the fossil-fuel industry. The cost of a radioactive waste disposal has been included in the price of nuclear electricity, while the cost of fossil fuel related to carbon emissions has not been included in the price of thermo-electricity. It means that the competitiveness of nuclear electricity will improve if it is institutionalized to reflect the external effects of each electricity source in the market prices through the intensified regulations of the global environment. Also an improved competitiveness of nuclear power will help to change the public attitudes toward it.

## 4. The limited supply of fossil fuel

### 4.1. The unstable supply of fossil fuel

There is a problem for fossil fuels such as petroleum, gas and coal which supply power for the modern industrial society. They are exhaustive resources which once used die out. In 2000, the petroleum (confirmed) reserves was $1.33 \times 10^{12}$ barrels which was estimated to meet the global consumption for about 40 years. It is predicted that by 2020, judging from the present trend, the consumption of fuels from the total global energy demand will reach about two times that of 1996 (refer to Table 1). By 2050, if the achievements of technological innovation increase at least twofold for the present energy efficiency, then the demand for primary energy will be around two times the present one. With the introduction of new technology in the future, in addition, it will be possible to exploit the oil fields, in northern Siberia and on the abysmal bed of the Atlantic, which are too far away or too difficult to drill at present. It means that we would not really see the exhaustion of fossil fuels by 2050 (Shell International, 2001).

Nevertheless, the world might begin to suffer a serious lack of traditional petroleum by 2020 or 2030. Particularly with the 2% annual increase of petroleum consumption, as the US Department of Energy (DOE) has predicted, the existing amount of supply will be likely to reach an end not in 40 years but in 25 or 30 years (Klare, 2001/Korean version translated by Kim and Heo, 2002). With this increasing concern for the exhaustion of energy resources, there will be discontinuous changes for the energy resources and their production systems from the existing and traditional ones (Shell International, 2001). Besides, the price volatility of fossil fuels makes it difficult for electric utilities to adapt themselves to the ever-changing conditions of the global marketplace. In this situation, nuclear energy will turn out to be a promising energy source to cope technically with the crisis of energy resources. Nuclear energy provides a price stability for the electric utilities because of the low proportion for the fuel cost in its whole cost. Accordingly, in the case that the price of fossil fuels rises owing to an increase in economic demands or for political reasons, the public attitude could possibly become favourable toward nuclear energy for the stability of its price and supply.

Table 1
Global energy consumption by fuel (unit: $10^{15}$ BTU)

| Type | Present status | | | Future estimation | | |
|---|---|---|---|---|---|---|
| | 1996 | 2000 | 2005 | 2010 | 2015 | 2020 |
| Petroleum | 145.7 | 157.7 | 172.7 | 190.4 | 207.5 | 224.6 |
| Natural gas | 82.2 | 90.1 | 111.3 | 130.8 | 153.8 | 177.5 |
| Coal | 92.8 | 97.7 | 107.1 | 116 | 124.8 | 138.3 |
| Nuclear | 24.1 | 24.5 | 24.9 | 25.2 | 23.6 | 21.7 |
| Others | 30.7 | 32.7 | 38.3 | 41.9 | 45.6 | 49.7 |
| Total | 375.5 | 402.7 | 454.3 | 504.2 | 555.1 | 611.8 |

*Source*: US DOE (1999), International Energy Outlook, Quoted in Klare (2001)/Korean translation by Kim and Heo (2002, p. 73).

Particularly when the availability of national fossil fuels is limited, those characteristics of a volatile insecure supply will work as an opportunity to promote the exploitation of nuclear energy in the future.

### *4.2. The recognition of a sustainable development*

The limitedness of natural resources on the earth, particularly that of the fossil-fuel resources, leads many people to have a pessimistic view of the future civilization. The Club of Rome in its research report, *The Limits of Growth* (1972), warned that human growth might stop within a century because of environmental destruction and the exhaustion of resources resulting from a rapid economic growth.[1] The quintessential end of a sustainable development is to keep or increase all the natural or artificial assets available for the next generation. Nuclear power, with its very high density of energy when compared with the other resources, will make a great contribution to the reduced consumption of natural assets or more specifically that of natural resources.[2] Even the present nuclear power plants, by adopting the once-through option of a nuclear fuel cycle, command 10,000 times more per-mass energy from uranium than from fossil or renewable energies (NEA, 2000).

On the other hand, petroleum serves as a raw material for manufacturing other things such as lubricants, plastics, and artificial fibers. The American Petroleum Association says that $4.5 \times 10^8$ barrels, about 7% of all the petroleum consumed in the USA, are used annually to produce these materials (Klare, 2001/Korean translation by Kim and Heo, 2002). Uranium is scarcely used to produce energy. The production of electricity through uranium has expanded the base of the energy resources available to humans and the variety of energy choices (NEA, 2000). In the course of seeking an alternative to sustain the uses of the fossil-fuel resources for non-energy purposes, a plan will be required to reduce the consumption of fossil fuels as an energy source. Nuclear power, whose value consists of serving as a single purpose, will turn out to be an effective alternative for this plan.

## 5. Strengths of nuclear energy

### *5.1. The long-term stability of an energy supply*

Nuclear fuels, once spent and reprocessed, could be used as MOX ones in a light-water reactor, in which case it is possible to increase the efficiency of natural uranium utilization by about 30%. This technique, already developed in Europe and Japan, is now being put into considerable use. However, if we turn fertile uranium into plutonium by introducing a fast breeder reactor, we can have the same amount of uranium produce 60 or 70 times more energy than the direct disposal of spent nuclear fuels. By introducing this method into practice, judging from today's amount of its use, natural uranium will last for more than 3000 years (IAEA, 1998). Another strength of nuclear power, on the other hand, is its high density of energy. Energy density is defined as the amount of fuels used to produce a given amount of energy.[3] To operate a nuclear power plant of 1000 MWe for a year, 25 tons (10 $m^3$) of concentrated uranium is needed, whereas a 1000 barrels of petroleum, or 2,300,000 tons of coal are needed (Blumenthal and Lindeman, 1995). The nuclear energy system, accordingly, can manage the ceramic form of nuclear fuel on a very small area of land (NEA, 2000).[4] Table 2 compares the energy density of each source.

Thanks to the recycling ability and the high density of nuclear fuels, nuclear energy promotes an energy security by securing enough time to solve problems in the case when a supply is interrupted. From these strengths, a country with scarce resources, like Korea, shows a considerable interest in the exploitation of nuclear energy and the recycling of spent nuclear fuels. Table 3 compares the area of land required of a unit installment.[5]

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1 Quoted in Shin (2001, pp. 13–14): Meadows, et al. (1972).

2 Natural resources take such a variety of forms as clean air and water, mineral and energy, farmland and soil, various landscape architectures and wastelands, etc.

3 Energy density can also be a rough standard to measure the extent of environmental influence. For energy density affects the process of gathering a fuel, the required amount of transportation, the amount of emission of environment-polluting material, and the amount of wastes (IAEA, 1998).

4 The requirement of a large size of land for producing the unit electricity can be a negative effect on the social acceptability of renewable energy source (NEA, 2002).

5 The availability of solar power and wind power are considered to be 20–40% (IAEA, 1998).

Table 2
Energy density by fuel (IAEA, 1998)

| Energy sources | Production of unit electricity (kWh/kg) | The power plant of 1000 MWe: the fuel consumption of annual operation |
|---|---|---|
| Coal | 3 | 2,600,000 tons: 2000 train cars (1300 tons/car) |
| Petroleum | 4 | 2,000,000 tons: 10 oil tankers |
| Nuclear power | 50,000 (Possible up to 3,500,000 in reprocessing) | 30 tons of uranium: a reactor core (10 $m^3$) |

### 5.2. Little greenhouse effect

In the exploitation of nuclear energy, there is little emission of fine dusts and gases such as $SO_x$ and $NO_x$, which not only cause acid rain and urban smog but also destroy the ozone layer. Throughout all the processes of a nuclear fuel cycle, in particular, negligible amounts of carbon compounds are produced. A coal power plant, by displacing one nuclear generator of 1 GWe, will produce $1.75 \times 10^6$ tons of carbon; the petroleum power plant, $1.2 \times 10^6$ tons; the natural-gas power plant, $0.7 \times 10^6$ tons (NEA, 2000).[6] That is to say, if the gas power plants displace the nuclear ones currently operating all over the world, $3.0 \times 10^8$ tons of carbon will be added annually, causing about a 5% increase of the carbon emissions in relation to energy. If nuclear power plants are replaced by the existing mix of fossil-fuel plants including coal, petroleum and gas, there will be an 8% increase of energy-related carbon emissions all over the world. The countries obliged to follow Annex I of the Climate Change Agreement according to the Kyoto Protocol should reduce by 5.2% the 1990-standard emission of greenhouse gases in terms of a yearly mean from 2008 to 2012. Without depending on nuclear power, it is very difficult for these countries to follow the Kyoto Protocol. According to the Bureau of Energy Information under the control of the US DOE, if a tax of 250 $ is imposed on a ton of emitted carbon dioxide to meet the target designated in the Kyoto Protocol, the gas power plants will produce electricity two times more expensively than the nuclear power plants in America (Wolfe, 2001). Fig. 1 compares the greenhouse effect of nuclear power and the other energy sources. It means that nuclear energy appears to be the most representative device to cope with the problems of climate changes and acid rain until more radical solutions are developed in the future.

## 6. Weaknesses of nuclear energy

### 6.1. The pending social problems for the exploitation of nuclear power

A research report of the WEC and the IIASA in 1995, and the 'Technology Report 1' of the IPCC in 1996 says that the future of nuclear power depends on how the problems of safety, waste disposal and nuclear expansion can be solved, and how much the controversy over the greenhouse effect brings about an advantage for nuclear power as a relief to reduce the emissions of carbon dioxide (IAEA, 1998). First, since the TMI accident, efforts for enhancing safety in designing, constructing and licensing nuclear power plants have increased the complexity of the system and the length of a plant construction. As a result, it has weakened the market competitiveness of the capital-intensive nuclear system. In addition to the public concern about the possible danger of a nuclear accident, these efforts have resulted in a high recognition of the risk in nuclear industrial investment, which has led to a stagnation of the nuclear industry. Second, what attracts most attention out of the radioactive wastes is the high-level ones. Radioactivity of low-level wastes dies off in 300 years or so, while it takes thousands of years or hundreds of thousands of years for spent nuclear fuels, high-level wastes, to die off (Wolfe, 2001).

The plutonium forming 1% of the spent nuclear fuel occupies 90% of the whole radioactivity of the spent nuclear fuels over a period of 100,000 years. When it comes to the management of radioactive wastes, it is possible

[6] The real numbers may vary according to the electric capacity, the efficiency of fossil-fuel power plant, the fuel's state, etc. (NEA, 2000).

Table 3
Land requirement by fuel (IAEA, 1998)

| Energy source | The required land for 1000 MWe electricity installment ($km^2$) |
|---|---|
| Fossil fuel and nuclear power | 1–4 |
| Solar heat or light electricity | 20–50 (small-city size) |
| Wind power | 50–150 |
| Bio-mass (cultivated area) | 4000–6000 |

to extract 99.8% of the plutonium during the course of a reprocessing. Reprocessing is useful in extracting plutonium and then reducing the amount of wastes, which will be stored for thousands of years. After reprocessing, the amount of solid material with a long half life is now about 1 $m^3$ in every ton of nuclear fuel. If restored without a reprocessing, every ton will produce about 2 $m^3$ of waste. COGMEGA in France is now seeking to reduce solid waste to 0.3–0.5 $m^3$ in every ton of nuclear fuel (Shin, 2002). Last, under the present situation in which the technical means has not been developed to draw a clear line between its peaceful uses and military abuses, the materials for a nuclear weapon, uranium-235 (U-235) and plutonium-239 (Pu-239), can be extracted in the usual courses of an enrichment and a reprocessing, respectively, in the case of the nuclear fuel cycle of a light-water reactor. Uranium-235, whose enrichment reaches over 90%, is classified as nuclear weapon-grade one. The technique to produce low-enriched uranium of 3–5% for the peaceful use of nuclear energy, in theory, can be appropriated to produce high-enriched uranium for a nuclear weapon. To enrich uranium, a complex physical process is needed for separating the different nuclear species with specific chemical characteristics. Even though the process is very difficult and very costly at the same time, it is not wholly impossible to appropriate the capacity of the commercial technology for a military purpose. For the military use, the plutonium produced in a commercially operated nuclear power plant has some problems with its quality. By suffering a considerable economic loss, however, it is possible to regulate the burning rate of uranium-235 in a reactor and enhance its purity. About 200–250 kg of reactor-grade plutonium, the amount which a light-water reactor of 1000 MWe produces in its operation, can be used to manufacture 30 or 40 nuclear weapons (Holdren, 1989).

### *6.2. The cost structure of the nuclear energy system*

A new nuclear power plant will have to compete in terms of the total cost of electricity production with various alternatives. The next-generation nuclear power plants are now aimed to reduce by more than 25% the cost in comparison with the existing ones (NEA, 2002; IAEA, 2002). The total expenses of an energy system are calculated by the sum of all the capital and the marginal costs. The capital costs of a nuclear power plant are variable according to its design, the supply of materials, the method of construction, labour force and management ability, quality guarantee, regulations and the process of the license, etc. The marginal costs comprise fuel expenses and operating or maintaining ones.[7]

According to Table 4,[8] the capital costs with a 5% discount rate amount to 55–60% of the whole expenses of a nuclear power production, the operating and maintaining costs to 20–30%, and the fuel expenses to 15–20%. The unit cost of an electric production in a coal power plant is composed of about 35% of the capital costs, 20% of the operating and maintaining costs, and 45% of the fuel costs; and that in a gas power plant of about 20% of the capital costs, 10% of the operating and maintaining costs, and 70% of the fuel costs (NEA, 2002; IAEA, 2002).

Table 5 indicates that the investment cost of a nuclear plant designed with the present technology, including the cost of its dismantlement and the interest during its construction, is estimated as 1700–3100 $/kWe. It means that the

[7] The expenses related to nuclear safety and dismantlement are included in its capital cost, which the operator of the nuclear power plant retrieves during its life span. The undiscounted cost of dismantlement is counted as 10% or 20% of the initial capital cost (NEA, 2000).

[8] At the 5% discount rate, in many OECD member countries and non-members, the existing nuclear power plant is considerably competitive in comparison with other electric sources. But the application of 10% discount rate will be appropriate if the electric market is under the competitive system or in privatization (NEA, 2000).

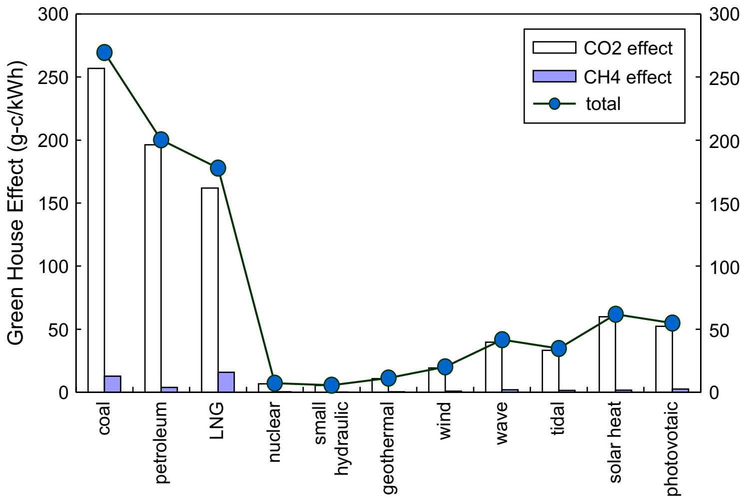


Fig. 1. Greenhouse effect by fuel (Woochiyama et al., 1994).

total investments for constructing a nuclear power plant of 1 GWe capacity are more than $2 \times 10^9$ $ on average. The capital cost of a coal power plant is generally 1000–2500 $/kWe, and that of a gas power plant is much less, that is, 450–900 $/kWe. Compared with the 5–7 years for the construction of a nuclear power plant, likewise, it takes only 1.5–3 years for a gas power plant to be completed, and about 3–5 years for a coal one. In terms of capital costs, there are three kinds of investment risks involved in building a new nuclear power plant. The first is a completion risk, or the risk of a delayed retrieval of the investments because the construction is not completed on time as expected. The second is a regulatory risk due to the excessive regulations to improve the safety, which requires additional investments. And the last is a political risk because of possible changes in a government's policy, which are favourable for the introduction and expansion of nuclear power plants (IAEA, 2002). The OECD regulations on investments already apply a 1% additional burden to the loan interest for the exports of nuclear power plants to developing countries.

The costs of a nuclear power plant are very sensitive to the interest rate because of its high costs in capital and its long period of construction.[9] The future of a nuclear power plant is uncertain and dependent on how much the future market will reflect these kinds of risks. Accordingly, for a nuclear energy system to grow under a free market system, its capital costs and operating costs should be lower than those of a natural-gas power production. To make it more important, the capital cost of a future nuclear power plant should be substantially lower than the present one (INSC, 1996/Korean translation by Chang-kun Lee).

## 7. Findings

This article has comprehensively discussed the strategic environments for nuclear exploitation for the next half century. And the results are summarized in Tables 6–8 while integrating external factors with internal characteristics. At first, from a perspective of a sustainability, nuclear power will have a competitive advantage over other alternatives in the future in terms of a mass and stable supply of base load electricity, least emission of greenhouse gases and a high density of energy. In spite of these strengths, it is necessary to overcome the so-called intrinsic weaknesses to promote the future exploitation of nuclear power. Together with safety, radioactive waste and nuclear proliferation, the economic risk of an investment in nuclear energy should be resolved prior to anything else (Christensen et al., 2001).

[9] On the other hand, the capital cost of a coal power plant depends greatly on the policy of pollution regulations. When the carbon tax is introduced as an international action to lessen climate changes, the capital cost of a fossil-fuel (particularly coal and petroleum) power plant will increase. The cost of gas is very sensitive to the fuel price (IAEA, 2002).

Table 4
Nuclear electricity generation cost by country (NEA, 2000)

| | DR (%) | Cap. cost (%) | OM cost (%) | Fuel cost (%) | Total cost (cent/kWh) |
|---|---|---|---|---|---|
| Canada | 5 | 67 | 24 | 9 | 2.5 |
| | 10 | 79 | 15 | 6 | 4 |
| Finland | 5 | 59 | 21 | 20 | 3.7 |
| | 10 | 73 | 14 | 13 | 5.6 |
| France | 5 | 54 | 21 | 25 | 3.2 |
| | 10 | 70 | 14 | 16 | 4.9 |
| Japan | 5 | 43 | 29 | 27 | 5.7 |
| | 10 | 60 | 21 | 19 | 8 |
| Korea | 5 | 55 | 31 | 14 | 3.1 |
| | 10 | 71 | 20 | 9 | 4.8 |
| USA | 5 | 55 | 27 | 19 | 3.3 |
| | 10 | 68 | 19 | 13 | 4.6 |

DR = discount rate; Cap. = capital; OM = operating and maintaining.

Nuclear accidents in light-water reactors have weakened the confidence in their safety; even with all the advantages of nuclear power. Radioactive waste management still remains a social issue. Despite the international efforts to prevent the spread of nuclear weapons, nuclear proliferation is the most sensitive and pending issue in international politics. As the US DOE reported, nuclear power will command good external environments such as increased demands for electricity, limited availability and an increasing cost of fossil fuels, responses to the global regulations on the emissions of greenhouse gases, etc.

While taking advantage of an urbanization and S&T development, it is noted that the nuclear society must internally accomplish the world-level technological innovations to cope with the development of alternative energy sources and to solve the intrinsic problems of nuclear safety and proliferation (Christensen et al., 2001). The intensified regulation of the global environments works as an opportunity factor for nuclear power, leading the public to have a high concern about the problems of air pollution and climate change and the international society to prepare regulations for an environmental protection. At the same time, however, the public has increased their attention toward the nuclear burden on health and the environment.

To cope with the various future behaviors of energy consumption, it is required to develop not only a large-size centralized system for a nuclear power but also a medium or small sized nuclear system for a decentralized supply of energy. But when we consider the economic advantage of a medium or small sized nuclear system and its contiguity to the final consumers, a remarkable improvement in nuclear safety, radioactive protection and waste management should be achieved. The reason why the liberation of the markets works as a threat factor for nuclear developments

Table 5
Electricity generation cost and construction period by plant (IAEA, 2002)

| | kWe Instal. costs ($) | 1000 MWe Instal. total costs ($10^9$ $) | Const. length (years) | Plant scale (MWe) | Turnkey costs ($10^9$ $) | Electric prod. costs (cent/kWh) |
|---|---|---|---|---|---|---|
| Nuclear LWR | 2100–3100 | 2.1–3.1 | 6–8 | 600–1750 | 1.5–4.2 | 4.9–6.8 |
| Nuclear best practice | 1700–2100 | 1.7–2.1 | 4–6 | 800–1000 | 1.3–2.1 | 4.0–4.7 |
| Coal, pulverized, ESP | 1000–1300 | 1.0–1.3 | 3–5 | 400–1000 | 0.5–1.3 | 3.2–4.5 |
| Coal, FGD, ESP, SCR | 1300–2500 | 1.3–2.5 | 4–5 | 400–1000 | 0.6–2.5 | 3.6–6.3 |
| Gas CCGT | 450–900 | 0.45–0.9 | 1.5–3 | 250–750 | 0.2–0.6 | 2.6–4.8 |
| Wind farm | 900–1900 | 0.9–1.9 | 0.4 | 20–100 | 0.03–0.12 | 3.5–9.2 |

ESP = electrostatic precipitator, FGD = fuel gas desulphurization; SCR = selective catalytic reduction; CCGT = combined cycle gas turbine; GJ = gigajoule; instal. = installed; const. = construction; prod. = production; the cost per installed kWe includes the interest under construction. The costs of electric production comprises the 10% discount rate, 20 years of planning and fuel costs (coal: $1/GJ–$2/GJ, natural gas: $1/GJ). The cost of a wind-power plant may be dependent on the average speed of wind and the coefficient of utilization.

Table 6
External opportunities and internal competences

| External opportunities | | Internal competences | | Counter-measures |
|---|---|---|---|---|
| Factors | Features | Strength | Weakness | |
| Electrification | Increased demand of total amount of electricity | Mass production of electricity only<br>Stable supply of base load | Low social acceptance of general nuclear situations | Improvement of nuclear situations<br>− safety, waste management |
| Regulation of global environments | Obliged reduction of greenhouse gases<br>Internalization of environmental externality | Least emission of greenhouse gases<br>Inclusion of waste management and decommissioning | Safety/waste management<br>Nuclear burden of health/environments | − nuclear non-proliferation<br>− economical efficiency<br>• structure of production cost |
| Unstable supply of fossil fuels | Stability of energy supply and management | Energy recycling<br>High density of energy | Nuclear proliferation<br>Management of recycling waste | • efficiency of electric production<br>Improvement of public acceptance |

is related to the high capital costs of nuclear systems. The nuclear systems, coping with the free markets in America and Europe for the last 10 years, have reduced the costs of nuclear electricity generation through their improved availability and a prolongation of their lifetime. But there is a limit to promoting a competitiveness by improving the capability of a plant operation. It will not be easy to expect a private enterprise under the present nuclear system of high capital costs to compete with other energy sources in a liberated marketplace. More important is the necessity to make a technological breakthrough to improve the nuclear structure of high capital costs.

## 8. Conclusion

The reason for discussing the strategic environments for technological development for nuclear energy is to promote the achievements of R&D and the technological innovation activities. That is to say, the analysis of strategic environments is employed to prepare the innovation strategies for increasing the internal strengths of a nuclear system and complimenting its weaknesses as well as making better use of the opportunity factors of the external environments and evading as many threat factors as possible. This article, in discussing the future

Table 7
External opportunities or threats and internal competences

| External opportunities or threats | | Internal competences | | Counter-measures |
|---|---|---|---|---|
| Factors | Features | Strength | Weakness | |
| Urbanization | (+) Increasing demands of total energy/electricity<br>(+) Increasing demands of large-scale concentrated electricity<br>(+) Demand of low occupation of land<br>(−) Aversion, danger, installation evasion | Mass production of electricity only<br>Stable supply of base load<br>Low rate of land occupation | Safety<br>Negative recognition of waste management | Solving safety and waste problem |
| S&T development | (+) Improving the present technology of nuclear power<br>(−) Innovations of other technology/new energy | S&T-concentrated system | Long-period life cycle of innovation<br>Technological complexity | Effort to increase the achievements of technological innovations |
| Environmental consciousness | (+) Protection of global environments<br>(−) Demands of the reduced burden of nuclear power over health and environments | Global environmental friendliness | Negative recognition of safety and waste management | Solving safety and waste problem |

Table 8
External threats and internal competences

| External threats | | Internal competences | | Counter-measures |
|---|---|---|---|---|
| Factors | Features | Strength | Weakness | |
| Consumer behavior | Increasing demand of decentralization | | Large-size centralized system | Development of mid/small-size reactor |
| Market liberalisation | Preference of low risk in investment: fast retrieval of capital; small-scale investments; economical priority | | Large-size centralized system; high capital cost | Improvement of cost structure<br>Improvement of electric production efficiency<br>Development of mid/small-size reactor<br>Development of multi-purpose system (electricity, hydrogen, process heat) |

strategic environments of a nuclear exploitation, is intended to raise the value of nuclear energy innovation by 2050. It is also intended to promote the utilization of the already-developed technology and to seek the strategic technological paths and the means for a management in order to increase the socio-economic value of the development of nuclear technology.

In summary, it is found that favourable circumstances for facilitating in the development of nuclear energy might be influenced by factors such as an electrification and international regulation in accordance with global climate change, the insecurity of a fossil-fueled energy supply, and the progress of a digital economy. In contrast, consumer behavior for energy choice, coupled with a deregulation of the marketplace is likely to be the threats. As for an internal competence, this article concluded that energy density and the security of a supply, and the amount of greenhouse gas emissions provide the advantages of nuclear energy while the social issues on proliferation risk, safety and accidents, and radiation and toxic effects belong to the weaknesses to be solved mainly by technological innovation with a long-lasting commitment from the global nuclear society. Some effective ways for a technological trajectory are suggested to improve the internal competence while coping with the changes of the socio-economic environments. Furthermore, this article is expected to offer a basic understanding of a technological foresight with which nuclear energy could be the most competitive energy supplier for a sustainable future society.

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## References

Blumenthal, A., Lindeman, E., 1995. Handbook: the International Nuclear Fuel Cycle. New York Nuclear Corporation, USA.

Christensen, D., Sorenson, K., Sanders, T., Surles, T., Tseng, J., Collins, A., 2001. Managing the National's Nuclear Materials: the 2025 Vision for the Deportment of Energy, LA-UR-00-3489.

Holdren, J.P., 1989. Civilian nuclear technologies and nuclear weapons proliferation. In: Schaerf, C., Reid, B.H., Carlton, D. (Eds.), New Technologies and Arms Race. MacMillan Press, pp. 161—198.

International Nuclear Societies Council (INSC), 1996. A Vision for the Second Fifty Years of Nuclear Energy: Vision and Strategies Translated by Chang-kun Lee, Korea Atomic Energy Research Institute (KAERI) (in Korean).

International Atomic Energy Agency (IAEA), 1998. Sustainable Growth and Nuclear Energy. IAEA, Vienna.

International Atomic Energy Agency (IAEA), 2002. Nuclear Technology Review 2002. IAEA, Vienna.

Klare, M.T., 2001. Resource War. Metropolitan Books, New York, US. Translated by Tae-yoo Kim and Eunyung Heo, 2002, Sejong Research Center, Seoul (in Korean).

Meadows, D.H., et al., 1972. The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of mankind. Universe Books, New York.

McNeill Jr., C.A., 2001. Nuclear growth in the 21st century. Nuclear Industry 21 (8), 42—45 (in Korean).

Nuclear Energy Agency (NEA), 2000. Nuclear Energy in a Sustainable Development Perspective. OECD/NEA, Paris.

Nuclear Energy Agency (NEA), 2002. Society and Nuclear Energy; Towards a Better Understanding. OECD/NEA, Paris.

Shell International, 2001. Energy Needs Choices and Possibilities: Scenarios to 2050, Global Business Environment, London.

Shin, E., 2001. Korean Economy and Energy Policy, Tanim, Seoul (in Korean).

Shin, H., 2002. An analysis of the economical efficiency of French nuclear power production. Nuclear Industry 22 (6), 4–9 (in Korean).
Williams, L.G., 2001. The 21st-century task for nuclear safety. Nuclear Industry 21 (8), 26–30 (in Korean).
Wolfe, B., 2001. Nuclear power: a prevention of global energy disaster. Nuclear Industry 21 (7), 36–41 (in Korean).
Woochiyama, Yooji, et al., 1994. An analysis of the power plant's greenhouse effect. Journal of Plasma and Fusion Research. Japanese Electric Research Institute, August (in Japanese).