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Long-term nuclear knowledge management (NKM) of innovative nuclear energy systems (INES) – A case study of the Japan Atomic Energy Research Institute (JAERI)

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Abstract

Within JAERI, funds invested in a 45-year study of LWR totaled 4.2b$ for research and 3.4b$ (34,718 man years) for personnel. The benefits to taxpayers from this JAERI work were estimated to be about 6.3b$, resulting in a favorable cost–benefit ratio of 1.5 (6.3/4.2). JAERI is a national research institute and this figure may be regarded as sufficiently high, and many high risk and complex tasks were completed successfully.

Funds invested in the 32-year study of HTGR were 1.5b$ for R&D and 0.3b$ (2966 man years) for personnel. Commercialized HTGR will result in a cost reduction of electricity during power generation. Retail cost is 0.36b$/year and the share of JAERI (MCP) is 0.018b$/year.

Funds invested in the 32-year study of FR were 5.4b$ for R&D and 0.6b$ (6331 man years) for personnel. Estimate is that after commercialization in 2050, a FR will generate revenue from electricity as high as 1687b$ during the period 2050–2100, or 34b$/year – which is greater than that of LWR. However, there is substantial uncertainty in these estimates. To achieve long-term INES, it is necessary to develop the sustainable scenarios and the long-term robust NKM, as shown in the present study.

Keywords: Nuclear knowledge management (NKM); Innovative nuclear engineering systems (INES); Japan Atomic Energy Research Institute (JAERI); LWR; HTGR; FR

1. Introduction

Energy is one of the most important factors necessary for economic growth, and there exists a direct relationship between an increasing demand and supply of energy (DSE) and economic growth (Agency for Natural Resources and Energy, 2004). By 2030, increased levels of DSE in the world may be 60% higher compared to 2002, including 22% for coal and 36% for oil. The share of nuclear energy is expected to be relatively stable, actually decreasing slightly from 7% in 2002 to 5% in 2030 (IEA, 2003). For Japan, the availability of natural resources is limited and in-country DSE is as low as 19% (OECD/IEA, 2004). A promising option for energy security is to ensure a portfolio of energy sources. Currently in Japan, the input share of oil in gross electric power output is 11%, coal is 24%, LNG is 28%, nuclear is 26%, and the others are 11% (Esaki, 2006). The current trend seems to be valid because Japan's dependency declined from 76% (1976 before the second oil shock) to 47% (2007).

Increased use of nuclear energy can save fossil resources and reduce environmental degradation. However, lack of appropriate nuclear sites and the acceptable disposal of radioactive wastes are constraints on nuclear expansion. If one is putting LWR alone in the main stream, we cannot restrict access to uranium resources. One promising option is to increase the efficiency of LWR operations, to adopt a load-follow operation, and to fortify fuel cycling earlier. The more promising way may emphasize and support the concept of innovative nuclear

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energy systems (INES) and to actively promote technology innovation.[1]

This paper describes the result of case studies of long-term nuclear knowledge management (NKM), where LWR, the high temperature gas-cooled reactor (HTGR), and the fusion reactor (FR) are taken as important factors of future INES. We assess the potential benefits of these alternatives under conditions of substantial uncertainty.[2]

2. Purpose and method

2.1. NKM

Knowledge management (KM) is defined by the International Atomic Energy Agency (IAEA, 2005) as an integrated, systematic approach to identifying, managing and sharing an organization's knowledge, and enabling persons to create new knowledge collectively and thereby helping to achieve the objectives. NKM identifies, optimizes, and actively manages intellectual assets either in the form of explicit knowledge held in intangible products or tacit knowledge possessed by individuals or communities in the nuclear fields (Snowden, 1988).

2.2. Purpose

In the present study, the authors wish not only to show the validity of long-term NKM as a key factor of INES – namely LWR, HTGR, and FR, but also to assess their hypothetical benefits through the year 2100 under conditions of substantial uncertainty. It should be stressed that those factors are important intellectual assets of JAERI developed to date. Additionally, in the Framework for Nuclear Energy Policy constructed up by the Japan Atomic Energy Commission, a LWR, a fast breeder reactor (FBR), a HTGR, and a FR are all defined as eligible and prominent candidates for long-term nuclear energy sources.

3. Results and discussion

In the following discussion, the rate of currency is constant for all years; one dollar ($) = 121 yen (¥). The values are expressed in constant, 1995 denominations.

3.1. LWR

3.1.1. Economic impact of LWR on the electricity market

In 1997, gross electricity production totaled 3494 bkW h (billion kilo-watt-hour) and 865 bkW h in the US (Energy Information Administration http://www.eia.doe.gov/), and Japan, respectively. The US level was four times greater than that of Japan. Gross electricity generated in the US is highly biased to the use of fossil fuels such as coal, whereas in the case of Japan most can be attributed to nuclear energy. The US produced 629 bkW h of nuclear-based electricity, which sold for 39b$, while Japan produced 311 bkW h, which sold for 47b$; the difference in value being some 21%.

In terms of economics, the explicit beneficiary of LWR in Japan is ambiguous because those technologies were originated in the US: the Federal R&D expenditures from 1950 (before the Atoms for Peace Program) to 1962 were 1.9b$ and those from 1963 to 1975 were 1.3b$ (2003 base), totaling 3.2b$ (Bezdek and Wending, 2006) during the 1950–1975 period. Because of that initial investment, revenues of electricity generated by the 52 LWR units in Japan are 47b$/year and 11b$ for relevant reactor components (1999 base).

3.1.1.1. A share of JAERI. The following points are discussed for a better understanding of the economic share for JAERI.

Market creation effect (MCE) is hereinafter defined by

$$\mathrm{MCE} = \mathrm{MCP}(\text{market creation product}) \times \text{a rate of value added to the new products (from I–O) table}^{3} \quad (1)$$

$$\mathrm{MCP} = \text{Revenue from products born in a newly created market induced partly or fully affected by JAERI outputs} \times \text{a ratio of contribution by RD performance to a total amount of sales revenue} \times \text{a ratio of RD performance contributed by JAERI} \quad (2)$$

Then cost benefit effect (CBE) can be determined by

$$\mathrm{CBE} = \mathrm{MCE}/(\text{Total amounts of investment(research and personnel)}) \quad (3)$$

3.1.1.1.1. LWR market. The revenue from electricity sales during 1970–2000 (Ministry of Finance, 1970–2000) in Japan was 760b$. For the facilities, the revenue accruing from the upstream of the fuel cycle to the downstream of the fuel cycle covering the period from 1977 to 2000 was estimated (Japan Atomic Industrial Forum Inc., 1965–2000) to total 248b$. All revenues obtained in individual years were deflated to 1995 denominations.

$$\text{Then revenue of LWR in total was} = 760 + 248 = 1008\text{b\$} \quad (4)$$

[1] INES aims at studying the recent research activities relevant to the development of innovative nuclear reactor systems and innovative separation/transmutation systems with a broad perspective and flexible ideas. See http://www.lhweb.jp/coeines2/index.html.

[2] In October 2005, JAERI was reorganized and renamed the Japan Atomic Energy Agency (JAEA). The topic of this paper addresses research activities done within JAERI. For this reason, the fast breeder reactor (FBR) technology is omitted.

[3] Ministry of Economy, Trade and Industry, 1995.

3.1.1.1.2. R&D ratio of LWR and JAERI. As discussed in the previous paper (Yanagisawa, 2006), two R&D ratios were defined as follows:

$$\text{RD percent of LWR on average from 1978 to 1999} = 6.2\% \quad (5)$$

$$\text{RD percent of JAERI} = 20\% \quad (6)$$

3.1.1.1.3. MCP and MCE. In the nuclear market, the MCP of JAERI is given by

$$\text{MCP(electricity)} = 760\text{b\$} \times 0.062 \times 0.2 = 9.4\text{b\$}$$

$$\text{MCP(facilities)} = 248\text{b\$} \times 0.062 \times 0.2 = 3.1\text{b\$}$$

By using the I–O table, MCE of JAERI for LWR is given by

$$\text{MCE} = 9.4 \times 0.542 + 3.1 \times 0.386 = 6.3\text{b\$} \quad (7)$$

This is the research output (results) of JAERI.

3.1.1.1.4. Invested amounts of JAERI

$$\text{Invested amount (i.e., income) of JAERI} = 4194\text{M\$ or } 4.2\text{b\$ including personnel cost} \quad (8)$$

3.1.1.1.5. Cost benefit effect (CBE). For JAERI, funds invested in the 45-year study of LWR were 4.2b$, including human resources of 34,718 man years. A large part of the funds consisted of supporting the construction and operation of JPDR, JMTR and NSRR.[4] The positive return from JAERI to the taxpayers is about 6.3b$, as shown in Eq. (7). Long-term robust NKM can possibly result in a CBE attributed to JAERI for LWR of 1.5 (6.3/4.2). Thus, comparing the indexed income of 1.0, the outcome of JAEWRI is 1.5 (>1). JAERI is a national research institute and this figure may be regarded as sufficiently high because many high risk and complex tasks were completed successfully.

3.2. HTGR

For HTGR, an investment by JAERI was about 1.7b$ during 1969–2000. It consisted of 1.5b$ for R&D expenditures and 0.2b$ for personnel cost – 2966 man years. Of the former, 62% was invested in facilities such as HTGR. In the US, R&D expenditures for gas-cooled reactor were 0.529b$ during 1950–1962 (Bezdek and Wending, 2006) (2003 base). Because of the initial investment, R&D in JAERI was advanced further. With several assumptions one can try to estimate a direct MCP of HTGR during 2010–2050.

3.2.1. Cost reduction of electricity by HTGR

According to the base scenario, after 2010 decommissioned LWRs will be replaced by HTGRs in various locations. After these replacements, electricity costs will decrease because the electricity cost of LWR is 4.9¢/kW h[5] and that of HTGR is 4.3¢/kW h.[6]

3.2.1.1. Retail cost. Gross electricity generated by LWR was about 300 bkW h in 1997 (Yanagisawa et al., 2002). Employing long-term NKM it is assumed that this situation will remain in the future. An expected share of HTGR will be 20%. Therefore, the amount of retail cost of electricity by substituted HTGR is

$$300\ \text{bkW h} \times 0.2(\text{share}) \times (4.9 - 4.3)¢/\text{kW h} = 0.36\text{b\$} \quad (9)$$

3.2.1.2. A contribution of Japan to the world. The present R&D of HTGR is shared by six countries (Germany – AVR and THTR, the US – Peach Bottom and FSV, England – DRAGON, China – THR, Russia – GT-MHR and Japan – HTTR), and the R&D contribution ratio of Japan contributions to the world is 1/6 (0.167).

3.2.1.3. A contributions of JAERI to Japan. According to the Survey of Research and Development (2000) (Statistic Bureau, 2000), R&D expenditure distributed to all domestic nuclear institutions is 3.7b$ and those distributed to JAERI is 1.0b$. Extrapolating this relationship into the future, the R&D contribution rate of JAERI to Japan is 0.28.

3.2.1.4. MCP. The expected share of JAERI due to the generation of electricity by commercialized HTGR is as follows:

$$\text{MCP} = 300\ \text{bkW h} \times 0.2(\text{share}) \times (4.9 - 4.3)¢/\text{kW h} \times 0.167 \times 0.28 = 0.018\text{b\$/year} \quad (10)$$

Accumulating MCP from 2010 to 2050 period is given by

$$0.018\text{b\$} \times 41\ \text{years}/2 = 0.37\text{b\$ (triangular approach)} \quad (11)$$

Through this estimation, the life-time of conventional LWR is assumed to be 40 years.

3.2.1.5. A rebate to year 2000. We have noted that the investment in HTGR totaled 1.5b$ during 1969–2000. According to a hypothetical scenario, one assumes that the investment will be 0.79b$ during 2001–2010 and 2.5b$ during 2011–2050. For the former, a linear approximation during 2000–2010 periods is used and a triangular approximation during 2010–2050 is used for the latter. Over the period 2001–2050, the funding amount will peak in 2010 (at 0.12b$) and then

[4] JPDR: Japan Power Demonstration Reactor, JMTR: Japan Materials Testing Reactor, NSRR: Nuclear Safety Research Reactor.

[5] According to the Nuclear Industry Newspaper (23rd December 1999), a prime cost of electric power generation by commercial nuclear power plant will be 4.9¢/kW h, where 40 years operation of 1.3 GWe nuclear power plant with a load factor of 80% is assumed. The prime cost of 1.3 GWe LWR consisted of the capital cost (1.9¢), maintenance cost (1.6¢) and fuel cycle cost (1.4¢).

[6] According to Moyamoto et al. (2001), the prime cost of 600 MWt HTGR consists of the capital cost (2.1¢), maintenance cost (1.2¢) and fuel cost (0.90¢). The detailed calculation process for the first term is abbreviated here and the third term is used in the fuel cost of MHTGR in the US. The sum of the three items is 4.3¢/kW h.

gradually decreases, approaching 0b$ in 2050. Taking all possible effects during 2010–2050 into consideration, the rate of discount at year 2000 is determined to be: $1760/(1760 + 950 + 3000) = 0.31$, and the discount to 2000 is approximately 31%. It should be noted that the research costs of 1.5b$ during 1969–2000 have not been deflated. The direct effects discounted to the year 2000 then amount to

$$0.37\text{b\$} \times 0.31 = 0.11\text{b\$} \quad (12)$$

3.3. Fusion reactor (FR)

The JAERI investment in the fusion reactor (FR) program through 2000 was about 6b$, a value almost 40% of the total JAERI budget (15b$ for research). This consists of 5.4b$ for R&D cost and 0.6b$ for personnel (6331 man years) cost. When assessing long-term NKM, one must examine the cost reduction of electricity due to commercialized FR and the CBE due to the creation of an FR market. The former is, however, not included in the present study. Under the basic scenario, the commercialization of FR will be started in 2050 and operations will progress through 2100.

3.3.1. A CBE during creation of the FR market

The creation of the FR market will produce two types of research impacts: One is the retail sale of electricity generated by commercialized FR and the other is the retail sales due to the construction and operations of FR facilities and equipments. The latter is, however, not included in the present study, too.

3.3.1.1. Assumptions. To estimate the size of the electricity market created by FR, the following assumptions are made:

(1) The growth rate of DSE after 2000 will be changed as follows:
  - Through 2010; 1.2%.[7]
  - 2010–2050; 0.7%.[8]
  - 2050–2100; 0.5%.[9]

(2) The share of commercialized FR is assumed to be 12.6% in 2070 and 23.4% in 2100.
(3) Currently, there is no index of cost for FR electricity sales cost. Therefore, we index the value from the LWR series. In 1997 (Yanagisawa et al., 2002), the generated electricity from 52 LWR units was 0.3007×10^{12} kW h and the total revenue of those was 46.8b$, resulting in a nominal unit cost of 15.5¢/kW h/year. This value is cited to commercialized FR.
(4) Electricity generated by commercialized FR is increased linearly during 2050–2070 and during 2070–2100.

[7] General committee on natural resources and energy: "Future energy policy (2001.7)", where growth rate was cited as the standard case.

[8] General committee on natural resources and energy: "Fundamental policy committee (1997.12)", where growth rate was referred to CASE3.

[9] Decrease from 0.7 to 0.5 is due to a population reduction expected to occur after 2050.

Table 1
Electricity output generated by commercialized fusion reactor (FR)

Year of evaluation	Growth rate of demand and surply of electricity	Gross electricity generated (GkW h)	Share of FR (%)	Electricity output by FR (GkW h)
1999	–	917.6	0	0
2010	1.2% per year	1029.2	0	0
2050	0.7% per year	1360.4	0	0
2070	0.5% per year	1503.1	12.6	189.4
2100	0.5% per year	1745.7	23.4	408.5

Note: GkW h means Giga (10^9) kW h.

All assumptions are summarized in Table 1.

3.3.1.2. Gross sale of electricity generated by commercialized FR. Using the data in Fig. 1, the gross sale of electricity generated by commercialized FR during 2050–2100 is determined as

Area ①: 189.4 GkW h × (2070 − 2050)/2 × 15.5¢/kW h = 294b$.
Area ②: (189.4 GkW h + 408.5 GkW h) × (2100 − 2070)/2 × 15.5¢/kW h = 1393b$.

Gross sale of electricity = area ① + area ②
= 294b$+1,393b$ = 1,687b$ (13)

According to this result, the FR market is estimated to be 34b$/year (1687b$/50 years). The discounted cost from 2100 to the present is 63b$/year. This results in an estimate where the FR market is actually greater than that of LWR market (47b$/year).

3.3.1.3. The contribution of JAERI to the electricity generated by commercialized FR

3.3.1.3.1. The ratio of R&D. Japan has played an important research role in the R&D of FR from the beginning of technological development and will continue to play an active role in each stage of experimental, prototype and demonstrative fusion reactors. It is expected for this development to take more than 90 years. Electric generation by commercialized FR technology may not occur if the R&D data are not successful. This means that the role of R&D for commercialization of FR is very significant. By this reason, we estimate 15% (10% × 1.5) to be the ratio of R&D, where 10% is the potential maximum R&D ratio at any one private business in Japan.

3.3.1.3.2. The ratio of the JAERI contribution. In assisting the development of commercialized FR, electric power

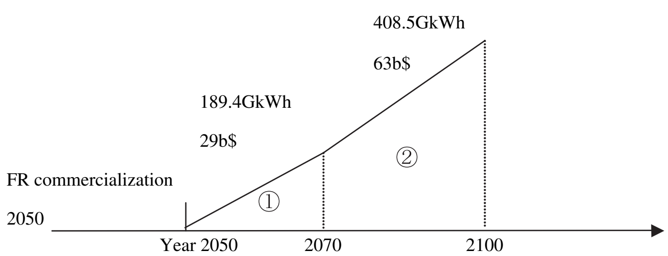

Fig. 1. Gross sale of electricity generated by FR, 2050–2100.

companies, plant makers, and JAERI will all be contributing up to 2050. Then, the ratio of the JAERI contribution will be 1/3 (33%), corresponding to the primary cost of retail sale.

3.3.1.3.3. Impacts attributed to JAERI from FR power generation. The final impacts attributed to JAERI from the creation of a nuclear power generating market by the commercialized FR are given by

$$1687\text{b\$} \times 0.15(\text{RD ratio}) \times 0.33(\text{JAERI contribution}) = 83\text{b\$} \quad (14)$$

Using the economic input–output (I–O) tables, we use the ratio of value added to the electricity, that is, 0.542.

$$\text{MCE} = 83\text{b\$} \times 0.542 = 45\text{b\$} \quad (15)$$

4. Conclusion

LWR, HTGR and FR are important intellectual assets that have been developed by JAERI, and they are also promising technological visions for fostering the concept of INES. The authors incorporated case studies for assessing the potential benefits of these technologies by means of long-term NKM. Recognizing the substantial amount of uncertainty contained in the estimates, the results obtained are as follows.

1. Revenue from LWR was 760b$ during 1970–2000, and the share of JAERI (MCP) of this activity was 9.4b$/30 years. For JAERI, funds invested in the 45-year study of LWR were 4.2b$ for research and 3.4b$ (34,718 man years) for personnel. The benefit from this JAERI activity to the taxpayers was estimated to be about 6.3b$, and the cost–benefit ratio of the JAERI program is thus 1.5. JAERI is a national research institute and this figure may be regarded as sufficiently high because many high risk and complex tasks were conducted successfully.
2. The use of HTGR induces a cost reduction of electric power after its commercialization, and the resultant revenue will be 0.36b$/year in Japan. The share of JAERI in this activity (MCP) is 0.018b$/year.
3. Revenues generated by the commercialized FR technology will be 1687b$/50 years (2050–2100), or 34b$/year. The discounted value of 34b$ through year 2000 is 63b$/year, which is greater than that of LWR (47b$ a year). The share attributable to JAERI for this activity (MCP) is 83b$/50 years.
4. To ensure the success of long-term INES, it is necessary to derive and assess the sustainable scenarios and incorporate long-term and robust NKM.

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