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# Systems option for sustainable development—effect and limit of the Ministry of International Trade and Industry's efforts to substitute technology for energy

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## Abstract

The global environmental consequences of $CO_2$ discharge resulting from energy use are causing increasing concern regarding the sustainability of our development future. Despite the fragile nature of its energy structure, Japan successfully overcame two energy crises in the 1970s and managed to maintain economic growth which resulted in a dramatic improvement in its industrial technology. The success of these efforts can be attributed to the substitution of an unconstrained production factor (technology) for a constrained production factor (energy), a process similar to that seen in an ecosystem. The Ministry of International Trade and Industry's (MITI) industrial technology policy functioned well in stimulating such substitution, thereby inducing the vitality of industry for this substitution. Given the two-sided nature of $CO_2$ emissions and energy consumption, Japan's experience can provide informative suggestions for addressing current worldwide concern regarding global warming, particularly with respect to post Kyoto countermeasures. Nevertheless, following the relaxation of energy constraints and the succeeding 'bubble economy' and its bursting, MITI's ability to induce substitution efforts by industry has weakened, leading to a fear that Japan may again face the prospect of energy and environmental constraints. This paper attempts to analyze a systems option for sustainable development by introducing a comprehensive systems approach with a detailed description of energy and non-energy technologies in an energy-economic model. By utilizing this approach, MITI's efforts to induce industry initiatives, and subsequent efforts to overcome the two energy crises by substituting technology for energy are reviewed. In addition, sources of the current fear concerning energy and environmental constraints and the effectiveness of MITI's industrial technology policy in view of this fear are analyzed.

*Keywords:* MITI's policy; Inducement; Technology substitution; Technology knowledge stock of energy R&D; Global warming

## 1. Introduction

The global environmental consequences of environmental emissions resulting from energy use are causing mounting concern regarding the sustainability of our development future. The necessary response to this concern is to find a solution which can overcome energy and environmental constraints while also maintaining sustainable development. An equation leading to such a solution can be simply considered a dynamic game of 'three Es': economy, energy

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and environment. Provided that these can be represented by production ($Y$), energy consumption ($E$) and $CO_2$ emissions ($C$). First, $Y$ can be represented by the following simple equation:

$$Y = E * (E/Y)^{-1} \tag{1}$$

where $E/Y$ is the unit energy consumption or energy efficiency.

Thus, economic growth depends on changes in both energy consumption and energy efficiency as follows:

$$\Delta Y/Y = \Delta E/E - \Delta(E/Y)/(E/Y) \tag{2}$$

where $\Delta Y = \mathrm{d}Y/\mathrm{d}t$.

Despite numerous handicaps, Japan's economy successfully achieved sustainable development by focusing on efforts to improve the productivity of relatively scarce resources (Economic Planning Agency, 1965–1995). This included capital stock up until the 1950s, followed by the supply of labor, environmental capacity constraints, and the energy supply after the first energy crisis in 1973 (Economic Planning Agency, 1965–1995; Meyer-Krahmer, 1992). The development of manufacturing industry proved to be the driving force behind this achievement. In addition, technology development played a key role in the rapid enhancement of productivity levels through its successful substitution for limited resources such as energy (Watanabe et al., 1991).

During the years 1955–1973, the period before the first energy crisis in late 1973, Japan's manufacturing industry enjoyed an average annual growth of 13.3% which was largely supported by a cheap and stable supply of energy. During this period, the average increase rate of energy dependency was 12.9% per year, while the annual change rate of energy efficiency was only −0.4%. Contrary to this, during the years 1974–1994, after the first energy crisis, Japan's manufacturing industry achieved a notable energy efficiency improvement of 3.4% per year. Therefore, it was able to enjoy an average 3.0% per year production increase (GDP growth was 4.1%) while minimizing energy dependency at a −0.4% as illustrated in Fig. 1.

As the global environmental consequences of environmental emissions resulting from energy use have become critical, dependency on energy has resulted in additional constraints as follows:

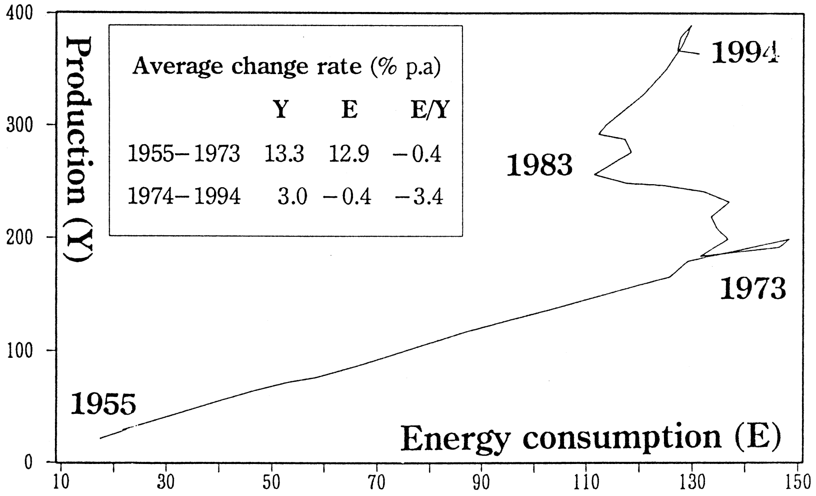
$$C = E * C/E \tag{3}$$

$$\Delta C/C = \Delta E/E + \Delta(C/E)/(C/E) \tag{4}$$

Thus, production ($Y$) will be governed by $C$, $E/Y$ and $C/E$ as follows:

$$\Delta Y/Y = \Delta C/C - \Delta(E/Y)/(E/Y) - \Delta(C/E)/(C/E) \tag{5}$$

where $C/E$ represents fuel switching to minimize emissions of $CO_2$.



Average change rate (% p.a)

| | Y | E | E/Y |
|---|---|---|---|
| 1955–1973 | 13.3 | 12.9 | −0.4 |
| 1974–1994 | 3.0 | −0.4 | −3.4 |

Fig. 1. Trends in the shift from an energy dependent mode to a green mode in the Japanese manufacturing industry (1955–1994).

Table 1
Comparison of paths in attaining development in major countries/regions in the world (1979–1988)—average change rate: % per annum

| | Production $[\Delta(Y/Y)]$ | Energy efficiency $[\Delta(E/Y)/(E/Y)]$ | Fuel switching $[\Delta(C/E)/(C/E)]$ | $CO_2$ emissions $[\Delta(C/C)]$ |
|---|---|---|---|---|
| Japan | 3.97 | −3.44 | −0.59 | −0.06 |
| USA | 2.78 | −2.62 | −0.11 | 0.05 |
| W. Europe | 2.01 | −1.78 | −1.33 | −1.10 |
| USSR/E. Europe | 1.72 | 0.45 | −0.83 | 1.34 |
| LDCs | 3.53 | 0.85 | −0.16 | 4.22 |

[a] Production is represented by GDP.
Sources: Y. Ogawa by using IEA's IEA Statistics, Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries, 1992 (Ogawa, 1991).

Options for increasing production can be considered a game involving the following variables: $CO_2$ emissions $(C)$, energy efficiency $(E/Y)$ and fuel switching $(C/E)$. Table 1 compares the development paths of Japan, the USA, western Europe, the former USSR and eastern Europe, and less-developed countries (LDCs) for the 10 years following the second energy crisis in 1979 (1979–1988). Looking at Table 1, we note that Japan recorded the highest economic growth with an average annual GDP growth rate of 3.97%. Such growth was possible due to a notable energy efficiency improvement of 3.44%, a 0.59% rise in fuel switching and a 0.06% decline in $CO_2$ emissions. The LDCs followed Japan in terms of GDP growth with an average annual growth rate of 3.53%. During the 10-year period, fuel switching had a positive effect as it rose by 0.16%. However, energy efficiency fell by 0.85%, leading to a 4.22% increase in $CO_2$ emissions. The USA attained 2.78% average annual GDP growth supported by a 2.62% energy efficiency improvement and a 0.11% rise in fuel switching. $CO_2$ emissions increased by 0.05%. In western Europe, GDP growth measured 2.01% as energy efficiency improved by 1.78%, fuel switching increased by 1.33% and $CO_2$ emissions decreased by 1.10%. Average annual GDP growth in the countries of the former USSR and eastern Europe was 1.72%. Energy efficiency declined by 0.45% while fuel switching rose 0.83%. Emissions of $CO_2$ increased by 1.34%.

The relative advantages and disadvantages of energy efficiency improvement and fuel switching are generally governed by economic, industrial, geographical, social and cultural conditions of a country or region. Japan's notable achievement in realizing a conspicuous improvement in energy efficiency was, given that it is an energy importing trade and technology based nation, initiated by industry as part of its survival strategy so as to be free from the burden of energy cost. However, due to geological constraints and dependency on coal as an oil substituting energy, Japan's fuel switching ability was limited (Watanabe, 1995a). This was not the case in western Europe, where nations benefited from their geographical advantage of being able to rely on readily available natural gas and biofuels. However, contrary to Japan's economic and industrial structure, the efforts of industry in western Europe towards energy efficiency improvement were not so strong.

Thus, Japan's success in overcoming energy and environmental constraints while also maintaining sustainable growth can largely be attributed to industry's intensive efforts to improve energy efficiency. Technology played a key role in this achievement through its successful substitution for energy due to a combination of industry efforts and government, chiefly by the Ministry of International Trade and Industry (MITI),[1] stimulate and induce change (Watanabe and Honda, 1991). This success suggests that substituting technology for energy may be a means of overcoming energy and environmental constraints while maintaining sustainable development, and that an appropriate combination of both efforts by industry and government can effectively stimulate such a substitution. However, since the relaxation of energy constraints (starting in 1983), the sharp ap-

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[1] MITI's responsibilities include energy and industrial technology policies.

preciation of the yen (triggered by the Plaza Agreement in 1985) and the succeeding 'bubble economy' (1987–1990) [2] and its bursting (1991), Japan's technology substitution for energy has weakened leading to a fear that Japan may again face the prospect of energy and environmental constraints.

To date, a number of studies have identified the sources supporting Japanese industry's technological advancement (e.g., Mowery and Rosenberg, 1989; US Department of Commerce, 1990) and MITI's role in this achievement (see brief review in Watanabe and Honda, 1991, 1992). Mansfield (1983), in his extensive study on the effects of government support on privately financed energy R&D, identified that federally supported R&D expenditures substituted for private expenditures from 3% to 20% and induced an additional 12% to 25% increase in private R&D investments. He concluded that while the direct returns from federally financed R&D projects might be lower, the projects seemed to expand the opportunities faced by firms and induced additional R&D investments by them. Scott (1983) demonstrated Mansfield's postulate by providing supportive results such as the fact that government-supported R&D encourages company-financed R&D. The author (e.g., Watanabe and Clark, 1991) identified similar functions in MITI's industrial technology policy.

A number of studies have also identified a substitution mechanism of certain production factors for energy. Since the first energy crisis in 1973, with the introduction of the translog production function, there have been a number of attempts to identify the possible substitutability of energy to other production factors (e.g., Christensen et al., 1973; National Institute for Research Advancement, 1983). However, these works deal with labor, capital and energy (while other works also deal with materials) as production factors, and none have taken the technology factor into account. Although some pioneering work attempted to use a time trend or dummy variable as a proxy for technological change, such methodologies are hardly satisfactory for analyzing the nonlinear effects of R&D investment. Hogan and Jorgenson (1991) pointed out that change in technology might be the most important effect, possibly even dominating the simple substitution among input factors resulting from the scarcity of production resources. While attempting to describe technology as a linear function of time, they postulated the significance of expanded efforts for a nonlinear technology description. The author (Watanabe, 1992a, 1995b,e), by measuring technology knowledge stock and incorporating it into a translog cost function, identified the sources of Japan's success in overcoming energy crises in the 1970s by means of technology substitution for energy. Attempts have also been made to apply this substitution mechanism for a solution to the global environment (Watanabe, 1993, 1995d). This work warned that the current stagnation in industry R&D might weaken the existing substitution leading to the rise of energy (and environmental) constraints (Watanabe, 1992b, 1995c). Although all of these studies contribute to proving the above hypothetical views, they have not taken a comprehensive systems perspective on the complementary role of government and industry by describing details of energy and non-energy technologies. Given the comprehensive and systematic nature of the global warming and policy relevance to this issue, particularly to technology options for sustainable growth centered on the allocation of R&D investment to energy R&D and non-energy R&D, a comprehensive systems approach seems to be essential.

This paper undertakes such an approach and by analyzing MITI's policy system, attempts to prove the hypothetical views that MITI's policy directed to the appropriate technology option, and functioned well in stimulating technology substitution for energy, thereby inducing the vitality of industry for this substitution. Secondly, it provides an assessment of MITI's industrial technology policy for mitigating global warming by stimulating substitution under the current R&D stagnation.

Section 2 reviews MITI's efforts to induce industry's energy R&D. Section 3 analyzes the mecha-

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[2] In the latter half of the 1980s, the Japanese economy entered into a spiral of spending and investment speculations that brought about an unsustainable economic bubble during which land and stock prices rose more than three to five times within a span of 5 years. The boom is exemplified in financial investment, especially in land and stocks which provided investors a myth that their assets had ballooned, resulted in less investment in technology and capital. This phenomena, referred to as Japan's 'bubble economy', started in 1987 and lasted until 1990.

Table 2
Trends in the ratio of government energy R&D expenditure and GDP in G7 countries (1975–1994)—percentile (1/100%)

| | 1975 | 1980 | 1985 | 1990 | 1994 |
|---|---|---|---|---|---|
| Japan | 0.67 | 1.26(0.32) | 1.18(0.26) | 0.87(0.16) | 0.91(0.23) |
| USA | 0.77 | 1.46(0.89) | 0.60(0.30) | 0.45(0.30) | 0.33(0.27) |
| Germany | 1.18 | 1.28(0.42) | 0.93(0.23) | 0.35(0.14) | 0.19(0.08) |
| UK | 1.04 | 0.98(0.29) | 0.82(0.26) | 0.30(0.10) | 0.11(0.07) |
| Canada | | 0.91(0.51) | 1.04(0.62) | 0.57(0.32) | 0.42(0.20) |
| Italy | | 0.73(0.09) | 1.29(0.10) | 0.61(0.40) | 0.34(0.18) |
| France | | | | 0.49(0.10) | 0.42(0.20) |

[a] Figures in Germany before 1990 are only for the FRG.
[b] Figures in parenthesis indicate the ratio of non-nuclear energy R&D expenditure.
Sources: Energy Research, Development and Demonstration in the IEA Countries (IEA, 1980); Review of National Programmes (IEA, 1981); Energy Policies and Programmes of IEA Countries, 1987 Review (IEA, 1988); Energy Policies and Programmes of IEA Countries, 1994 Review (IEA, 1995).

nism of Japan's notable success in substituting technology for energy. Section 4 provides an assessment of the effect and limit of existing policy. Section 5 briefly summarizes implications for sustainable development.

## 2. MITI's efforts to induce energy R&D

### 2.1. Structure of Japan's energy R&D

R&D investment has various characteristics, including uncertainty, huge risk, high cost, and a long lead-time. In addition to these, energy R&D has a strong public nature, a close relationship with national security and is sensitive to such opaque factors as trends in international oil prices. Thus, strong government policy involvement based on a long-term and comprehensive perspective is required for energy R&D. This is particularly the case in Japan where the energy structure is extremely fragile compared to other advanced countries. Table 2 compares trends in the ratio of government energy R&D expenditure and GDP in G7 nations after the first energy crisis. Looking at the table we note that Japan, unlike other advanced countries, maintained a higher level of government energy R&D expenditure even after the downward movement in international oil prices (starting from 1983). Japan's ratio of government energy R&D expenditure and GDP in 1994 was 0.91 percentile (1/100%) while in the USA, Germany and the UK it was 0.33, 0.19 and 0.11 percentile, respectively. However, Japanese government energy R&D expenditure is biased with respect to nuclear energy R&D. Its non-energy R&D ratio in 1994 was 0.23 percentile, which is lower than the ratio in the USA (0.27) and comparable to the ratios of France (0.20), Canada (0.20) and Italy (0.18).

Energy R&D policies in all nations are executed depending upon indigenous energy security conditions and policy systems. Among these policies in advanced nations, Japan, with an extremely fragile energy structure, has made energy R&D policy one of its highest priority policy issues. This can be clearly observed particularly after the second energy crisis in 1979 with the following: (i) almost 3/4 of the government energy R&D budget has been appropriated to nuclear energy R&D with a long/very-long-term perspective; and (ii) comprehensive energy R&D policy with a medium- and long-term perspective has been executed at a cross-point between R&D policy and energy and industrial policies aiming at inducing industry's vitality.

The former includes R&D on nuclear fusion and breeders initiated primarily by the Japan Atomic

Table 3
Trends in Japanese government energy R&D expenditure and MITI's share (billion yen at 1985 fixed prices)

| | Energy R&D total | | Non-nuclear energy R&D | |
|---|---|---|---|---|
| | Government total | MITI (share) | Government total [non-nuclear share] | MITI (share) [non-nuclear share] |
| 1980 | 310.1 | 81.3 (26.2%) | 78.4 [25.3%] | 71.2 (90.8%) [87.5%] |
| 1985 | 371.6 | 115.1 (31.0%) | 91.1 [24.5%] | 89.7 (98.4%) [78.0%] |
| 1994 | 403.0 | 112.6 (27.9%) | 101.9 [25.3%] | 92.2 (90.5%) [81.9%] |

Source: Energy Policies of IEA Countries, 1996 Review (IEA, 1997).

Research Institute and the Power Reactor and Nuclear Fuel Development under the Science and Technology Agency's initiative. The latter includes comprehensive energy R&D policies aiming at technology substitution for energy initiated by MITI with a medium- and long-term energy security perspective.

Table 3 summarizes trends in Japanese government energy R&D expenditure and MITI's share in 1980, 1985 and 1994. It indicates that (i) almost 3/4 of total government energy R&D was for nuclear R&D; (ii) MITI's energy R&D (more than 78% was for nonnuclear R&D) share was 26% to 31%; and (iii) MITI was primarily responsible for Japanese

Table 4
Trends in MITI and manufacturing industry's R&D expenditure (1955–1994): billion yen (1985 fixed prices), %

| Year | MITI's R&D budget | | | | | | Manufacturing industry's R&D expenditure | | | Government support ratio | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MITIR[a] | MER[b] | MTDE[c] | MTDD[d] | b/a[e] | c/a[f] | *R*[g] | ER[h] | h/g[i] | Total[j] | Ene[k] | non-E[l] |
| 1955 | 12.0 | 2.4 | 0.4 | 2.0 | 20.0% | 3.6% | 227.3 | 6.5 | 2.8% | 10.5% | 14.7% | 10.4% |
| 1956 | 12.9 | 2.6 | 0.5 | 2.1 | 20.4% | 3.7% | 281.0 | 7.0 | 2.5% | 10.0% | 15.0% | 9.9% |
| 1957 | 13.8 | 3.0 | 0.5 | 2.5 | 21.7% | 3.7% | 320.3 | 8.2 | 2.6% | 9.9% | 14.6% | 9.7% |
| 1958 | 16.3 | 3.5 | 0.6 | 2.9 | 21.4% | 3.7% | 325.6 | 9.3 | 2.8% | 9.0% | 15.0% | 8.8% |
| 1959 | 18.3 | 3.9 | 0.7 | 3.2 | 21.3% | 3.8% | 391.8 | 10.1 | 2.6% | 7.3% | 15.4% | 7.1% |
| 1960 | 19.7 | 4.2 | 0.7 | 3.5 | 21.1% | 3.6% | 491.7 | 11.1 | 2.2% | 6.2% | 15.1% | 6.0% |
| 1961 | 20.7 | 4.4 | 0.8 | 3.6 | 21.0% | 3.6% | 593.4 | 11.3 | 1.9% | 6.4% | 15.4% | 6.3% |
| 1962 | 21.4 | 4.5 | 0.8 | 3.7 | 20.9% | 3.6% | 628.0 | 11.8 | 1.9% | 5.9% | 15.1% | 5.7% |
| 1963 | 23.6 | 4.9 | 0.8 | 4.1 | 20.8% | 3.5% | 684.0 | 13.0 | 1.9% | 5.1% | 15.1% | 4.9% |
| 1964 | 27.5 | 5.7 | 1.0 | 4.7 | 20.9% | 3.5% | 778.4 | 15.0 | 1.9% | 5.8% | 15.3% | 5.6% |
| 1965 | 26.9 | 5.7 | 1.0 | 4.7 | 21.3% | 3.6% | 741.5 | 15.1 | 2.0% | 5.3% | 15.2% | 5.1% |
| 1966 | 34.0 | 7.1 | 1.2 | 5.9 | 20.8% | 3.5% | 845.3 | 18.5 | 2.1% | 4.0% | 15.3% | 3.7% |
| 1967 | 37.0 | 7.7 | 1.3 | 6.4 | 20.9% | 3.5% | 1062.1 | 20.4 | 1.9% | 3.2% | 15.2% | 3.0% |
| 1968 | 43.0 | 9.0 | 1.5 | 7.5 | 21.0% | 3.6% | 1354.5 | 23.9 | 1.8% | 3.6% | 15.1% | 3.4% |
| 1969 | 46.1 | 9.6 | 1.6 | 8.0 | 20.8% | 3.6% | 1587.9 | 25.4 | 1.6% | 3.4% | 15.2% | 3.2% |
| 1970 | 48.6 | 10.2 | 1.7 | 8.5 | 21.0% | 3.6% | 1966.1 | 26.9 | 1.4% | 3.2% | 15.2% | 3.0% |
| 1971 | 53.2 | 11.7 | 2.0 | 9.7 | 22.0% | 3.7% | 2006.7 | 30.7 | 1.5% | 3.9% | 15.3% | 3.7% |
| 1972 | 67.3 | 15.2 | 2.6 | 12.6 | 22.5% | 3.8% | 2201.4 | 39.8 | 1.8% | 2.9% | 15.2% | 2.6% |
| 1973 | 78.5 | 17.6 | 3.0 | 14.6 | 22.4% | 3.8% | 2290.8 | 46.4 | 2.0% | 3.5% | 15.2% | 3.3% |
| 1974 | 87.1 | 22.5 | 4.3 | 18.2 | 25.8% | 4.9% | 2259.1 | 59.0 | 2.6% | 3.1% | 20.9% | 2.7% |
| 1975 | 87.9 | 30.5 | 6.5 | 24.0 | 34.7% | 7.4% | 2230.0 | 80.0 | 3.6% | 3.4% | 21.0% | 2.8% |
| 1976 | 87.3 | 30.6 | 7.8 | 22.8 | 35.1% | 8.9% | 2324.9 | 80.6 | 3.5% | 2.5% | 20.9% | 1.8% |
| 1977 | 85.0 | 36.4 | 9.3 | 27.1 | 42.8% | 10.9% | 2484.6 | 105.0 | 4.2% | 2.4% | 20.9% | 1.6% |
| 1978 | 91.5 | 44.0 | 12.8 | 31.1 | 48.0% | 14.0% | 2666.7 | 115.7 | 4.3% | 2.0% | 21.0% | 1.1% |
| 1979 | 126.9 | 56.0 | 17.5 | 38.5 | 44.1% | 13.8% | 2865.5 | 165.6 | 5.8% | 2.3% | 21.0% | 1.1% |
| 1980 | 170.4 | 81.3 | 39.4 | 41.9 | 47.7% | 23.1% | 3133.8 | 249.3 | 7.9% | 2.9% | 21.3% | 1.3% |
| 1981 | 192.3 | 102.2 | 45.0 | 57.2 | 53.1% | 23.4% | 3544.3 | 266.8 | 7.5% | 3.2% | 22.9% | 1.6% |
| 1982 | 181.7 | 103.2 | 52.5 | 50.7 | 56.8% | 28.9% | 3851.8 | 269.6 | 7.0% | 3.0% | 22.9% | 1.5% |
| 1983 | 181.4 | 108.9 | 52.7 | 56.2 | 60.0% | 29.0% | 4344.1 | 239.1 | 5.5% | 2.9% | 26.9% | 1.5% |
| 1984 | 171.5 | 110.7 | 49.4 | 61.3 | 64.6% | 28.8% | 4776.5 | 235.9 | 4.9% | 2.7% | 26.0% | 1.5% |
| 1985 | 198.7 | 115.1 | 54.9 | 60.2 | 57.9% | 27.6% | 5543.6 | 243.3 | 4.4% | 2.6% | 26.1% | 1.5% |
| 1986 | 223.6 | 120.0 | 56.7 | 63.3 | 53.7% | 25.4% | 5898.9 | 266.8 | 4.5% | 3.1% | 26.9% | 2.0% |
| 1987 | 226.4 | 117.1 | 56.8 | 60.3 | 51.7% | 25.1% | 6238.4 | 254.4 | 4.1% | 3.1% | 27.6% | 2.1% |
| 1988 | 221.5 | 111.5 | 47.8 | 63.7 | 50.3% | 21.6% | 6761.4 | 258.0 | 3.8% | 2.8% | 25.9% | 1.9% |
| 1989 | 224.4 | 115.0 | 48.7 | 66.3 | 51.2% | 21.7% | 7402.7 | 271.5 | 3.7% | 2.6% | 25.4% | 1.7% |
| 1990 | 232.8 | 121.1 | 47.7 | 73.4 | 52.0% | 20.5% | 8071.1 | 275.9 | 3.4% | 2.7% | 26.3% | 1.9% |
| 1991 | 237.2 | 108.9 | 38.8 | 70.2 | 45.9% | 16.4% | 8522.2 | 287.3 | 3.4% | 2.8% | 23.5% | 2.1% |
| 1992 | 240.9 | 109.5 | 39.7 | 69.8 | 45.4% | 16.5% | 8337.5 | 289.7 | 3.5% | 2.8% | 23.4% | 2.1% |
| 1993 | 265.3 | 112.5 | 42.0 | 70.5 | 42.4% | 15.8% | 7953.5 | 277.6 | 3.5% | 2.8% | 23.2% | 2.1% |
| 1994 | 264.2 | 112.6 | 44.2 | 68.4 | 42.6% | 16.7% | 7825.5 | 280.4 | 3.6% | 2.8% | 23.1% | 2.1% |

government non-nuclear energy R&D with more than 90% of the total government budget.

MITI's involvement in the broad area of energy R&D covers R&D on energy conservation, renewable energy, coal, oil and gas, nuclear power, electric power and energy storage. This R&D can be classified into the following policy programs: (i) programs for *R&D on technology driven energy* of the Sunshine Project (R&D on new energy technology, including sola, geothermal, coal conversion, hydrogen, wind, ocean and biomass energy) and the Moonlight Project (R&D on energy conservation technology); and (ii) programs for *R&D on technology development for diversifying energy* sources utilizing coal technology, oil and gas technology, nuclear energy technology and electric power technology.

On the basis of the above review, Table 4 summarizes trends in the R&D expenditure of MITI and the manufacturing industry over the period 1955–1994 by classifying total R&D and energy R&D. In the case of MITI's energy R&D, both technology driven energy R&D and R&D on technology development for diversifying energy sources are included. The government (MITI) support ratio for both energy and non-energy R&D initiated by manufacturing industry is also shown. Looking at Table 4, we note the following noteworthy trends with respect to Japan's energy R&D over the medium- to long-term.

(i) The government support ratio for energy R&D initiated by manufacturing industry was higher than 14% over all of the periods examined, and it increased to more than 20% after the first energy crisis in 1973. The corresponding ratio for non-energy R&D decreased as Japan's technological level improved, and it now stands at almost 2%. These trends demonstrate the significant consequences of Japan's energy R&D in terms of national security (Industrial Structure Council of MITI, 1982).

(ii) Reflecting the above policy consequences, the ratio of MITI's energy R&D budget out of its total R&D budget increased dramatically from 20% before the first energy crisis to 35% in 1975, 48% in 1980, 65% in 1984, and 43% currently. Such a dramatic increase can be attributed particularly to the R&D budget for technology driven energy R&D, which represented almost 30% of MITI's total R&D budget and was 10 times higher than before the first energy crisis. This share changed to a decreasing trend as international oil prices started to fall in 1983, and accounts for nearly 16% currently.

(iii) In line with the foregoing, the share of energy R&D expenditure in manufacturing industry reached its highest level in the early 1980s and changed to a decreasing trend. It is currently 3.5%, which is almost the same level as after the first energy crisis.

### 2.2. Paths to establishing a policy system for technology substitution for energy

Japan has adopted different industrial policies throughout its economic development, all of which reflect the international, natural, social, cultural and historical environment of the post-war period (Watanabe and Clark, 1991). In the late 1940s and 1950s, Japan made every effort to reconstruct its war-ravaged economy, laying the foundation for vi-

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Notes to Table 4:

[a] MITIR: MITI's total R&D budget; [b] MER: MITI's energy R&D budget; [c] MTDE: MITI's R&D budget for technology driven energy R&D; [d] MTDD: MITI's R&D budget for technology development for diversifying energy sources.

[g] *R*: Manufacturing industry's total R&D expenditure; [h] ER: manufacturing industry's energy R&D expenditure.

[j] Total: Ratio of government R&D funds in manufacturing industry's R&D expenditure total; [k] Energy: ratio of government R&D funds in manufacturing industry's energy R&D expenditure; [l] non-E: ratio of government R&D funds in manufacturing industry's non-energy R&D expenditure.

Sources: Report on the Survey of Research and Development (Management and Coordination Agency, 1956–1995, annual issues); Report on the Survey of Research and Development—Supplemental Surveys on R&D on Energy (Management and Coordination Agency, 1977–1995, annual issues); Annual Report on MITI's policy (MITI, 1955–1994, annual issues); Historical Review of MITI's policy (MITI, 1993); White Paper on Japanese Science and Technology (Science and Technology Agency, 1962–1995, annual issues); Report on the Survey of Industry's R&D Activities (Science and Technology Agency, 1966–1995, annual issues); State and Evaluation of Energy Conservation in Japan (Mitsubishi Research Institute, 1979); Economic Analysis of Technological Innovation and R&D (Wakasugi, 1986); Japan's R&D Investment (Uchino, 1962).

able economic growth. During the decade of the 1960s, Japan actively sought to open its economy to foreign competition by liberalizing trade and the flow of international capital. In the process, supported by a cheap and stable energy supply, it achieved rapid economic growth (see Fig. 1) led by the heavy and chemical industries. Unfortunately, the heavy concentration of such highly material-intensive and energy-intensive industries and population in Japan's Pacific belt area led to serious environmental pollution problems (Watanabe, 1973), which necessitated a reexamination of industrial policy (MITI, 1993).

Recognizing the need for a change in direction, MITI formulated a new plan for Japan's industrial development. Published in May 1971 as 'MITI's Vision for the 1970's (Industrial Structure Council of MITI, 1971)', this plan proposed a shift to a knowledge-intensive industrial structure which would reduce the burden on the environment by depending more on technology and less on energy and materials. The vision stressed the significant role of innovative R&D which leads to less dependency on materials and energy in the process of production and consumption. It also stressed that such reduced dependency could be possible by means of intensive conservation and recycling of materials and energy in a long, global and ecological context, and that R&D aiming to develop 'limit-free energy technology' (technology-driven clean energy) was significant (Industrial Structure Council of MITI, 1971).

In order to identify the required basic concept for industry and the industrial technology policies to contribute to the establishment of the industrial structure proposed in its vision, MITI organized an ecology research group in May 1971 (MITI, 1972a). Consisting of experts from ecology-related disciplines, this group defined the ecology science for studying the global environment (MITI, 1972b). Specifically, it proposed the concept of 'Industry–Ecology' as a comprehensive method for analyzing and evaluating the complex mutual relations between human activities centering around industry and the surrounding environment (MITI, 1972b). On the basis of its extensive research work, and encouraged by its first research report in March 1972 (Watanabe, 1973), MITI attempted to develop both a new policy principle to be applied to its industry and industrial technology policies as well as a new policy system based on this principle from April 1972 (Watanabe, 1972). In the summer of 1973, MITI concentrated on further developing R&D programs and creating an environmentally friendly energy system in order to reestablish an ideal equilibrium for the ecosystem (MITI, 1993).

The first energy crisis occurred a few months later, stimulating the urgent reduction of redundancy by taking ecological considerations into account. MITI focused its efforts on securing an energy supply in the face of increasing oil prices. Given these circumstances, it initiated a new policy based on the Basic Principle of Industry Ecology to secure a solution for basic energy problems by means of R&D on new and clean energy technology. This policy led to the establishment of a new program, the Sunshine Project (R&D on New Energy Technology) in July 1974 (MITI, 1993). The Basic Principle of Industry Ecology suggests substitution among available production factors in a closed system in order to achieve sustainable development under certain constraints [3] (Odum, 1963). The Sunshine Project initiated this approach by enabling the substitution of technology driven energy (an unlimited source) for limited energy sources, such as oil. Further substitution efforts were to be made not only in the energy supply field but also in the field of energy consumption. Improvement in energy efficiency by means of technological innovation could reduce dependency on energy (i.e., the substitution of technology for energy). In line with this policy consideration, MITI initiated the Moonlight Project (R&D on Energy Conservation Technology) in 1978 (MITI, 1993).

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[3] Under the circumstances of a 'constrained economy', it is generally pointed out that most efforts to overcome constraints have been directed at substituting unlimited production factors for a constrained (or limited) production factor (Binswanger, 1977). This is similar to an ecosystem in that in order to maintain homeostasis (checks and balances that dampen oscillations), when one species slows down, another speeds up in a compensatory manner in a closed system (substitution), while depending on supplies from an external system leads to dampen homeostasis (complement) (Odum, 1963). This concept of 'substitution' provides informative suggestions for a 'constrained economy'. In this particular case, energy is the constrained production factor and technology is the unlimited production factor.

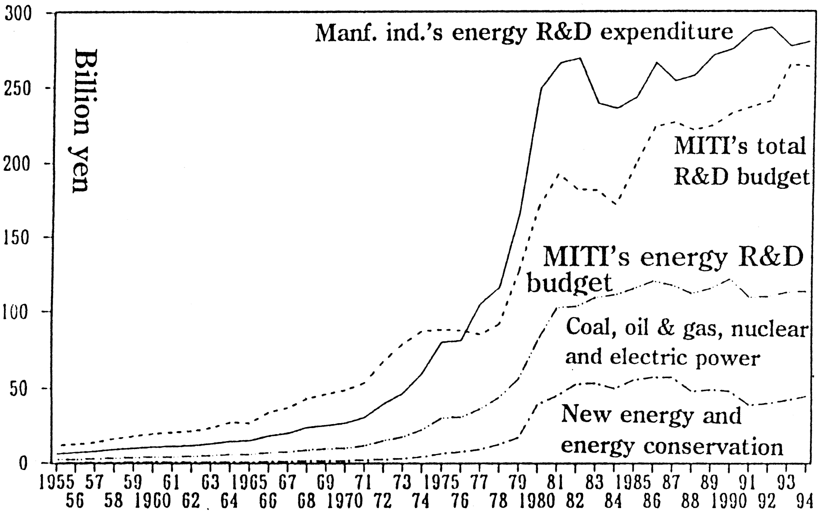

Fig. 2. Trends in energy R&D expenditure by MITI and Japan's manufacturing industry (1955–1994)—1985 fixed prices (billion yen).

Facing the second energy crisis in 1979, MITI implemented policies to substitute an unlimited resource (technology) for a limited resource (energy) in order to induce industrial vitality for sustainable development. MITI's budget for the Sunshine Project and the Moonlight Project represented 4.9% of its total R&D budget in 1974, 13.8% in 1979, and 28.9% in 1982 (see Table 4 and Fig. 2).

### *2.3. Function of MITI's energy R&D policy*

The functional points of MITI's energy R&D policy aiming for sophisticated energy use through technology substitution for energy can be summarized as follows: (i) Encourage broad involvement of cross sectoral industry in national R&D program projects such as the Sunshine Project and Moonlight Project by stimulating the competitive nature of industry. (ii) Stimulate cross sectoral technology spillover and inter-technology stimulation. (iii) Induce vigorous industry activity in the broad area of energy R&D. (iv) This inducement should then lead to an increase in industry's technology knowledge stock of energy R&D which has a transtechnological and sectoral stimulation function. (v) This inducement can then play a catalytic role for industry's technology substitution for energy.

Table 5 identifies firms participating in the Sunshine Project and Moonlight Project in 1992. Looking at the table we note that a significant number (115 firms in total) of leading intersectoral firms (one-half of the top 40 R&D firms) participated in not a few projects, which infers active trans-projects and that trans-firm transfers and spillovers of technology resulted.

As demonstrated in Table 6, a significant number of patents have been applied for by a broad range of project participants. Table 6 demonstrates a case of patent applications derived from the fuel cell R&D projects of the Moonlight Project. Noteworthy is that more than 60% of the patents were applied for by the machinery industry, not such energy dependent industries as electric power, city gas, oil and chemicals. This demonstrates an active technology spillover from high-tech industry to energy intensive industry.

Table 7 summarizes an analysis of the inducing impacts of MITI's energy R&D such as energy conservation, solar, coal, oil and gas, nuclear and electric power on similar energy R&D initiated by the Japanese manufacturing industry. Looking at the table we note that MITI's energy R&D significantly induced industry's R&D based on a 1- to 2-year time-lag.[4] The correlations of technology driven

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[4] The inducement of relative prices of energy is small or statistically insignificant in many cases examined. This suggests that trends in energy prices are reflected in trends for MITI's energy R&D budget (see Eq. (13) in Section 4).

Table 5
Firms participating in the sunshine project and moonlight project in 1992

| | |
|---|---|
| *The Sunshine Project (61)* | |
| Chemicals (15) | 24 Asahi Chemical Industry, 29 Mitsubishi Kasei, Mitsui Toatsu Chemicals, Kaneka, Daito Hoxan, Japan Catalytic Chemicals, Nippon Steel Chemical, Idemitsu Oil, Tonen, Nippon Oil, Cosmo Oil, Nikko Kyoseki Oil, Oil Resources Development, Sumitomo Coal Mining, Mitsui Coal Liquefaction |
| Ceramics (4) | 33 Asahi Glass, Kyocera, NGK Spark Plug, Shinagawa Refractories |
| Iron and steel (7) | Nippon Steel, 33 Sumitomo Metal Industries, 26 Kobe Steel, NKK, 28 Kawasaki Steel, Japan Steel Works, Japan Metal and Chemicals |
| Nonferrous metals and products (5) | Sumitomo Electric Industries, Sumitomo Metal Mining, Hitachi Cable, Mitsui Mining and Smelting, Osaka Titanium |
| Machinery (20) | 3 Hitachi, 6 Toshiba, 35 Ishikawajima–Harima Heavy Industries, 12 Mitsubishi Industries, 10 Mitsubishi Electric, 38 Fuji Electric, 32 Oki Electric Industry, 15 Sharp, 17 Sanyo Electric, Ebara, Mitsui Engineering and Shipbuilding, 2 Matsushita Electric Industry, Yuasa Battery, Japan Storage Battery, Matsushita Battery, Bab and Cock Hitachi, Yamatake–Honeywell, Koto Electric, 1 Toyota Motor, 8 Nissan Motor |
| Public utilities (4) | EPDC, Tohoku Electric Power, Okinawa Electric Power, Tokyo Gas |
| Construction (6) | JGC, TEC Electrics, Chiyoda, Kandenko, Ohte Development, Geothermal Technology Development |
| *The Moonlight Project (54)* | |
| Chemicals (3) | 24 Asahi Chemical Industry, 29 Mitsubishi Kasei, Ube Industries |
| Ceramics (4) | 33 Asahi Glass, Kyocera, NGK Spark Plug, NGK Insulators |
| Iron and steel (3) | 33 Sumitomo Metal Industries, 26 Kobe Steel, NKK |
| Nonferrous metals and products (5) | Sumitomo Metal Industries, Hitachi Cable, Fujikura, Showa Electric Wire and Cable, Furukawa Electric |
| Machinery (23) | 3 Hitachi, 6 Toshiba, 35 Ishikawajima–Harima Heavy Industries, 12 Mitsubishi Industries, Kawasaki Heavy Industries, 10 Mitsubishi Electric, Fuji Electric, 17 Sanyo Electric, Ebara, Mitsui Engineering and Shipbuilding, Kubota, Yokogawa Electric, Murata, Maekawa Manufacturing, Aishin Seki, Daikin Industries, Sumitomo Precision Products, Hitachi Zosen, Niigata Engineering, Yammer Diesel, Yuasa Battery, Japan Storage Battery, Matsushita Battery |
| Public utilities (11) | Hokkaido Electric Power, Tohoku Electric Power, 19 Tokyo Electric Power, Chubu Electric Power, Hokuriku Electric Power, Kansai Electric Power, Chugoku Electric Power, Shikoku Electric Power, Kyusyu Electric Power, EPDC, Osaka Gas |
| Construction (5) | JGC, TEC Electrics, Chiyoda, Shimizu, Obayashi |

[a] Figures heading firms indicate orders of R&D expenditure in 1992 out of 40 firms (19 firms out of 40 participated).
[b] Figures in parentheses indicate number of firms in respective sectors.

Table 6
Number of patent applications derived from the moonlight project —a case of fuel cell R&D (January 1991–August 1994)

| Sector | SOFC[a] | PEFC[b] |
|---|---|---|
| Chemicals and ceramics | 78 (10.9%) | 5 (3.5%) |
| Machinery | 436 (60.9%) | 98 (69.0%) |
| Energy (electric power, city gas and oil) | 132 (18.4%) | 5 (3.5%) |
| Government | 21 (2.9%) | 3 (2.1%) |
| Foreign participants | 41 (5.7%) | 3 (2.1%) |
| Others | 8 (1.1%) | 28 (19.7%) |
| Total 716 (100%) | 716[c] (100%) | 142 (100%) |

[a] SOFC: Solid oxide fuel cells (started in 1981).
[b] PEFC: Polymer electrolyte fuel cells (started in 1992).
[c] Include 23 utility models.
Source: Trends in Patent Applications (Patent Office, 1995).

energy R&D as R&D on energy conservation, renewable energy and coal technologies led by both the Moonlight Project and the Sunshine Project are distinctive, while the correlations of R&D on technology development for diversifying energy sources as R&D on oil and gas, nuclear energy and electric power are relatively less distinctive. This analysis demonstrates the above hypothetical views discussed earlier.[5]

Coinciding with the establishment of the Sunshine Project (1974) and the Moonlight Project (1978), similar strategies for sophisticated energy use were postulated in the USA, including 'A Time to Choose' by The Ford Foundation (1974) and 'Soft Energy Paths' by Lovins (1977). The former stressed the significance of the redirection of federal energy R&D to goal oriented programs with major goals of energy conservation, diversity of energy supplies and environmental protection. It argued that a major new thrust in R&D addressed to energy conservation opportunities was urgently needed to sustain 'the Technical Fix Scenario' (an attempt to anticipate the results if long-term energy prices and government policies were to encourage greater efficiency in energy conservation) beyond the 1990s. Although this postulate resembles MITI's energy R&D policy aiming at technology substitution for energy, it simply aimed at developing individual near- and medium-term technologies for energy saving rather than stimulating cross sectoral technology spillover and inter-technology stimulation of prioritizing R&D on technology driven energy. Furthermore, it stressed direct government purchasing toward energy conservation equipment to provide a market for the most advanced energy saving technologies rather than a catalytic role by government in industry's technology substitution for energy. Thus, notwithstanding its invaluable and thoughtful insights, as far as industry's involvement in securing sophisticated energy use is concerned, 'A Time to Choose' was hardly satisfactory in inducing vigorous industry activity in the broad area of energy R&D (Tavoularreas and Kaysen, 1977; Kates and Burton, 1986).

Contrary to the Ford Foundation's proposal, 'Soft Energy Paths' raised a basic and fundamental question regarding dependency and energy utilization in a mass production economy. Its basic principles lie on a small and stand-alone system rather than an integrated system depending upon the economies of scale. Although some principles postulated by 'Soft Energy Paths' were incorporated into MITI's policy, it was hardly operational in restructuring MITI's overall energy R&D policy. This policy was not operational because of the difficulty in sustaining the coevolution of existing socioeconomic activities and long-lasting institutional systems. However, as the global environmental consequences of $CO_2$ discharge resulting from energy use causes mounting concern regarding the sustainability of our future development, principles postulated by A.B. Lovins have been gaining support and his recent postulate, 'Factor Four' (Weizacker et al., 1998), has generally been well accepted by industry in its efforts toward sustainable growth under strong energy and environmental constraints.

## 3. Technology substitution for energy—Japan's notable achievement

### *3.1. Factors contributing to success in achieving environmentally friendly sustainable development*

Despite many handicaps, Japan realized a notable improvement in its energy efficiency after the energy

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[5] A questionnaire to manufacturing firms involved in MITI's energy R&D Program projects undertaken in 1993 (valid sample: 54 firms) revealed firm expectations of MITI's energy R&D as follows: supplement industry's R&D (38%), induce industry's R&D (35%), relax energy constraints (24%) and others (3%).

Table 7
Inducing impacts of MITI's energy R&D on energy R&D initiated by the Japanese manufacturing industry (1977–1994)

| | Adj. $R^2$ | DW |
|---|---|---|
| (1) R&D on energy conservation (CONSV) vs. MITI's moonlight (ML) and non-energy R&D (MITInERD) | | |
| $\ln(\text{CONSV}) = 3.149 + 0.437_{(6.41)} \ln(\text{LAG2}(\text{ML})) + 0.285_{(2.09)} \ln(\text{LAG1}(\text{MITInERD})) + 0.003_{(0.02)} \ln(\text{Pey})^{\text{Relative energy price}} + 0.411\, D_{(4.58)_{1979-1981=1}}$ | 0.950 | 1.57 |
| (2) R&D on solar energy (SOLAR) vs. MITI's solar energy R&D (SS) | | |
| $\ln(\text{SOLAR}) = 0.981 + 0.871_{(13.62)} \ln(\text{LAG1}(\text{SS})) + 0.011_{(0.05)} \ln(\text{Pey}) + 0.285 D_{(2.48)_{1979,\,1980=1}}$ | 0.936 | 1.17 |
| (3) R&D on coal energy (COAL) vs. MITI's coal conversion (SC) and coal combustion (MC) | | |
| $\ln(\text{COAL}) = -0.584 + 0.289_{(6.91)} \ln(\text{LAG2}(\text{SC})) + 0.845_{(3.12)} \ln(\text{LAG1}(\text{MC})) + 0.509_{(1.10)} \ln(\text{Pey}) + 1.630\, D_{(5.60)_{1980=1}}$ | 0.947 | 2.39 |
| (4) R&D on oil and gas (OILGAS) vs. MITI's oil and gas R&D (MOG) | | |
| $\ln(\text{OILGAS}) = 0.998 + 0.858_{(11.11)} \ln(\text{LAG1}(\text{MOG})) + 1.362_{(6.31)} \ln(\text{Pey}) + 0.721\, D_{(5.36)_{1979,\,1980=1}}$ | 0.898 | 1.92 |
| (5) R&D on nuclear energy (NUCLEAR) vs. MITI's nuclear energy R&D (MN) | | |
| $\ln(\text{NUCLEAR}) = 3.990 + 0.425_{(8.98)} \ln(\text{LAG2}(\text{MN})) + 0.022_{(0.17)} \ln(\text{Pey}) - 0.192\, D_{(-2.38)_{1979,\,1980=1}}$ | 0.896 | 1.93 |
| (6) R&D on electric power (ELECTRIC) vs. MITI's electric power R&D (MEP) | | |
| $\ln(\text{ELECTRIC}) = -1.882 + 1.413_{(10.49)} \ln(\text{LAG1}(\text{MEP})) + 0.865_{(1.55)} \ln(\text{Pey}) + 1.431\, D_{(3.95)_{1979,\,1980=1}}$ | 0.868 | 2.05 |

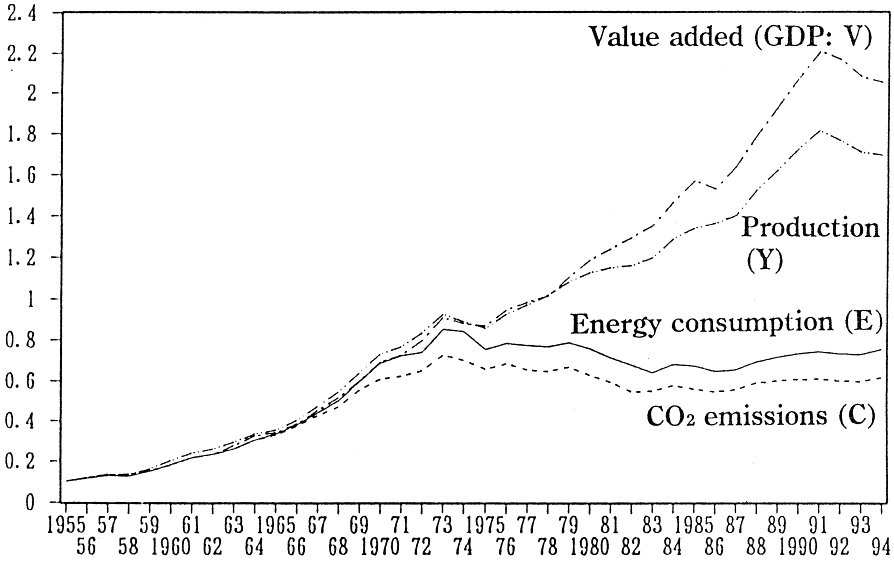

Fig. 3. Trends in production, energy consumption and $CO_2$ discharge in the Japanese manufacturing industry (1955–1994)—Index: 1955 = 0.1.

crises of the 1970s and was able to maintain sustainable economic development with a minimum increase in energy dependency and $CO_2$ emissions. Fig. 3 demonstrates the dramatic path of Japan's manufacturing industry over the last four decades.

Looking at Fig. 3, we note that despite the damaging impact of the energy crises, industry was able to maintain steady development and increase production while keeping energy consumption and $CO_2$ emissions to a minimum. In order to elucidate the sources of this dramatic shift, Table 8 and Fig. 4 analyze factors contributing to changes in manufacturing industry $CO_2$ emissions over the period 1970–1994. Table 8 and Fig. 4 demonstrate that while the average annual increase in production by value added between 1974 and 1994 was maintained at a reasonable level of 4.06%, average $CO_2$ emissions fell by 0.71%. Table 8 and Fig. 4 indicate that 71% of this reduction in $CO_2$ can be attributed to efforts to improve energy efficiency ($\Delta(E/Y)/(E/Y)$) while 22% can be attributed to a change in industrial structure. The contribution of fuel switching ($\Delta(C/E)/(C/E)$) was only 4%. This analysis coincides with the examination in Section 1 and confirms that Japan's success in attaining environmentally friendly sustainable development after the first energy crisis in 1973 depended largely on the results of efforts to reduce energy dependency.

If we examine $CO_2$ discharge trends and contributing factors at different times, we find that the

Table 8
Factors contributing to change in $CO_2$ emissions in the Japanese manufacturing industry (1970–1994)

| Period | $CO_2$ emissions ($\Delta CO_2/CO_2$) | Fuel switching [$\Delta(C/E)/(C/E)$] | Energy efficiency [$\Delta\,(E/Y)/(E/Y)$] | Change in industrial structure [$-\Delta(V/Y)/(V/Y)$] | GDP growth ($\Delta V/V$) | Miscellaneous ($\varepsilon$) |
|---|---|---|---|---|---|---|
| 1970–1973 | 7.12 | −2.19 | −0.20 | −1.10 | 11.00 | −0.39 |
| 1974–1978 | −2.29 | −0.24 | −3.98 | −0.32 | 2.31 | −0.06 |
| 1979–1982 | −4.11 | −1.09 | −6.31 | −2.93 | 6.34 | −0.12 |
| 1983–1986 | 0.11 | 1.28 | −5.00 | −0.13 | 4.27 | −0.31 |
| 1987–1990 | 2.60 | −0.72 | −2.66 | −1.83 | 8.04 | −0.23 |
| 1991–1994 | 0.52 | −0.15 | 1.10 | −0.13 | −0.24 | −0.06 |
| 1974–1994 | −0.71 | −0.19 (4.0%) | −3.40 (71.3%) | −1.03 (21.6%) | 4.06 | −0.15 (3.1%) |

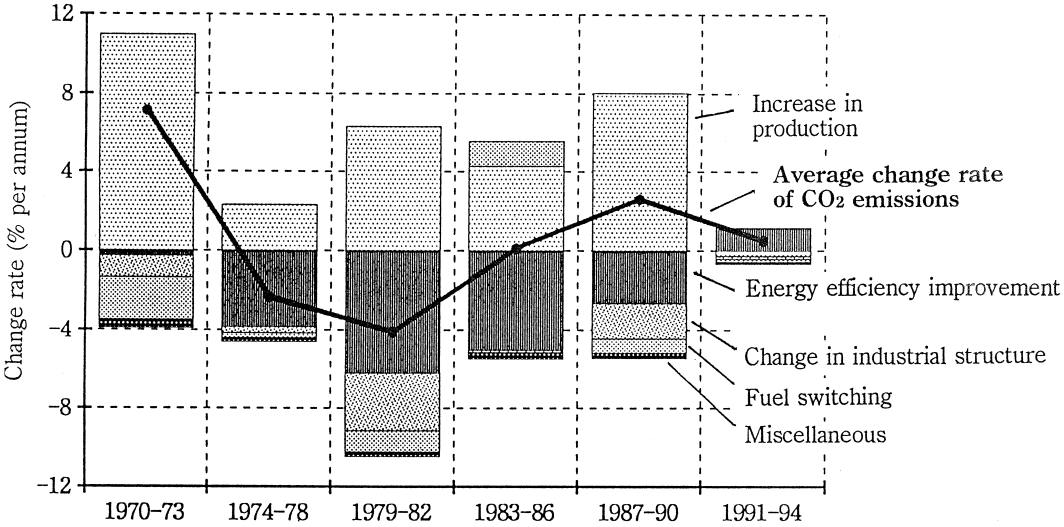

Fig. 4. Trends in factors and their magnitude contributing to change in $CO_2$ emissions in the Japanese manufacturing industry (1970–1994).

$CO_2$ discharge level dramatically decreased after the first energy crisis in 1973 as energy efficiency improvement efforts increased. This is largely the result of substituting technology (energy conservation technology) and capital (energy conservation facility) for energy (Watanabe, 1992a). On the other hand, the contribution of fuel change (which also represents the outcome of similar substitutions involving oil alternative technologies and capital investment) is much less significant due to an increase in dependency on coal as a promising oil alternative energy.[6] If we look carefully at these trends, we note that $CO_2$ emissions increased after 1983 (the start of the fall of international oil prices) due to an increase in coal dependency and a decrease in energy efficiency improvement efforts. Since 1987 (the start of Japan's so called 'bubble economy') energy efficiency improvement efforts have significantly decreased, leading to increase in $CO_2$ emissions. Although $CO_2$ emissions decreased again from 1991 following the start of the bursting of the 'bubble economy', this is due solely to a decrease in GDP due to the bursting of the 'bubble economy', while energy efficiency improvement efforts have continued to decline, thereby resulting in a change in energy intensive mode.

### 3.2. *Mechanism for achieving energy efficiency improvement*

Japan's success in attaining environmentally friendly sustainable development after the first energy crisis in 1973 depended largely on the results of efforts to reduce energy dependency. This was accomplished through an improvement in energy efficiency that was chiefly initiated by the industrial sector. This dramatic improvement in energy efficiency was a response to counter the sharp increase in energy prices caused by the energy crises. This response first focused on managerial improvement by means of energy saving education, operational management and maintenance efforts.

As such managerial efforts reached their limit, the next step was investment in higher productivity

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[6] Japan made intensive and extensive efforts to develop and introduce renewable energy as a prospective technology-driven clean energy. At the same time, in order to secure stable and bulky oil alternative energy sources, Japan made comprehensive efforts to switch from oil to coal, particularly after the second energy crisis in 1979. This, despite an increase in non-$CO_2$ emitting energy sources such as nuclear power generation and renewable energy, resulted in a deterioration of the expected effects of fuel switching and shifted Japan's energy policy towards such efforts as the clean use of coal and further acceleration of the development and introduction of renewable energy (Watanabe, 1995a).

by buying, installing, equipping and replacing process/production improvement facilities and sensing/control equipment systems for improving the efficiency of complicated flows of energy, materials and semiprocessed products in production processes.

As energy prices continued to sharply increase after the second energy crisis in 1979, these efforts again reached their limit, leading industry to move on to the next step, innovation of total production systems (The Energy Conservation Center, 1990–1995).

The latter two steps, which began in earnest from the late 1970s, were possible largely due to technological innovation by means of the introduction of innovative energy conservation facilities, production processes, sensing and control systems, and new production systems incorporating innovative technologies. This can be understood as Japan's survival strategy in a constrained economic environment. Furthermore, this strategy was an effort to substitute a constraint-free production factor such as technology for a constrained production factor such as energy.

### *3.3. The technology option and its contribution to energy efficiency improvement*

As demonstrated earlier, dramatic improvement in energy efficiency from the late 1970s can be attributed largely to technological innovation aiming at substituting for energy. Hogan and Jorgenson (1991) pointed out that the change in technology might be the most important effect in this improvement through substitution for the scarcity of production resources. They stressed the significance of the description of technology change in energy-economic models and made extensive efforts in this treatment. However, their efforts were hardly satisfactory as their technology description depended on a linear function of time. Consequently, they postulated that the common economic modeling assumption of constant technology, or even exogenous technological change, became less tangible and that greater attention to the effects of technological change should be refocused in research and analysis with energy-economic models. Stimulated by their postulate, an endogenous technological change process focusing on the technology option and its contribution to energy efficiency improvement was analyzed.

#### *3.3.1. The technology option: mechanism of technology contribution to energy efficiency improvement*

Change in energy efficiency $(\Delta E/Y)$ is a result of a dynamic transition between changes in energy dependency $(\Delta E)$ and production $(\Delta Y)$ based on dependable energy. Technology $(T)$ generally has a significant impact on changes in energy and production. Therefore, the technology contribution to energy efficiency improvement is how technology contributes to maximizing production while minimizing energy. In this particular case, technology should be classified into non-energy technology and energy technology (see Section 2.1). While the former aims primarily at maximizing production, the latter consists of both energy conservation and supply oriented technologies and aims primarily at minimizing energy dependency, chiefly on oil.

Non-energy technology interacts largely with capital to increase production (a complementary relationship), thereby making a significant contribution to any production increase. However, the process of increasing capital to achieve an increase in production inevitably results in increasing a certain energy component (the complement between capital for a production increase and energy).[7] Energy technology, on the other hand, interacts largely with capital for an energy efficiency improvement (also a complementary relationship), thereby making a significant contribution to reducing energy dependency (capital substitution for energy). Although it also stimulates a production increase, the magnitude is relatively small.[8] The contribution of technology to energy efficiency improvement can be considered a dynamic transition chiefly among the above actors; non-energy technology vs. capital for a production increase, energy technology vs. capital for energy efficiency improvement, energy and production.

#### *3.3.2. Measurement of technology knowledge stock of energy and non-energy R&D*

In order to make a quantitative analysis of the dynamic transition with respect to the technology

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[7] See Table 10 in Section 3.3.3. This explains Hogan and Jorgenson's puzzle that technology change has been negatively correlated with energy prices (Hogan and Jorgenson, 1991).

[8] See also Table 10.

Table 9
Trends in change rate of R&D expenditure and technology knowledge stock in the Japanese manufacturing industry (1970–1994)—% per annum

| | R&D expenditure (fixed price) | | Technology knowledge stock | | |
|---|---|---|---|---|---|
| | Total R&D | Energy R&D | Total stock | Stock of energy R&D | Stock of non-energy R&D |
| 1960–1969 | 15.78 | 9.83 | | | |
| 1970–1973 | 9.91 | 16.56 | 16.00 | 10.58 | 16.08 |
| 1974–1978 | 3.16 | 20.82 | 12.51 | 15.57 | 12.47 |
| 1979–1982 | 9.65 | 25.44 | 5.89 | 24.31 | 5.55 |
| 1983–1986 | 11.30 | 0.04 | 6.81 | 14.31 | 6.59 |
| 1987–1990 | 8.16 | 0.90 | 8.16 | 3.84 | 8.31 |
| 1991–1994 | −0.70 | 0.46 | 7.76 | 2.25 | 7.91 |

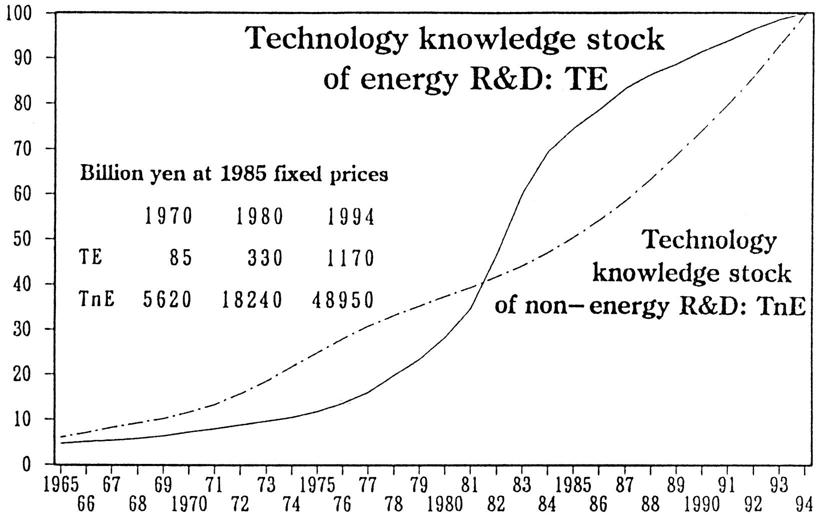
option and its contribution to energy efficiency improvement, both energy technology (TE) and non-energy technology (TnE) were measured by calculating the technology knowledge stock of energy R&D and non-energy R&D as follows (see Section A.2).

First, in line with previous approaches (Watanabe, 1992a) and considering that the rate of obsolescence of technology increases as technology knowledge stock increases (Watanabe, 1996c), and that firms react to shorten the time lag of R&D to commercialization as the rate of obsolescence of technology increases, technology knowledge stock along with a dynamic rate of obsolescence of technology and the time lag between R&D and commercialization can be measured by the following equation (see details concerning the equation in Section A.2):

$$T_t = R_{t-m_t} + (1-\rho_t)T_{t-1},$$
$$\rho_t = \rho(T_t),$$
$$m_t = m(\rho_t) \qquad (6)$$

where $T_t$: technology knowledge stock in the period $t$, $R_t$: R&D expenditure in the period $t$, $m_t$: time lag of R&D to commercialization in the period $t$, and $\rho_t$: rate of obsolescence of technology in the period $t$.

Second, using Eq. (6), trends in the technology knowledge stock of both energy R&D and non-en-



Billion yen at 1985 fixed prices

| | 1970 | 1980 | 1994 |
|---|---|---|---|
| TE | 85 | 330 | 1170 |
| TnE | 5620 | 18240 | 48950 |

Fig. 5. Trends in technology knowledge stock of energy R&D and non-energy R&D in the Japanese manufacturing industry (1965–1994).

Table 10
Comparison of elasticities of energy and production by energy and non-energy technology in the Japanese manufacturing industry (1974–1994)

| | Energy $(E)$ | Production $(Y)$ |
|---|---|---|
| Technology knowledge stock of energy R&D (TE) | −0.224 | 0.004 |
| Technology knowledge stock of non-energy R&D (TnE) | 0.349 | 0.584 |

Elasticities are measured by the following equations:

$\ln E = 9.668 - 0.224_{(-7.29)} \ln \mathrm{TE} + 0.349_{(5.60)} \ln \mathrm{TnE}$ adj. $R^2 = 0.774$ DW = 1.73

$\ln Y = 6.645 + 0.004_{(1.14)} \ln \mathrm{TE} + 0.584_{(9.37)} \ln \mathrm{TnE}$ adj. $R^2 = 0.981$ DW = 1.60

$\ln E/Y = 3.023 - 0.228_{(-13.66)} \ln \mathrm{TE} - 0.235_{(-6.93)} \ln \mathrm{TnE}$ adj. $R^2 = 0.995$ DW = 2.23

ergy R&D in the Japanese manufacturing industry over the period 1965–1994 were measured as summarized and illustrated in Table 9 and Fig. 5 (see tabulated outcome of measurement in Section A.2).

Looking at Table 9 and Fig. 5 the following results are evident.

(i) The priority of R&D shifted from non-energy R&D to energy R&D from the beginning of the 1970s[9] in the Japanese manufacturing industry. This trend reflects the economic impact of the energy crises in 1973 and 1979, and expenditure on energy R&D rapidly increased, particularly between 1974 and 1982. However, after international oil prices started to fall in 1983, energy R&D expenditure decreased dramatically.

(ii) Corresponding to these trends with a certain amount of time lag,[10] the technology knowledge stock of energy R&D increased dramatically during the period 1974–1982, continued to also increase in the period 1983–1986, and changed to a dramatic decline from 1987.

(iii) Such a rapid increase in the technology knowledge stock of energy R&D over a limited period (1974–1986), much like a local rainstorm, resulted in a rapid increase in the rate of technology obsolescence (which increased from 15.4% in 1974 to 21.2% in 1987). This resulted in a rapid decrease in the time lag between R&D and commercialization (which decreased from 3.4 years in 1974 to 1.4 years in 1987).

### *3.3.3. A comparison of the behavior of technology knowledge stock of energy R&D and non-energy R&D*

By using measured technology knowledge stock, the behavior of technology knowledge stock of both energy R&D and non-energy R&D in the Japanese manufacturing industry was compared over the period 1974–1994. Table 10 compares elasticities of energy and production by energy technology and non-energy technology respectively in the Japanese manufacturing industry over the period 1974–1994. Looking at Table 10, we note that while elasticities of energy and production by non-energy technology are 0.349 and 0.584, respectively (a 1% increase in non-energy technology induces 0.584% of production while increasing energy dependency by 0.349%), elasticities of energy and production by energy technology are −0.224 and 0.004. The elasticity of energy efficiency is a balance between elasticities of energy and production, and the elasticity of energy technology and non-energy technology displays almost the same level (−0.23). This suggests that notwithstanding the relatively small quantity of energy technology (almost 1/30 of the quantity of non-energy technology), its increase rate displays a similar contribution to the rate of energy efficiency improvement in the Japanese manufacturing industry over the period 1974–1994.

Close interaction between non-energy technology and capital for a production increase, as well as

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[9] Prior to the first energy crisis in 1973 and triggered by increasing concern regarding the environmental consequences of energy and a materials dependent economy, recognition of the significance of energy R&D aiming at technology-driven clean energy increased from the beginning of the 1970s (Industrial Structure Council of MITI, 1971).

[10] This time lag corresponds to the time lag of R&D expenditure to technology knowledge stock and to obsolescence of the stock, which changes as the stock changes.

Table 11
Technology inducement of energy conservation investment in the Japanese manufacturing industry (1975–1994)

| Energy conservation investment | Adj. $R^2$ | DW |
|---|---|---|
| $\ln(\text{ECinv}) = -1.02 + 0.18_{(2.19)} \ln(\Delta\text{TE}) + 0.15_{(2.18)} \ln(\Delta\text{TnE}) + 2.23_{(7.53)} \ln(\text{Pey})$ | 0.949 | 2.23 |
| Other investment | | |
| $\ln(\text{nECinv}) = -10.19 + 0.33_{(1.66)} \ln(\Delta\text{TE}) + 1.80_{(10.37)} \ln(\Delta\text{TnE}) + 0.98_{(1.39)} \ln(\text{Pey})$ | 0.852 | 1.12 |

Where ECinv and nECinv: energy conservation investment and other investment (1985 constant price); ΔTE and ΔTnE: changes in technology knowledge stock of energy R&D and non-energy R&D; and Pey: relative energy price.
Sources of energy conservation investment and other investment: Survey on Trends in Capital Investment (Japan Development Bank, 1975–1995, annual issues).

energy technology and capital for energy efficiency improvement can be demonstrated by comparing the inducing impact of the increase of both energy and non-energy technologies on both energy conservation investment and other investment. A comparative analysis of this influence in the Japanese manufacturing industry over the period 1975–1994 as summarized in Table 11 demonstrates that energy conservation investment was strongly induced by increases in relative energy prices and technology knowledge stock of energy R&D, while other investment was strongly induced by an increase in the technology knowledge stock of non-energy R&D.

In addition, energy R&D has trans-sectoral characteristics as demonstrated in Table 6. These characteristics can be clearly observed in the spillover of the technology knowledge stock of energy R&D from high-technology sectors to energy dependent sectors such as iron and steel and chemical industry sectors. These two major energy-dependent sectors accounted for nearly 60% of the Japanese manufacturing industry's energy consumption over the period 1980–1994. However, contrary to expectation, energy R&D expenditure in these sectors was limited, representing only 4% to 11% in iron and steel and 3% to 6% in chemicals. Contrary to such limited energy R&D in these major energy dependent sectors, energy R&D in high-technology sectors such as electrical machinery and transport equipment was extremely high. The shares of energy R&D expenditure in these sectors were 29% to 35% in electrical machinery and 27% to 40% in transport equipment while the share of energy consumption in these two sectors was only 2.5% to 4%. These observations of the adverse consequences of energy consumption and energy R&D expenditure between energy-dependent sectors and high-technology sectors demonstrates clear evidence of an active trans-sectoral spillover of technology knowledge stock of R&D.[11]

These analyses suggest that, as far as a contribution of the same quantity of technology to energy efficiency improvement is concerned, energy technology functions more efficiently than non-energy technology. Therefore, during the 1970s and early 1980s when the highest priority of technology contribution was to improve energy efficiency, the technology option was how to increase energy technology. Indeed, MITI appropriated its R&D budget for energy R&D on a priority basis to induce vigorous energy R&D efforts by industry as illustrated in Table 6 and Fig. 3. Such vigorous energy R&D investment in the latter half of the 1970s and early 1980s rapidly increased energy technology through the technology knowledge stock of energy R&D as illustrated in Fig. 5.

On the basis of the above observations, the characteristics of industry energy R&D (ER) and the subsequent technology knowledge stock of energy R&D (TE) can be summarized as follows: (i) high density of ER intersectoral factors common to all sectors other than non-energy R&D (Table 6); (ii) both are sensitive to government R&D funding (Table 7); (iii) there is a sharp inducement of energy efficiency improvement investment (Table 11); (iv)

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[11] Numerical analysis of the impacts of technology spillover by using a translog cost function clearly demonstrates this evidence (Watanabe, 1998).

Table 12
Estimated energy efficiency improvement function of services of input in the Japanese manufacturing industry (1974–1994)

| | Adj. $R^2$ | DW |
|---|---|---|
| $\ln\frac{E}{L} = 12.494 + 0.001_{(0.04)} \ln\frac{\text{Pl}}{\text{Pe}} - 0.226_{(-6.67)} \ln \text{TE} + 0.395_{(2.64)} \ln \text{TnE} - 0.009_{(-1.27)} t$ | 0.958 | 1.94 |
| $\ln\frac{E}{K} = 146.488 + 0.122_{(3.33)} \ln\frac{\text{Pk}}{\text{Pe}} - 0.286_{(-8.82)} \ln \text{TE} - 0.397_{(-5.83)} \ln \text{TnE} - 0.075_{(-4.96)} t$ | 0.995 | 1.87 |
| $\ln\frac{E}{M} = 100.261 + 0.208_{(5.48)} \ln\frac{\text{Pm}}{\text{Pe}} - 0.195_{(-5.68)} \ln \text{TE} - 0.225_{(-3.25)} \ln \text{TnE} - 0.052_{(-3.27)} t$ | 0.988 | 1.84 |
| $\ln\frac{E}{Y} = 118.187 + 0.188_{(5.15)} \ln\frac{\text{Py}}{\text{Pe}} - 0.228_{(-7.10)} \ln \text{TE} - 0.208_{(-3.22)} \ln \text{TNE} - 0.062_{(-4.29)} t$ | 0.991 | 1.89 |
| | $F$: 592.1<br>AIC: −149.2 | |
| [Reference] | | |
| $\ln\frac{E}{Y} = 90.625 + 0.188_{(5.15)} \ln\frac{\text{Py}}{\text{Pe}} - 0.046_{(-34.19)} t$ | 0.987 | 1.66 |
| | $F$: 488.7<br>AIC: −139.7 | |

[a] Figures in parentheses indicate $t$-value.
[b] $F$: $F$-value, and AIC: Akaike's information criteria.
[c] Taking into account structural differences of years 1993 and 1994 dummy variable (1993 and 1994 = 1, other years are 0) is used for all cases estimated.

there is a high contribution to energy efficiency improvement (Table 10); and (v) both change dynamically with a close correlation with trends in energy prices (Fig. 5).

These characteristics suggest that we can make a significant analysis of the contribution of technology to energy efficiency improvement in manufacturing industry by using its aggregated technology knowledge stock of energy R&D.[12]

### 3.4. Analysis of the contributing factor to energy efficiency improvement

Provided that technology (T) is embedded in other services of input (labor: $L$, capital: $K$, materials: $M$, and energy: $E$) to production ($Y$), the production function can be seen in the following way:

$$Y = F(L_{(T)}, K_{(T)}, M_{(T)}, E_{(T)}) \tag{7}$$

The change rate of energy efficiency ($\Delta(E/Y)/(E/Y)$ where $\Delta(E/Y) = \mathrm{d}(E/Y)/\mathrm{d}t$) can be calculated as follows:

$$\frac{\Delta(E/Y)}{(E/Y)} = \sum \frac{\partial Y}{\partial X} \frac{X}{Y} \frac{\Delta(E/X)}{(E/X)} \quad (X = L, K, M) \tag{8}$$

$E/X$ is a ratio of energy and other services of input, and provided that $E/X$ is governed by the ratio of prices of respective services of input and energy (Px/Pe) and technical change ($\lambda t$, where $t$ indicates the time trend) (Binswanger, 1977), $E/X$ can be estimated as follows:

$$E/X = E/X(\text{Px}/\text{Pe}, \lambda t) \tag{9}$$

where Pe and Px (= Pl, Pk, Pm) are prices of energy, labor, capital and materials, respectively.

On the basis of the foregoing analyses, decomposing $\lambda t$ into improvements from an increase in the technology knowledge stock of both energy R&D (TE) and non-energy R&D (TnE) generated by R&D investment, and other improvements with a linear function of time derived from such effects as economies of scale and learning effects ($\lambda' t$), Eq. (9) can be estimated by the following function for the

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[12] Hogan and Jorgenson shared a similar view on the aggregation as data on individual sectors lend themselves to a characterization of the direct effects on the ratio of inputs to GNP (Hogan and Jorgenson, 1991).

Table 13
Factors contributing to change in energy efficiency in the Japanese manufacturing industry (1970–1994)—% per annum

| Period | $[\Delta(E/Y)/(E/Y)]$ | Labor capital materials miscellaneous | | | | Contribution factors | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $L$ | $K$ | $M$ | $\varepsilon$ | Pe/Px | TE | TnE | $\lambda$ | $\varepsilon$ |
| 1974–1978 | −3.98 | 0.09 | −0.85 | −3.80 | 0.58 | −1.53 | −2.90 | −1.34 | −0.17 | 1.96 |
| 1979–1982 | −6.31 | −0.58 | −1.10 | −5.05 | 0.42 | −1.39 | −4.96 | −0.74 | −0.25 | 1.03 |
| 1983–1986 | −5.00 | −0.32 | −1.13 | −4.40 | 0.85 | 0.33 | −3.46 | −1.23 | −0.36 | −0.28 |
| 1987–1990 | −2.66 | 0.51 | −0.95 | −3.10 | 0.88 | 0.85 | −0.99 | −1.69 | −1.10 | 0.27 |
| 1991–1994 | 1.10 | 0.66 | −0.20 | −0.75 | 1.39 | 0.20 | −0.38 | −0.71 | −0.94 | 2.93 |
| 1974–1994 | −3.40 | 0.08 | −0.85 | −3.44 | 0.81 | −0.37<br>(8.0%) | −2.56<br>(55.4%) | −1.15<br>(24.9%) | −0.54<br>(11.7%) | 1.22 |

Japanese manufacturing industry over the period 1974–1994:[13]

$$\ln E/X = a + b_1 \ln(\mathrm{Px}/\mathrm{Pe}) + b_{21} \ln \mathrm{TE} + b_{22} \ln \mathrm{TnE} + \lambda' t \qquad (10)$$

The results of my estimation are summarized in Table 12. Table 12 shows all estimated parameters statistically significant at the 1% to 0.5% level except parameters relevant to non-R&D improvement by economies of scale and learning effects (15% level) and relative price (nonsignificant) of the energy efficiency of labor input. This implies that the ratio of energy and labor is almost independent from the relative price of input and less dependent on non-R&D autonomous improvement. The estimated parameters relevant to technology knowledge stock of energy R&D display statistical significance in all functions estimated, and this implies that the technology knowledge stock of energy R&D closely relates to the energy efficiency improvement in all services of input. While parameters relevant to technology knowledge stock of non-energy R&D also display statistical significance with a positive contribution to energy efficiency improvement for all services of input except labor which, contrary to other services of input, displays a contribution to an energy dependency.[14] Although the coefficient of $\lambda'$ (effects due to economies of scale and learning effects) is small, it displays statistical significance in cases of capital and materials.

Under the assumption that the production function is linear and homogeneous, and prices of respective services of input are decided competitively[15] by synchronizing Eqs. (8) and (9) the change rate of energy efficiency can be calculated as follows:

$$\frac{\Delta(E/Y)}{(E/Y)} = \sum \frac{\mathrm{GXC}}{\mathrm{GC}} \left( b_1 \frac{\Delta(\mathrm{Px}/\mathrm{Pe})}{(\mathrm{Px}/\mathrm{Pe})} + b_{21} \frac{\Delta\mathrm{TE}}{\mathrm{TE}} + b_{22} \frac{\Delta\mathrm{TnE}}{\mathrm{TnE}} + \lambda' \right) \qquad (11)$$

where GC is gross cost, and GXC, gross cost of $X$.

The results of the calculation are summarized and illustrated in Table 13 and Fig. 6. Looking at the table and figure, we note Japan's manufacturing industry's achievement of a 3.4% average annual improvement in energy efficiency over the period 1974–1994 can be attributed to the following components: 55.4% to energy technology (technology knowledge stock of energy R&D), 24.9% to non-energy technology, 8.0% to other efforts in response to the sharp increase in energy prices, and 11.7% to non-technology oriented autonomous energy efficiency improvement derived from such effects as economies of scale and learning effects.

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[13] In Eq. (10), since $\lambda$ can be estimated as $\lambda = b_{21}(\Delta\mathrm{TE})/(\mathrm{TE}) + b_{22}(\Delta\mathrm{TnE})/(\mathrm{TnE}) + \lambda'$ and $\lambda'$ saturates as TE and TnE increase resulting in $1\lambda'1 \ll 1\lambda 1$ (see the review in Section 3.2), $\lambda'$ was estimated as a function of TE, TnE and $t$ by means of the stepwise convergence method.

[14] Technology knowledge stock of non-energy R&D accelerates technology substitution for labor typically observed in the introduction of automation and labor saving technologies, which in turn leads to increasing dependency on energy.

[15] These assumptions are generally applicable in the Japanese manufacturing industry during the years after the first energy crisis in 1973 (Economic Planning Agency, 1965–1995) except for 1974 and 1975, and 1993 and 1994 when production growth was negative.

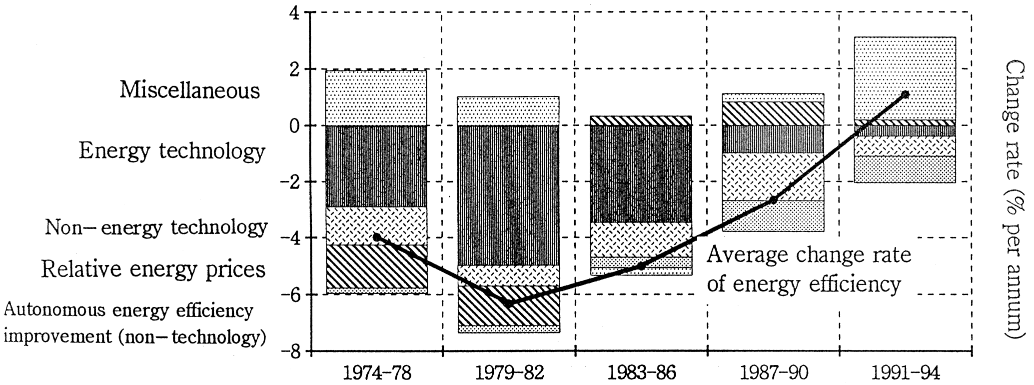

Fig. 6. Factors contributing to change in energy efficiency in the Japanese manufacturing industry (1970–1994).

The above analyses support the aforementioned hypothesis that Japan, in the face of the damaging impacts of the energy crises, made every effort to substitute a constraint free (or unlimited) production factor, technology, for a constrained (or limited) production factor (energy), as its survival strategy. However, if we look carefully at these trends, we note that the contribution of energy technology, the main contributor to energy efficiency improvement, has decreased since 1983 (the start of the fall of international oil prices). Furthermore, this decrease accelerated from 1987 (the start of Japan's 'bubble economy') and further accelerated from 1991 (the start of the bursting of the 'bubble economy'). This development was the main source of the deterioration in energy efficiency improvement, resulting in an increase in $CO_2$ discharge as analyzed in Table 8 and Fig. 4.

These analyses provide us with a warning that despite its success in overcoming energy and environmental constraints in the 1960s, 1970s and the first half of the 1980s, Japan's economy once again faces the prospect of energy and environmental constraints following the fall of international oil prices and the succeeding 'bubble economy' and its bursting (Industrial Technology Council of MITI, 1992).

## 4. Effect and limit of existing policy

### 4.1. Inducement of technology substitution for energy

The following recommendations arise from the analyses in Sections 2 and 3.

(i) Given that it is selected appropriately, the technology option can play a significant role in achieving a breakthrough for removing limitations on energy efficiency, and this process could be considered technology substitution for energy.

(ii) Energy efficiency improvement is a balance between changes in energy dependency and production, and considering the respective comparative advantages and disadvantages of energy technology and non-energy technology, the combination of these technologies should be carefully decided depending on econo-environmental circumstances of the historical era.

(iii) Considering the public nature of energy R&D, timely government initiatives can effectively induce vigorous industry R&D investment, which is essential for a timely increase in technology knowledge stock.

As demonstrated in a previous work (Watanabe, 1992a), intensive efforts have been made over the last two decades in Japan's manufacturing industry for technology substitution for energy in order to overcome increased energy constraints while maintaining sustainable development.

MITI's efforts to substitute technology and technology driven energy for energy and limited energy sources have clearly induced industry's energy R&D in such a way as to stimulate technological development across sectors and to generate trans-sectoral spillover. As a result of a combination of industry efforts and MITI's attempt to stimulate and induce such efforts, Japan's manufacturing industry in the 1970s and 1980s was able to overcome energy and environmental constraints while maintaining sustainable growth based on a sophisticated system which enabled technology substitution for energy (Watanabe, 1992a, 1995b,e).

### 4.2. Limits of inducement

Notwithstanding such success in constructing a sophisticated system enabling technology substitution for energy, the analyses of Section 3 (see Table 13 and Fig. 6) provides us with a warning that Japan's economy once again faces the prospect of energy and environmental constraints following the fall of international oil prices and the succeeding 'bubble economy' and its bursting. The analysis in Table 13 and Fig. 6 imputed this fear to the stagnation of energy technology (technology knowledge stock of energy R&D) due to the stagnation of industry's energy R&D expenditure.

In order to identify the sources of such stagnation, Eq. (12) analyzed factors governing the Japanese manufacturing industry's energy R&D expenditure over the period 1974–1994.

$$\begin{aligned}\ln \mathrm{ERD} = {} & -6.57 + \underset{(6.81)}{0.65} \ln \mathrm{MERD} \\ & + \underset{(3.54)}{0.27} \ln(\mathrm{MnERD}) + \underset{(3.32)}{0.74} \ln \mathrm{RD} \\ & + \underset{(4.10)}{0.64} \ln \mathrm{Me} + \underset{(2.26)}{0.25} \mathrm{Pet} \\ \text{adj. } R^2 = {} & 0.993 \ \mathrm{DW} = 2.07 \end{aligned} \tag{12}$$

where ERD and RD: manufacturing industry's energy R&D and total R&D expenditure; MERD and MnERD: MITI's energy R&D and non-energy R&D budget; Me: time lag between energy R&D and commercialization; and Pet: relative energy prices with respect to capital prices of technology.

Eq. (12) corroborates earlier findings that MITI's energy R&D budget, together with industry's own total R&D, provides a strong influence on manufacturing industry's energy R&D expenditure. This also supports the previous analyses showing that MITI's energy R&D sharply induces industry's energy R&D. In addition to these factors, Eq. (12) indicates that manufacturing industry's energy R&D is sensitive to a time lag between energy R&D and commercialization. Therefore, R&D decreases as this time lag decreases. This demonstrates that industry's profitable energy R&D seeds have been depleting due to a tempered undertaking in a limited period, much like a local rainstorm. Other factors comprised by Eq. (12) include MITI's non-energy R&D budget and relative energy prices with respect to capital technology.

Table 14 and Fig. 7 summarize and illustrate the result of an analysis of factors contributed to the decrease in manufacturing industry's energy R&D expenditure. The table and figures indicates that decreases in MITI's energy R&D budget, industry's total R&D expenditure and the time lag between energy R&D and commercialization are major sources of the stagnation of manufacturing industry's energy R&D from 1983.

MITI's energy R&D budget was influenced by the amount of MITI's overall R&D budget and also

Table 14
Factors contributing to change in energy R&D expenditure in the Japanese manufacturing industry (1974–1994)—% per annum

| Period | Industry energy R&D | MITI energy R&D | MITI non-energy R&D | Industry total R&D | Time lag of R&D to commercialization | Relative energy prices | Miscellaneous |
|---|---|---|---|---|---|---|---|
| | $\Delta$ERD/ERD | $\Delta$MERD/MERD | $\Delta$MnERD/MnERD | $\Delta$RD/RD | $\Delta$Me/Me | $\Delta$Pet/Pet | $\varepsilon$ |
| 1974–1978 | 31.77 | 20.33 | 1.08 | 8.19 | −3.01 | 6.44 | −1.26 |
| 1979–1982 | 32.99 | 20.64 | 6.22 | 11.36 | −7.34 | 2.25 | −0.14 |
| 1983–1986 | −0.09 | 2.37 | 2.15 | 7.73 | −8.70 | −2.29 | −1.35 |
| 1987–1990 | 3.46 | 1.78 | 1.03 | 7.88 | −4.25 | −2.04 | −0.94 |
| 1991–1994 | 0.35 | −1.08 | 2.32 | −0.50 | −3.39 | 1.33 | 1.67 |
| 1974–1994 | 14.56 | 9.36 | 2.49 | 6.99 | −5.23 | 1.39 | −0.44 |

[a] ERD and RD: manufacturing industry's energy R&D and total R&D expenditure; MERD and MnERD: MITI's energy R&D and non-energy R&D budget; Me: time lag of energy R&D to commercialization; Pet: relative energy prices with respect to capital prices of technology; and $\varepsilon$: miscellaneous.

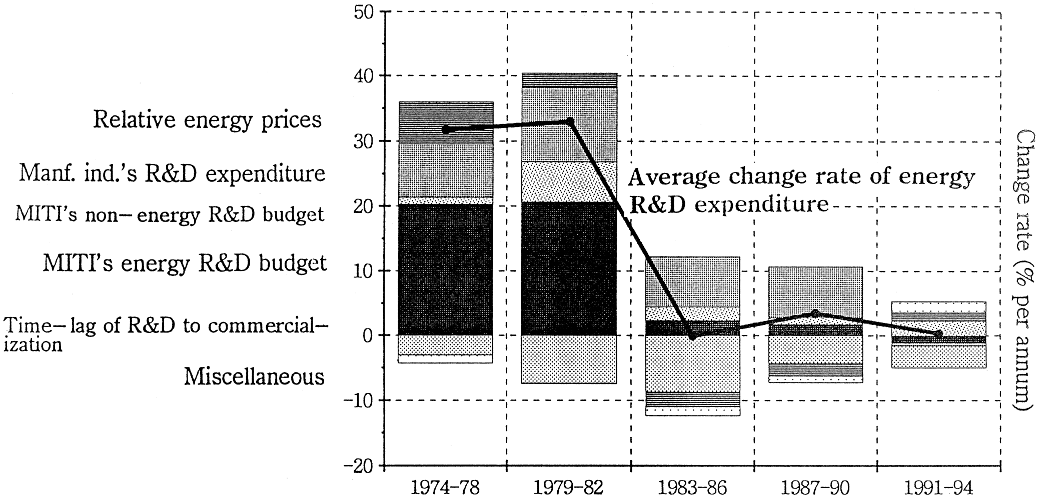

Fig. 7. Factors contributing to change in energy R & D expenditure in the Japanese manufacturing industry (1974–1994).

by trends in energy prices as corroborated in the following equation (1974–1994).

$$\ln \mathrm{MERD} = -0.99 + \underset{(29.00)}{1.06} \ln \mathrm{MRD} + \underset{(8.67)}{0.68} \ln \mathrm{Pey}$$

$$\text{adj. } R^2 = 0.988 \ \mathrm{DW} = 1.42 \qquad (13)$$

where MERD: MITI's energy R & D budget; MRD: MITI's overall R & D budget; and Pey: relative energy prices.

As international oil prices decreased and global environmental issues have caused mounting concern regarding the sustainability of our development future, MITI's priority for energy R & D shifted to other policy fields such as the Global Environmental Technology Program initiated in 1989 (MITI, 1988, 1994; Watanabe and Honda, 1992). Accordingly, together with government finance constraints after the energy crises, MITI's budget for energy R & D has stagnated since 1982 as illustrated in Table 4 and Fig. 2.

The stagnation of industry R & D is another structural problem (Watanabe, 1992b, 1995c). Japan constructed an elaborate virtuous cycle between technology and economic development (Economic Planning Agency, 1965–1995; Watanabe, 1995b). MITI stimulated and induced industry's efforts by establishing a sophisticated policy system which has strengthened dynamism conducive to industry's technological development (Watanabe and Honda, 1991). MITI's energy R & D programs aiming at technology substitution for energy and industry's subsequent towards such substitution were a major driving force for industry's vigorous R & D investment (Watanabe et al., 1991). However, following the relaxation of energy constraints, the 'bubble economy' and its bursting, Japanese industry faced a structural stagnation of R & D activities which may result in the collapse of the virtuous cycle between technology and economic development (Watanabe, 1995c).

Depletion of industry's profitable energy R & D seeds has become one of the sources of the stagnation of industry's R & D. This is typically the case in energy R & D as a repercussion of tempered undertaking over a limited period.

Other complications are that these major sources of the stagnation of manufacturing industry's energy R & D are interconnected with each other, leading to a vicious spin cycle which might distort the inducing potential of MITI's energy R & D (Watanabe, 1996b). Considering the significant impacts of MITI's energy R & D on the substitution of technology for energy and technology stock of energy R & D initiated by manufacturing industry as analyzed in this investigation, this stagnation has resulted in discouraging manufacturing industry's efforts in technology substitution for energy. It has also decreased the technology stock of energy R & D as illustrated in Fig. 5, which was the main source of a decrease in energy efficiency improvement in Japan's manufacturing industry as indicated in Fig. 6.

### *4.3. Breaking through the limits of inducement*

The above provides us with a clear warning that the construction of manufacturing industry's technology stock of energy R&D will structurally continue to stagnate, resulting in a breaking down of Japan's system of technology substitution for energy. This will lead to destructuring of the virtuous cycle between technology and economic development in the near future. This compels MITI to provide effective policy measures in order to reactivate efforts towards substituting technology for constrained production factors such as energy and environmental capacity. Moreover, given the two-sided nature of the global environmental issue and energy consumption, MITI should develop a comprehensive approach based on integrating related programs so as to alleviate concern for the sustainability of the world's development future in this era of energy and global environmental constraints (Industrial Structure Council, Comprehensive Energy Policy Council and Industrial Technology Council of MITI, 1992).

In order to respond to this necessity, and given the two-sided nature of the global environmental issue and energy consumption, a comprehensive approach based on R&D programs for new energy technology, energy conservation technology and global environmental technology can lead a way to sustainable development by simultaneously overcoming both energy and environmental constraints[16] (Industrial Technology Council of MITI, 1992).

In this regard, MITI decided to establish the New Sunshine Program (R&D Program on Energy and Environmental Technologies) in April 1993 by integrating the Sunshine Project (R&D on New Energy Technology: 1974), the Moonlight Project (R&D on Energy Conservation Technology: 1978) and the Global Environmental Technology Program (1989) (Industrial Technology Council of MITI, 1992). Through the integration of these R&D activities, effective and accelerated achievement of R&D in the fields of energy and environmental technologies is expected through the co-utilization and supplementation of such key technologies as catalysts, hydrogen, high-temperature materials and sensors common to new energy, energy conservation and environmental protection. In addition, from the viewpoint of a comprehensive systems approach, the New Sunshine Program is expected to provide a new concept for an environmentally friendly technology system and inspire a new principle to pursue under global environmental constraints (Watanabe, 1996a).[17]

Furthermore, in order to respond to the crucial problem of depletion of industry's profitable energy R&D seeds, the following programs with a broad systems option were established: (i) Proposal-Based Creative R&D Promotion Program (1995) which aims at cultivating the innovative energy and environmental R&D seeds; (ii) Precursory Research System (1997) which aims at exploring basic and fundamental technology; and (iii) Rapidly Marketable Innovative Technologies Development Program (1998) which aims at developing GHGs reduction technologies expected to be rapidly introduced in the market.

## 5. Implications for sustainable development

Increasing energy and environment constraints, especially the global environmental consequences of energy use, are causing mounting concern around the world, and it is widely thought that such constraints may be 'limits to sustain our development future'. Considering the two-sided nature of the global environmental issue and energy consumption, Japan's success in overcoming the energy crises while maintaining economic growth and attaining a dramatic improvement in technological level could provide useful suggestions to the question of how technology can be utilized to sustain development. The success

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[16] A similar concept was postulated by the Ford Foundation in 'A Time to Choose' in 1974 (The Ford Foundation, 1974).

[17] This is in line with A.B. Lovins's postulate in 'Soft Energy Paths' (Lovins, 1977).

of Japan's technological development in substituting for scarce resources in the 1970s and 1980s may be particularly instructive since it strongly suggests that a comprehensive systems approach which challenges the limits of sustainable development by substituting new technology for energy and environmental constraints could lead to a new frontier.

Given the above, MITI's industrial technology policy in the 1970s and the first half of the 1980s is instructive because it functioned well in stimulating such substitution, thereby inducing the vitality of industry. Facing a stagnation trend with respect to industry's R&D efforts due to the bursting of the 'bubble economy', MITI needs to take the initiative with a comprehensive systems approach which induces broader systems options for effective stimulation of the sustainable substitution of technology for energy in a global context.

In light of this, the systems options for the rational use of energy have become crucial. The options can be identified to find the most effective combination of energy efficiency improvement and fuel switching (and also carbon sequestration in the future). The complexity of the global environmental consequences is the heterogeneity of economic, industrial, geographical, social and cultural conditions of each respective country or region. This implies that while we cannot expect any uniform solution to the question, we can expect comparative advantages which every country/region can share. Therefore, we can expect broad-based systems options, and the possibility of realizing a maximum multiplier effect by synchronizing comparative advantages in a systematic way. Given that the global environmental issue is a problem common to all counties of the world, we should not overlook the opportunity for maximizing the multiplier effect. A comprehensive systems approach is therefore critical.

With this expectation in mind, the following suggestions should be considered.

(i) The above efforts should be focused on dimensions of technological breakthrough which might overcome economic, geographic and social constraints in different countries/regions.

(ii) Given that it is selected appropriately, the technology option can play a significant role in achieving a breakthrough of the limit of energy efficiency.

(iii) Energy efficiency improvement is a balance between changes in energy dependency and production, and considering the respective comparative advantage and disadvantage of energy technology and non-energy technology, the combination of these technologies should be carefully decided based on each country's econo-environmental circumstances.

(iv) Given that such econo-environmental circumstances change in a cyclical way depending on economic development and global energy and environmental conditions, an international complement of experience and comparative advantage can maximize the effectiveness of the technology option.

(v) In light of the public nature of energy R&D, timely government initiatives can effectively induce industry's vigorous R&D investment, which is essential for a timely increase in technology knowledge stock.

## Appendix A. Data construction and sources

### A.1. General concept

$$\text{Production: } Y = F(L, K, M, E, T), T = \text{TE} + \text{TnE}$$

$$\text{Gross cost: } C = C(Y, \text{Pl}, \text{Pk}, \text{Pm}, \text{Pe}, \text{Pt}) = \text{GLC} + \text{GCC} + \text{GMC} + \text{GEC} + \text{GTC}$$

In line with the previous approach (Watanabe, 1992a), in order to avoid duplication, technology-related factors are deducted from $L$, $K$, $M$, $E$ and GLC, GKC, GMC, and GEC; where $Y$: production; $L$: labor; $K$: capital stock; $M$: materials (intermediate input except energy); $E$: energy; $T$: technology knowledge stock; TE; technology knowledge stock of energy R&D; TnE: technology knowledge stock of non-energy R&D; $C$: gross cost; GLC: gross labor cost; GCC: gross capital cost; GMC: gross materials cost; GEC: gross energy cost; GTC: gross technology cost; and Pl, Pk, Pm, Pe, and Pt: prices of labor, capital, materials, energy, and technology.

Table 15
Ratio of patents under continued protection in the last year of patent right

| Registration year | Last year of patent right[a] | Ratio of patents under protection in the last year ($X$: %)[b] | $-\ln(X/100)/15$ ($\rho$: %) |
|---|---|---|---|
| 1970 | 1984 | 23.5 | 9.65 |
| 1971 | 1985 | 23 | 9.80 |
| 1972 | 1986 | 21.4 | 10.28 |
| 1973 | 1987 | 20.6 | 10.53 |
| 1974 | 1988 | 20.55[c] | 10.55 |
| 1975 | 1989 | 20.5 | 10.57 |
| 1976 | 1990 | 20.1[c] | 10.70 |
| 1977 | 1991 | 19.7 | 10.83 |
| 1978 | 1992 | 14.7 | 12.78 |
| 1979 | 1993 | 14 | 13.01 |
| 1980 | 1994 | 13.7 | 13.25 |

[a] Japan's patent law protects a patent right for 15 years after the year the patent was granted (patent registration).

[b] Equivalent to technology worthy to protect at the time of the last year of a patent right (the year when patent life automatically terminates). Source: Japan Patent Office.

[c] Due to unavailability of reliable data, an average of the ratio before and after the year of estimation is used.

### *A.2. Measurement of technology knowledge stock with dynamic rate of obsolescence of technology and time lag of R&D to commercialization*

Given R&D expenditure in the period $t$ ($R_t$), time lag of R&D to commercialization ($m$), and rate of obsolescence of technology ($\rho$), technology knowledge stock in the period $t$ ($T_t$) can be measured by the following equation:

$$T_t = R_{t-m} + (1-\rho)T_{t-1} \qquad \text{(A1)}$$

Given the increasing rate of $R_t$ in the initial period ($\mathrm{d}R_t/\mathrm{d}t/R_t = g$), technology knowledge stock in the initial period ($T_0$) can be measured as follows:

$$T_0 = R_{1-m}/(g+\rho) \qquad \text{(A2)}$$

Considering that the rate of obsolescence of technology ($\rho$) increases as technology knowledge stock increases (Watanabe, 1996c), and that firms need to shorten the time lag of R&D to commercialization ($m$) as the rate of obsolescence of technology increases (Watanabe, 1996c), $\rho$ and $m$ in the period $t$ should be described as follows:

$$\rho_t = \rho(T_t) \qquad \text{(A3)}$$

$$m_t = m(\rho_t) \qquad \text{(A4)}$$

Eq. (A3) can be generally described as follows: [18]

$$\rho_t = A\rho_0 \mathrm{e}^{(T_t/T_0)^{\alpha}} \qquad \text{(A5)}$$

where $A$: scale factor and $\rho_0$: $\rho$ of the initial period (Table 15).

By developing Eq. (A2), $m_t$ can be described as follows:

$$m_t = \frac{\ln R_0/T_0 - \ln(\rho_t + g)}{\ln(1+g')} + 1 \qquad \text{(A6)}$$

where $g' = g + \varepsilon$ ($\varepsilon$ indicates an adjustment factor as the period for estimation $g$ is generally longer than $m-1$)

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[18] In line with the Bosworth approach (Bosworth, 1978), Eq. (A5) can be estimated as follows by using patent data (see Table 15):

| | | Adj. $R^2$ | DW |
|---|---|---|---|
| 1970–1977 | $\ln(\rho) = -0.196$ <br> $+0.948T_{15(5.807)}^{0.10}$ <br> $-0.025D_{(-1.428)}$ | 0.878 | 1.70 |
| 1970–1980 | $\ln(\rho) = 0.608$ <br> $+0.150T_{15(12.273)}^{0.25}$ <br> $-0.090D_{(-4.003)}$ | 0.938 | 1.62 |

where $\rho$: rate of obsolescence of technology estimated by patent data; $T_{15}$: average of technology knowledge stock over 15 years between the year of the granting of a patent right (patent registration) and termination of its right; and $D$: Dummy variable (1976 and 1977 = 1, other years = 0). In case of the above estimation, $\alpha$ in Eq. (A5) can be estimated as 0.10–0.25.

Table 16
Lifetime of technology in the Japanese manufacturing industry in the 1970s and 1980s

| | Valid samples | Average |
|---|---|---|
| Total R&D over 1970–1989 | 276 | 10.2 years<br>($\rho$: 9.8%) |
| Total R&D over 1970–1979 | 106 | 11.0 years<br>($\rho$: 9.1%) |
| Energy R&D over 1970–1989 | 48 | 5.1 years<br>($\rho$: 19.5%) |

Source: Questionnaire to Major Firms (undertaken in April 1990: supported by AIST of MITI): Institute of Economic Research, Japan Society for the Promotion of Machine Industry, 'Report on the Promotion of Research Industry', (Tokyo, 1990).

Using average rates of $\rho$ and years of $m$[19] over the periods of 1970–1989 and 1970–1979 as indicated in Tables 16 and 17, $\rho_t$ and $m_t$ can be obtained as follows:

$$\rho_t = 0.03\mathrm{e}^{(T_t/T_0)^{0.15}} \tag{A7}$$

$$m_t = -4.54\ln(g + \rho_t) - 2.88 \qquad g = 0.158 \tag{A8}$$

Similarly, $\rho_t$ and $m_t$ for technology knowledge stock of energy R&D (TE) can be described as follows:

$$\rho_{\mathrm{e}t} = 0.05\mathrm{e}^{(\mathrm{TE}_t/\mathrm{TE}_0)^{0.15}} \tag{A9}$$

$$m_{\mathrm{e}t} = -10.06\ln(g + \rho_{\mathrm{e}t}) - 10.42 \qquad g = 0.098 \tag{A10}$$

Outcomes of the estimation of the rate of obsolescence of technology, time lag between R&D and commercialization, and technology knowledge stock for both total R&D and energy R&D are summarized in Table 18. In the tables, technology knowledge stock calculated by using both dynamic rate and lag as well as average ones are compared.

In order to assess the significance of the measurement of technological knowledge stock with dynamic rate of obsolescence and time lag of R&D to commercialization, comparative assessments of technology knowledge stock were made by means of correlation with patent and fittingness in a production function. The results are summarized in Tables 19 and 20, which indicate that technology knowledge stock calculated by using dynamic rate and lag is statistically more significant than the stock calculated by using average rate and lag.

### *A.3. Data construction and sources*

1. Production and production factors
    - $Y$ (production) = (gross cost at 1985 fixed prices [s1]),
    - $L$ (labor) = (number of employed persons [s1]) × (working hours [s2]),
    - $K$ (capital) = (capital stock [s3]) × (operating rate [s4]),
    - $M$ (materials: intermediate inputs except energy) = (intermediate inputs at 1985 fixed prices [s1]) − (gross energy cost at 1985 fixed prices [s5], [s6], [s7]),
    - $E$ (energy) = (final energy consumption [s7]), and
    - $T$ (technology) (see Eq. (A2)).
2. Technology related production factors (see details, Watanabe, 1992a)
    - Lr (labor for technology) = (number of researchers [s8]) × (working hours [s9]),
    - Kr (capital stock of R&D: KR) × (operating rate [s10]),
        - KRt = GTCkt + (1 − $\rho$kr)KRt − 1,
            - GTCk (R&D expenditure for capital at 1985 fixed prices [s8], [s11]),
            - $\rho$kr (rate of obsolescence of capital stock for R&D: inverse of the average of lifetime of tangible fixed assets for R&D [s10]),
    - Mr (materials for R&D [s8], [s11]),
    - Er (energy for R&D [s11]).

Table 17
Time lag of R&D to commercialization in the Japanese manufacturing industry in the 1970s and 1980s

| | Valid samples | Average (years) |
|---|---|---|
| Total R&D over 1970–1989 | 360 | 3.3 |
| Total R&D over 1970–1979 | 139 | 3.4 |
| Energy R&D over 1970–1989 | 55 | 1.8 |

Source: Same as Table 16.

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[19] Average years $m$ are used in identifying $\varepsilon$ of $g'$ in Eq. (A6).

Table 18
Trends in rate of obsolescence of technology, time lag of R&D to commercialization and technology knowledge stock in the Japanese manufacturing industry (1970–1994)

| | Technology knowledge stock of total R&D | | | | Technology knowledge stock of energy R&D | | | |
|---|---|---|---|---|---|---|---|---|
| | $\rho^a$ | $m$ | $T$ | $T'$ | $\rho_e$ | $m_e$ | TE | TE′ |
| 1970 | 8.24 | 3.59 | 5620.0 | 5620.0 | 14.51 | 3.79 | 83.8 | 83.8 |
| 1971 | 8.42 | 3.55 | 6494.9 | 6507.6 | 14.72 | 3.72 | 91.9 | 92.4 |
| 1972 | 8.63 | 3.51 | 7635.8 | 7630.5 | 14.95 | 3.62 | 101.6 | 100.8 |
| 1973 | 8.86 | 3.47 | 9010.5 | 9014.2 | 15.18 | 3.53 | 112.0 | 111.3 |
| 1974 | 9.10 | 3.43 | 10 599.8 | 10 517.6 | 15.40 | 3.44 | 122.7 | 128.8 |
| 1975 | 9.31 | 3.39 | 12 107.7 | 11 994.5 | 15.68 | 3.33 | 137.3 | 149.4 |
| 1976 | 9.50 | 3.35 | 13 658.2 | 13 501.1 | 16.04 | 3.19 | 158.3 | 178.5 |
| 1977 | 9.66 | 3.33 | 15 040.2 | 14 852.9 | 16.49 | 3.02 | 186.3 | 222.8 |
| 1978 | 9.78 | 3.30 | 16 205.0 | 18 013.5 | 17.09 | 2.79 | 230.0 | 258.8 |
| 1979 | 9.89 | 3.28 | 17 242.5 | 17 065.8 | 17.60 | 2.60 | 271.2 | 312.0 |
| 1980 | 9.99 | 3.27 | 18 241.1 | 18 094.2 | 18.24 | 2.37 | 330.1 | 365.3 |
| 1981 | 10.09 | 3.25 | 19 265.1 | 19 161.5 | 18.78 | 2.18 | 404.5 | 457.8 |
| 1982 | 10.19 | 3.23 | 20 376.8 | 20 326.2 | 19.27 | 2.01 | 546.2 | 615.6 |
| 1983 | 10.30 | 3.21 | 21 609.1 | 21 624.5 | 19.73 | 1.85 | 703.4 | 759.2 |
| 1984 | 10.43 | 3.19 | 23 047.6 | 23 129.6 | 20.21 | 1.69 | 813.1 | 876.9 |
| 1985 | 10.56 | 3.17 | 24 679.8 | 24 864.3 | 20.60 | 1.56 | 873.2 | 940.7 |
| 1986 | 10.70 | 3.14 | 26 514.9 | 26 807.4 | 20.87 | 1.47 | 921.0 | 988.5 |
| 1987 | 10.86 | 3.12 | 28 576.3 | 29 009.1 | 21.21 | 1.36 | 976.1 | 1034.1 |
| 1988 | 11.03 | 3.09 | 31 025.7 | 31 578.8 | 21.39 | 1.30 | 1011.2 | 1094.0 |
| 1989 | 11.21 | 3.06 | 33 656.3 | 34 467.4 | 21.52 | 1.26 | 1038.0 | 1129.6 |
| 1990 | 11.38 | 3.03 | 36 293.1 | 37 412.0 | 21.67 | 1.21 | 1070.4 | 1161.7 |
| 1991 | 11.54 | 3.00 | 39 079.7 | 40 512.5 | 21.83 | 1.16 | 1098.9 | 1200.9 |
| 1992 | 11.72 | 2.97 | 42 139.2 | 43 910.5 | 22.02 | 1.10 | 1130.7 | 1236.2 |
| 1993 | 11.91 | 2.94 | 45 538.1 | 47 660.4 | 22.15 | 1.06 | 1155.1 | 1276.5 |
| 1994 | 12.09 | 2.91 | 48 936.3 | 51 642.6 | 22.24 | 1.03 | 1170.0 | 1297.0 |

[a] $\rho$ and $\rho_e$: rate of obsolescence of technology of total R&D and energy R&D, respectively (%).
$m$ and $m_e$: time lag of R&D to commercialization with respect to total R&D and energy R&D, respectively (year).
$T$ and TE: technology knowledge stock of total R&D and energy R&D measured using the dynamic rate of obsolescence of technology and time lag of R&D to commercialization (billion yen by 1985 fixed price).
$T'$ and TE′: technology knowledge stock of total R&D and energy R&D measured using the average rate of obsolescence of technology and time lag of R&D to commercialization (billion yen by 1985 fixed price).

3. Cost
   - GC (gross cost [s1]),
   - GLC (gross labor cost) = (income of employed persons [s1]) + (income of unincorporated enterprises [s12]),
   - GCC (gross capital cost) = (gross domestic product [s1]) − (gross labor cost),
   - GMC (gross materials cost) = (intermediate input [s1]) − (gross energy cost),
   - GEC (gross energy cost) = (expenditure for fuel

Table 19
Comparative assessment of technology knowledge stock in the Japanese manufacturing industry by means of correlation with patents (1970–1994)

| | $b_1$ ($t$-value) | Adj. $R^2$ | DW | $F$-statistics | AIC value |
|---|---|---|---|---|---|
| $T$ with average $\rho$ and $m$ | 8.52 (32.13) | 0.980 | 0.95 | 584.5 | 491.0 |
| $T$ with dynamic $\rho$ and $m$ | 9.05 (34.55) | 0.983 | 1.02 | 675.7 | 487.4 |

Model: $\mathrm{PAT} = a + b_1 T + b_2 D$, where PAT: number of patents; $T$: technology knowledge stock; $D$: dummy variables (1986–1989 = 1, other years = 0); and $a$, $b_1$ and $b_2$: coefficients.

Table 20
Comparative assessment of technology knowledge stock in the Japanese manufacturing industry by means of fittingness in a production function (1965–1994)

| | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ | $\zeta$ | Adj. $R^2$ | DW | $F$ | AIC |
|---|---|---|---|---|---|---|---|---|---|
| $T$ with average $\rho$ and $m$ | 0.19 (3.07) | 0.12 (3.10) | 0.78 (17.91) | 0.02 (1.45) | 0.05 (1.92) | 0.9998 | 1.59 | 25 694.3 | − 293.47 |
| $T$ with dynamic $\rho$ and $m$ | 0.21 (2.98) | 0.13 (3.66) | 0.76 (16.31) | 0.02 (1.48) | 0.05 (1.93) | 0.9998 | 1.62 | 25 732.1 | − 293.52 |

[a] Figures in parentheses indicate *t*-value.
Model: $Y = AL^{\alpha}K^{\beta}M^{\gamma}E^{\delta}T^{\zeta}$, where $Y$: production; $A$: scale factor; $L$: labor; $K$: capital; $M$: materials; $E$: energy; and $\alpha$, $\beta$, $\gamma$, $\delta$, and $\zeta$: elasticities of respective production factors.

and electricity [s5]), and
GTC (gross technology cost) = (R&D expenditure and payment for technology imports [s8]).

4. Technology related cost (see details, Watanabe, 1992a)
GTCl (R&D expenditure for labor [s8]),
GTCk (R&D expenditure for capital [s8], [s11]),
GTCm (R&D expenditure for materials [s8], [s11]), and
GTCe (R&D expenditure for energy [s11]).

Sources of data

s1 ;Annual Report on National Accounts (Economic Planning Agency, 1965–1995)
s2 ;Year Book of Labor Statistics (Ministry of Labor, annual issues)
s3 ;Statistics of Enterprisers' Capital Stock (Economic Planning Agency, 1965–1995)
s4 ;Annual Report on Indices on Mining and Manufacturing (MITI, annual issues)
s5 ;Industrial Statistics (MITI, annual issues)
s6 ;Economic Statistics Annual (The Bank of Japan, annual issues)
s7 ;Comprehensive Energy Statistics (Agency of Natural Resources and Energy of MITI, annual issues)
s8 ;Report on the Survey of Research and Development (Management and Coordination Agency, annual issues)
s9 ;Survey on Researchers for the Promotion of Basic and Leading Science and Technology (Institute for Future Technology, Tokyo, 1990)
s10 ;Corporate Tax Law (MITI)
s11 ;Report on the Promotion of Research Industry (Institute of Economic Research, Japan Society for the Promotion of Machinery Industry, Tokyo, 1990)
s12 ;Quarterly Report on Unincorporated Enterprises (Management and Coordination Agency, quarterly issues).

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