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Scale economies, technological change and capacity factor: An economic analysis of thermal power generation in Japan

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SCALE ECONOMIES, TECHNOLOGICAL CHANGE AND CAPACITY FACTOR: AN ECONOMIC ANALYSIS OF THERMAL POWER GENERATION IN JAPAN

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By

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We certify that we have read this dissertation and that, in our opinion, it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Agricultural and Resource Economics.

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Finally, I dedicate this small peace of academic work to my late father, Mr. Tahei Iinuma, who led me spiritually to a journey into the academic world and my mother, Mrs. Ayako Iinuma, for her patience and generosity.

ABSTRACT

This study basically attempts to determine the technological characteristics which are responsible for productivity changes in thermal power generation in Japan over the period of 1964-1988. Specific objectives are to estimate the magnitude of scale economies, technological change, capacity factor effect, elasticity of substitution between input factors and movements of total factor productivity in thermal power generation in Japan and derive policy implications regarding thermal power in the future generation mix.

To achieve the objectives, a translog cost function incorporating variables representing technological change and capacity factor, in addition to the basic four variables, is used.

Several major findings and conclusions are: (1) There exist economies of scale in thermal power generation in 1964-1988, although the magnitude of economies of scale is very small. (2) The rate of technological improvement clearly declined after the period 1971-1975. (3) The capacity factor is critical in determining movements in total factor productivity. (4) Findings of this study suggest that the outlook for thermal power generation is dim, which calls for much broader policy options to revamp the Japanese electric power industry.

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INTRODUCTION

1. Overview of the Energy Economy in Japan

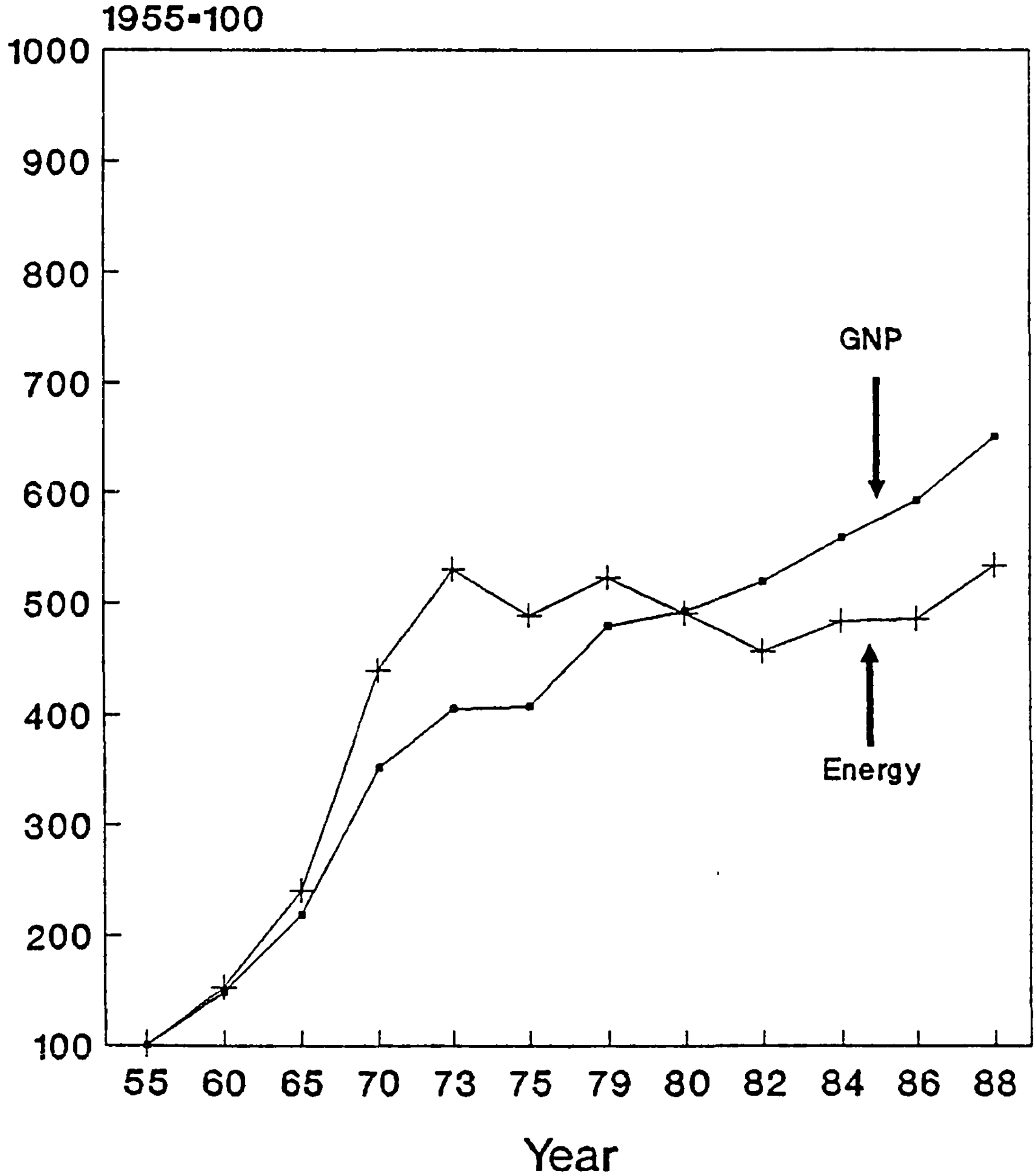
Adequate, reliable and economical energy supplies are fundamental to sustain economic well-being in every country. This is particularly true of Japan which has very limited energy resources. No one would deny that Japan could not have achieved economic development in the post-war era without securing sufficient energy supplies at reasonable costs.

The Japanese real Gross National Product (GNP) grew at an average annual rate of 9.3 percent between fiscal year (f.y.)[1] 1955 and f.y. 1973, which represents a five-fold increase in the size of real GNP. Total final energy consumption increased six-and-a-half times during the same period, reflecting such rapid economic growth rates. As figure 1 shows, there existed a close positive correlation between energy demand growth and GNP growth before the first oil crisis in 1973.

This historical relationship, however, collapsed afterwards, which was mainly due to improvement of energy efficiency in all sectors of the economy and changes in the industrial structure. During 1973-1988, real GNP expanded

1. Fiscal year in Japan begins on April 1 and ends on March 31. For simplicity, fiscal year is omitted throughout the text.

Figure 1. GNP Growth and Energy Demand Growth per Capita in Japan (1955 - 1988)



Source: Derived from Shigen Enerugii Chou, 1990.

by 81.5%, while total final energy consumption grew by only 13.5%.

The energy intensity measured by final energy consumption per real GNP declined markedly between 1973 and 1988 (figure 2). Among other things, improvement of energy efficiency in the energy-intensive industries was very impressive (table 1). The sectoral distribution of energy consumption also changed during the same period reflecting

Table 1

Energy Intensity in Energy-Intensive Industries in 1987

(1973 = 100)

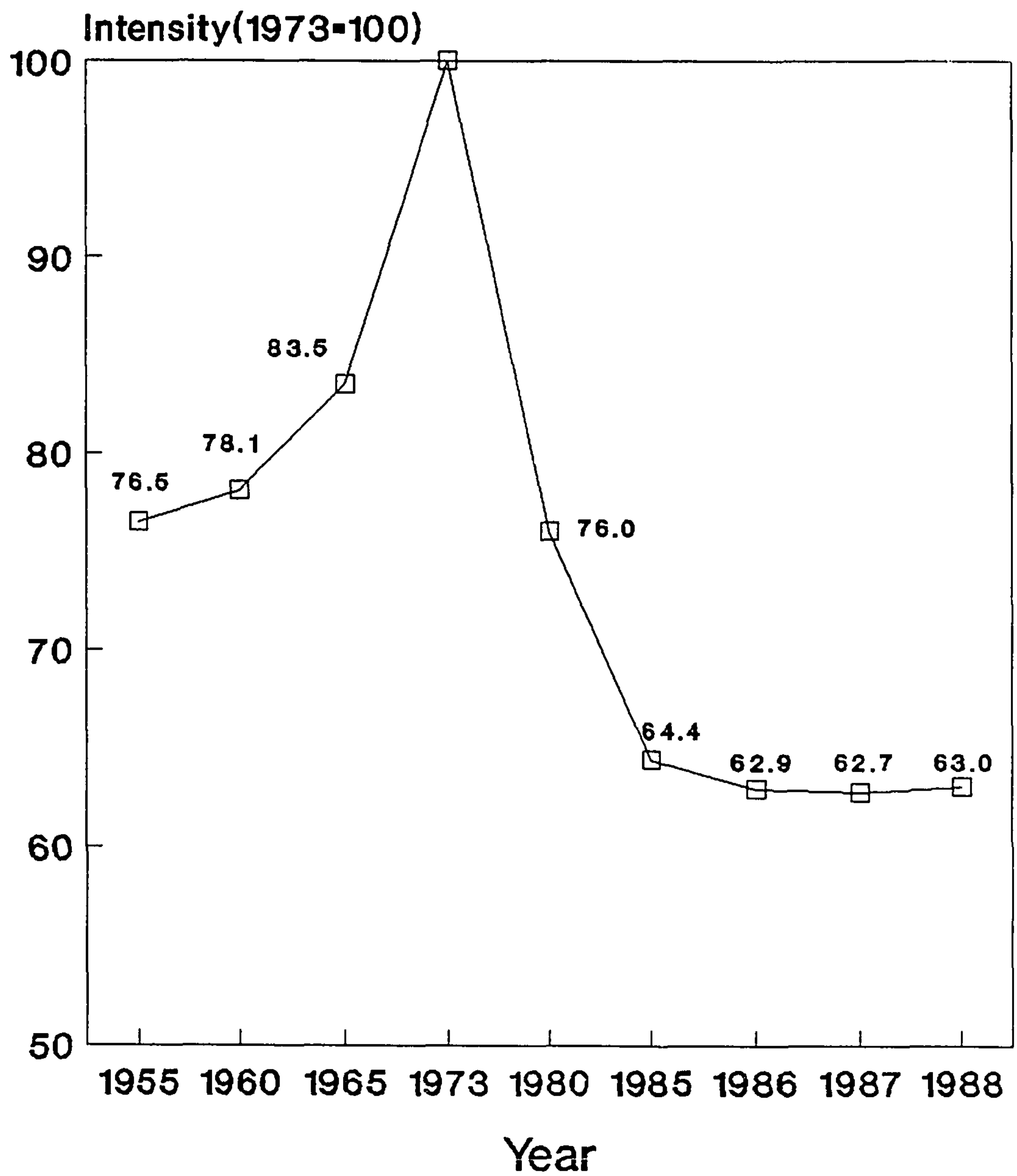
	Industries				
	Steel	Petrochemical	Cement	Paper&Pulp	Sheetglass
Energy Intensity	77.8	57.3	69.7	59.6	73

Source: The Energy Conservation Center, 1989.
Note: Figures for steel and petrochemical industries are 1973/1986 and 1976/1987 respectively.

the changed weight of each sector in the economy. As a result, average annual energy consumption growth between 1973 to 1985 was almost zero. In particular, energy consumption in the industrial sector, which accounts for more than 50% of total energy consumption, recorded negative growth between 1973 and 1986 (tables 2 & 3).

Yet, the oil crisis in the 1970's seems to have

Figure 2. Energy Intensity (1955-1988)



Source: Derived from Shigen Enerugii Chou, 1990.

Table 2

Annual Final Energy Demand Growth by Sector(1960-1988)

(Percent)

	1960-1973	1973-1979	1979-1985	1986	1987	1988
Household	7.9	5.2	2.7	0.7	0.6	2.7
Commercial	15.3	1.4	1.3	1.5	3.7	8.9
Transportation	10.8	4.2	1.0	3.5	4.1	5.6
Industry	11.6	-0.8	-2.1	-1.6	5.0	6.1
chemical	13.2	-0.7	-3.2	1.6	6.1	4.2
steel	13.2	-2.5	-2.7	-7.1	5.2	4.7
Total	11.4	0.9	-0.5	0.4	4.8	5.7

Source: Derived from Shigen Enerugii Chou, 1990.

Table 3

Composition of Energy Demand by Sector(1960-1988)

(Percent)

	1960	1973	1979	1985	1988
Household	13.5	8.9	11.4	13.8	13.6
Commercial	5.9	9.2	9.5	10.6	10.9
Industry	61.0	62.5	56.5	51.2	50.4
steel	16.6	20.5	16.7	14.6	13.4
chemical	12.7	15.6	14.2	12.0	12.1
Transportation	17.6	16.4	19.9	21.8	22.3

Source: Derived from Shigen Enerugii Chou, 1990.
Note: Figures do not sum to 100 because of roundoff and exclusion of non-energy use.

receded to the past. People are again forgetting scarcity of energy resources. Annual energy consumption growth in Japan averaged 0.9% between 1973 and 1988, but in 1987 and 1988 it exceeded 4%. Improvement in energy efficiency which resulted in remarkable energy savings is also reaching a plateau in Japan as well as in other industrialized countries (Flavin and Alan, 1988; Schipper and Andrea, 1989). Households are paying scant attention to energy saving, and industries are not making efforts to improve energy efficiency as much as before. Furthermore, energy-intensive industries such as steel and chemical are expanding production, on account of boosted domestic demand. Therefore, energy consumption in these industries is again rising.

The energy supply structure has also changed since the first oil crisis in 1973 (table 4). Before the first oil shock, the Japanese energy policy was geared to taking advantage of cheap and plentiful oil resources so that the structure of the economy became heavily dependent on oil. The share of oil in the total primary energy supply reached almost 80% in 1973. The Japanese economy was therefore hit severely by the first oil price shock, which resulted in negative economic growth rate in 1974. In light of such vulnerability to energy supply disruptions, the Japanese government adopted an energy policy to diversify from oil to

Table 4

Primary Energy Supply Structure(1960-1988)

(Percent)

	1960	1973	1980	1985	1988
Oil	37.6	77.4	66.1	56.3	57.3
Coal	41.2	15.5	17.0	19.4	18.1
Natural gas	0.9	1.5	6.1	9.4	9.6
Nuclear	-	0.6	4.7	8.9	9.0
Hydro	15.7	4.1	5.2	4.7	4.7
Geothermal	-	0	0.1	0.1	0.1
Others	4.6	0.9	1.0	1.2	1.3

Source: Derived from Shigen Enerugii Chou, 1990.

other sources such as nuclear and other fossil fuels. As a result of the new energy policy, coupled with higher oil prices, it seems that Japan succeeded in reducing dependence on oil because the share of oil in the total primary energy supply decreased by 20% between 1973 and 1988. However, oil is still a major energy source which accounted for 57.3% of the total in 1988. Moreover, the share of oil increased again in 1987 and 1988 due to lower oil prices.

If the recent changes in both demand and supply continue, it will mean greater energy demand and reliance on oil in the future than many had expected. Thus, the Ministry of International Trade and Industry (MITI) recently warned that a third oil crisis is possible after the middle of the 1990's based upon the following prospects (Shigen Enerugii Chou, 1989b):

1. Energy demand world-wide, especially in the Pacific-Rim countries including ASEAN, China and NIEs which are the growth centers of the world economy, is expected to grow steadily.

2. Nuclear energy as an alternative to oil will not be as dependable as previously thought because of widespread public anti-nuclear sentiment.

3. Dependence on OPEC oil will increase due to a possible decline in oil production in non-OPEC countries.

In addition to the above probable developments, the current crisis in the Middle East will have at least a short run effect on oil supplies from this region. Yet, oil imports from Iraq and Kuwait account for about 10% of Japan's total oil imports. Supply cut from these countries can be made up for by other oil sources and measures such as shifting to other fuels and conservation. Furthermore, Japan learned from the first oil crisis how to cope with unstable oil supplies. The case of the second oil crisis exemplifies flexibility of the Japanese economy to the oil shock. Japan experienced only a slowing of its annual economic growth rate to 3.4% in 1980 from 5.3% in 1979. Therefore, the impacts of supply interruption from Iraq and Kuwait on the economy will be little.

Another problem is looming: global warming. According to some estimates, roughly 50% of the projected global warming in the coming 40 years will be caused by the energy sector (Allen and Christensen, 1990). The greenhouse effect is said to be brought about by carbon dioxide (CO_2), methane, nitrous oxide and chlorofluorocarbons. Among these greenhouse gases, CO_2 is responsible for roughly half of global warming and 80% of the CO_2 is emitted by burning fossil fuels which are so important for modern economies (Kats, 1990).

Current technologies, however, do not permit us to contain CO_2 effectively. Nor are pollution-free alternatives such as solar energy economically viable. Nuclear energy cannot be a dominant energy source due to its inherently risky nature and public opposition. Thus, we are facing a dilemma regarding the choice between economic growth and environmental degradation, assuming present economic structure and lifestyle. The only option for the foreseeable future is to improve energy efficiency on both the demand and supply sides to alleviate the trade-off between economic well-being and environmental pollution.

2. Electricity and Economic Development

Electrical energy and the electric power industry have historically played a vital role in the economic development of industrialized countries (Rosenberg, 1983; Schurr, 1983). They will continue to play an important role if the electric utility can provide stable and adequate supplies at reasonable costs to end-users. This is true not only because electrical energy is indispensable for various sectors in the economy, but also because the electric power industry is a major consumer of primary energy as well as a major supplier of energy for end-users.

In Japan, the electric power industry accounted for approximately 37.3% of total primary energy consumption in

1988 (figure 3). This ratio, the so-called electrification ratio,[2] has been increasing since the oil crises and is expected to rise further to 40% in 1995, and to 42% in 2000 (Denkijigyou Shingikai Jukyuu Bukai, 1987). The projection for the rising share of electrical energy in the total energy market is based upon the prospect that the consumption of electricity will continue to keep pace with economic growth, while total energy consumption will not grow as much as electrical energy consumption.

The electric power industry is also a typically capital-intensive industry. It accounts for a large portion of domestic investment. In 1988 total net investment in the Japanese electric power industry amounted to 3,449 billion yen (US$ 23 billion),[3] about 10% of the total net domestic investment, which demonstrates the fundamental importance of the electric power industry in the national economy (Keizaikikaku Chou Chousakyoku 1989; Shigen Enerugii Chou, 1989a). On account of this, MITI in Japan sometimes guides electric utilities administratively to adjust implementation of their investment plans to prevailing economic conditions.

Therefore, the performance of the electric power industry as a basic industry in the national economy has

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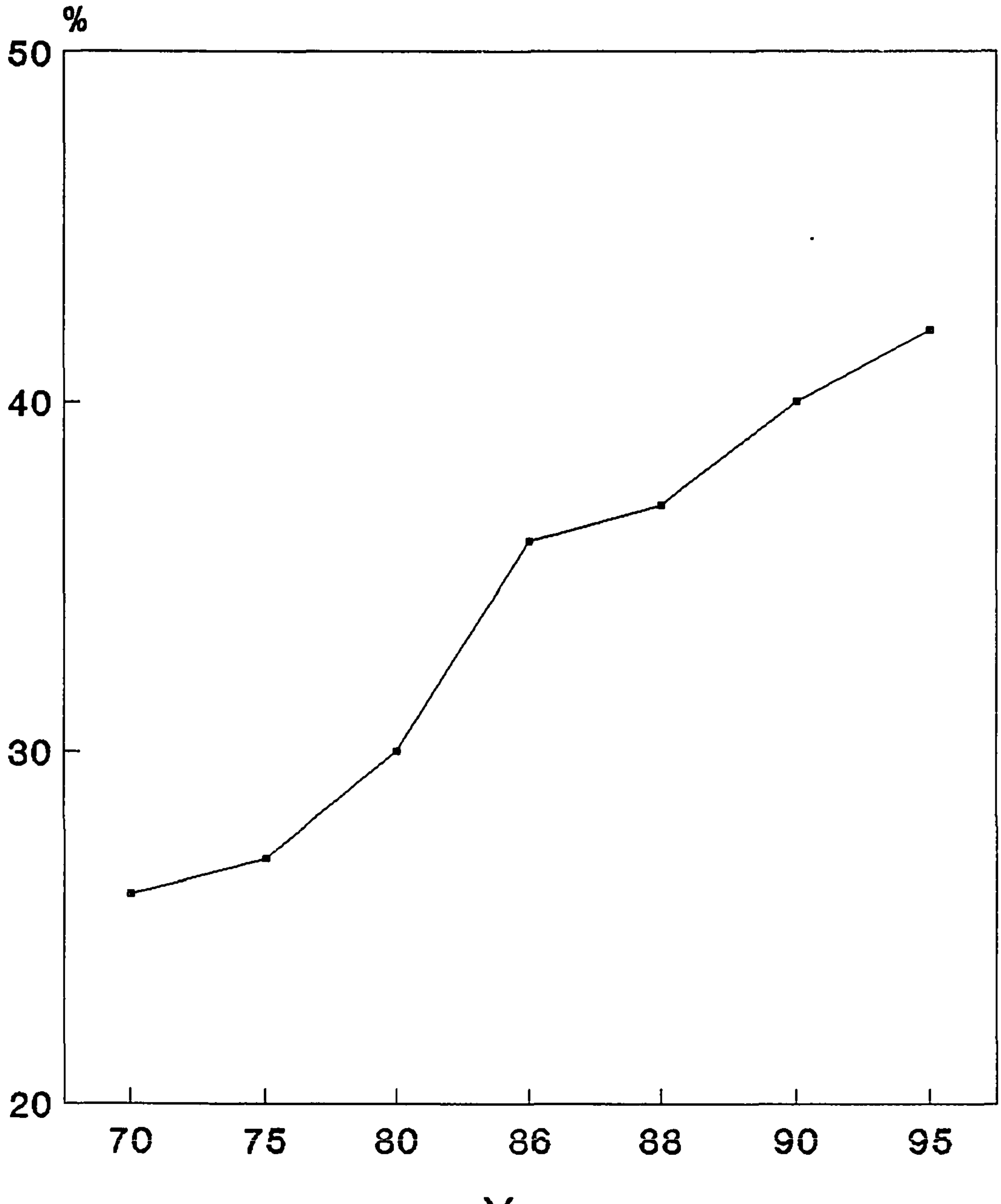
2. In this study, we use the electrification ratio defined as follows:
   The electrification ratio = (primary energy consumption in the electric power sector)/(total primary energy consumption)
3. US$1 = 150 Japanese Yen

Figure 3. The Electrification Ratio (1970 - 1995)



Source: Derived from Shigen Enerugii Chou, 1990.

often been subject to public scrutiny. This is the case not only in Japan but also in many other countries. Heated debates on ongoing privatization of the electric power industry in the United Kingdom and regulatory reforms in the U.S. market for wholesale electricity proposed by the Federal Energy Regulatory Commission illustrate the important role that electricity plays in the economy (Secretary of State for Energy, 1988; U.S. Federal Energy Regulatory Commission, 1988a, 1988b, 1988c).

From the early 1950's to 1973, Japanese electric power utilities expanded their scale of operation to meet the country's ever-increasing electricity consumption. Electricity consumption in Japan increased annually by approximately 12% between 1951 and 1973, which reflected high growth rates of real gross national product during this period. To meet double-digit electricity demand growth, the electric power industry constructed larger thermal generating plants (table 5), in particular, oil-fired generating plants embodying technical innovations, such as higher steam pressure and temperature to bring about higher thermal efficiency. As a result, the share of thermal generation reached more than 80% in 1973 (table 6). The dominant role of thermal generating units undoubtedly reflected the fact that oil prices were very low at that time.

Table 5

Newly Installed Thermal Generation Units by Size (1956 - 1987)

(Number)

	Capacity			
Period	75MW	125MW-265MW	325MW-600MW	700MW-1090MW
1956-60	11	18	-	-
1961-65	2	49	6	-
1966-70	-	29	18	-
1971-75	-	7	48	3
1976-80	-	1	18	5
1981-87	-	1	17	7

Source: Derived from Shigen Enerugii Chou Koueki Jigyoubu, 1964-1990.

Table 6

Electricity Generation Mix in Japan (1960-1988)[a]

(Percent)

	1960	1965	1973	1980	1988
Hydro	52.2	41.8	16.3	16.6	13.3
Conventional	52.2	41.8	15.1	15.8	12.0
Pumped-storage	-	-	1.1	0.7	1.3
Thermal	47.8	58.2	81.3	67.5	60.1
Oil	16.7	31.6	71.1	44.0	24.9
Coal	31.1	26.0	4.4	4.4	9.5
LNG[b]	0.0	0.1	2.2	15.0	21.2
LPG	-	-	-	0.8	0.6
Other gases	-	0.4	3.7	3.1	3.6
Geothermal	-	-	0.0	0.2	0.2
Nuclear	-	0.0	2.4	16.0	26.6
Total	100.0	100.0	100.0	100.0	100.0

Source: Derived from Shigen Enerugii Chou Koueki Jigyoubu, 1964-1990.
a. Figures show percentage share in terms of output generated.
b. LNG includes natural gas.

Consequently, the electric power industry appears to have enjoyed economies of scale stemming from larger units, technological progress embodied in new generating facilities and low fuel prices before the first oil crisis in 1973. Electricity rates were therefore very stable for both lighting and power uses[4] until 1973 (figure 4). Furthermore, the electricity rate for lighting use was virtually decreasing and the rate for power was almost constant in real terms (figure 5). Meanwhile, stable electricity prices, coupled with overall economic development, made it possible for consumers in every sector of the economy to use more electricity. In particular, cheaper electricity resulted in wider applications of electricity in the industrial sector which was the engine for post-war economic development in Japan (Minami, 1986).

3. Institutional Structure and Technological Background

In Japan there are sixty-six electric utilities which are engaged in the electricity supply business. Most of the electric utilities are privately-owned. Among these, nine privately-owned electric power companies accounted for approximately 75% of both total installed generating capacity and total generation in 1988 (table 7).

These nine electric companies are vertically integrated

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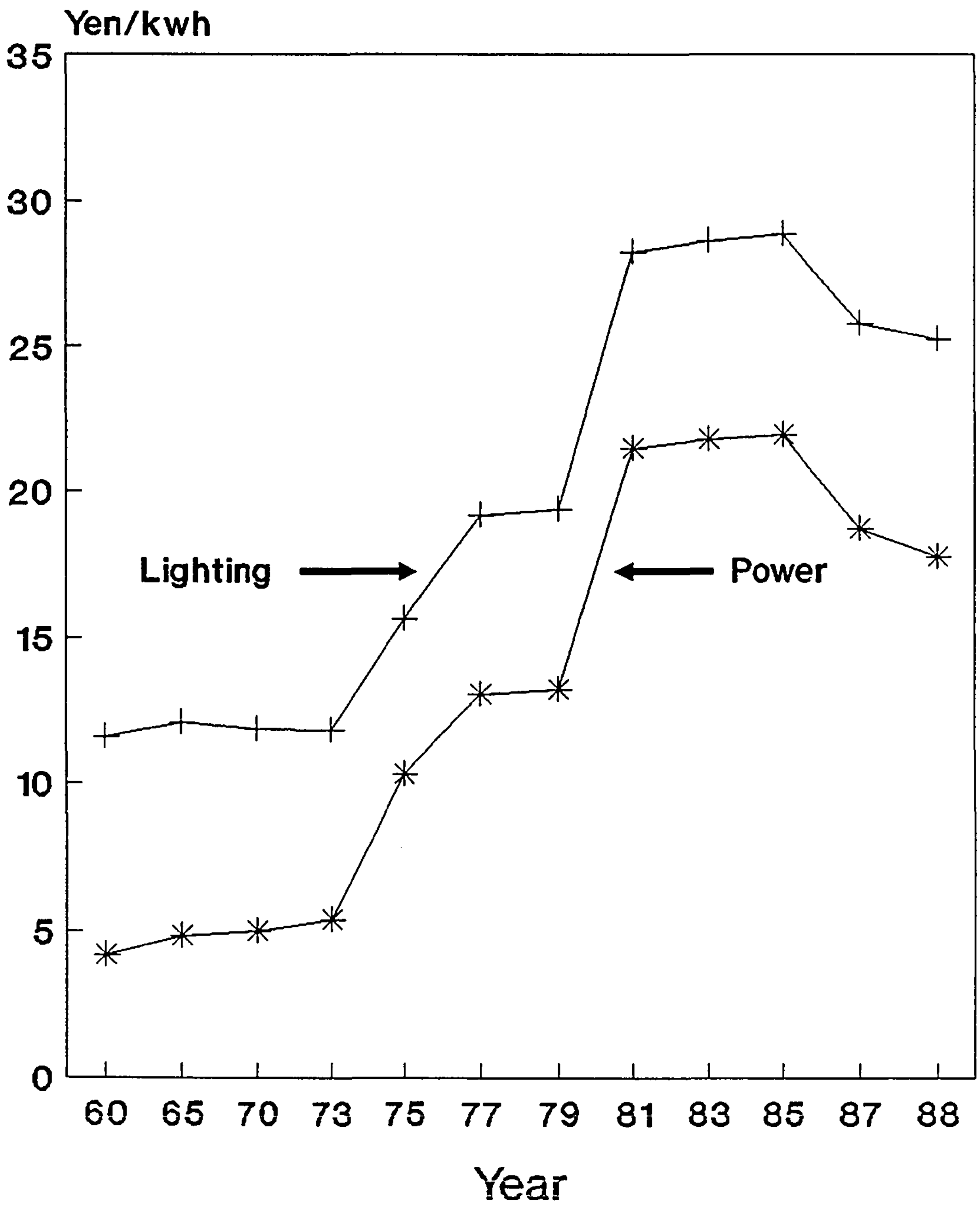
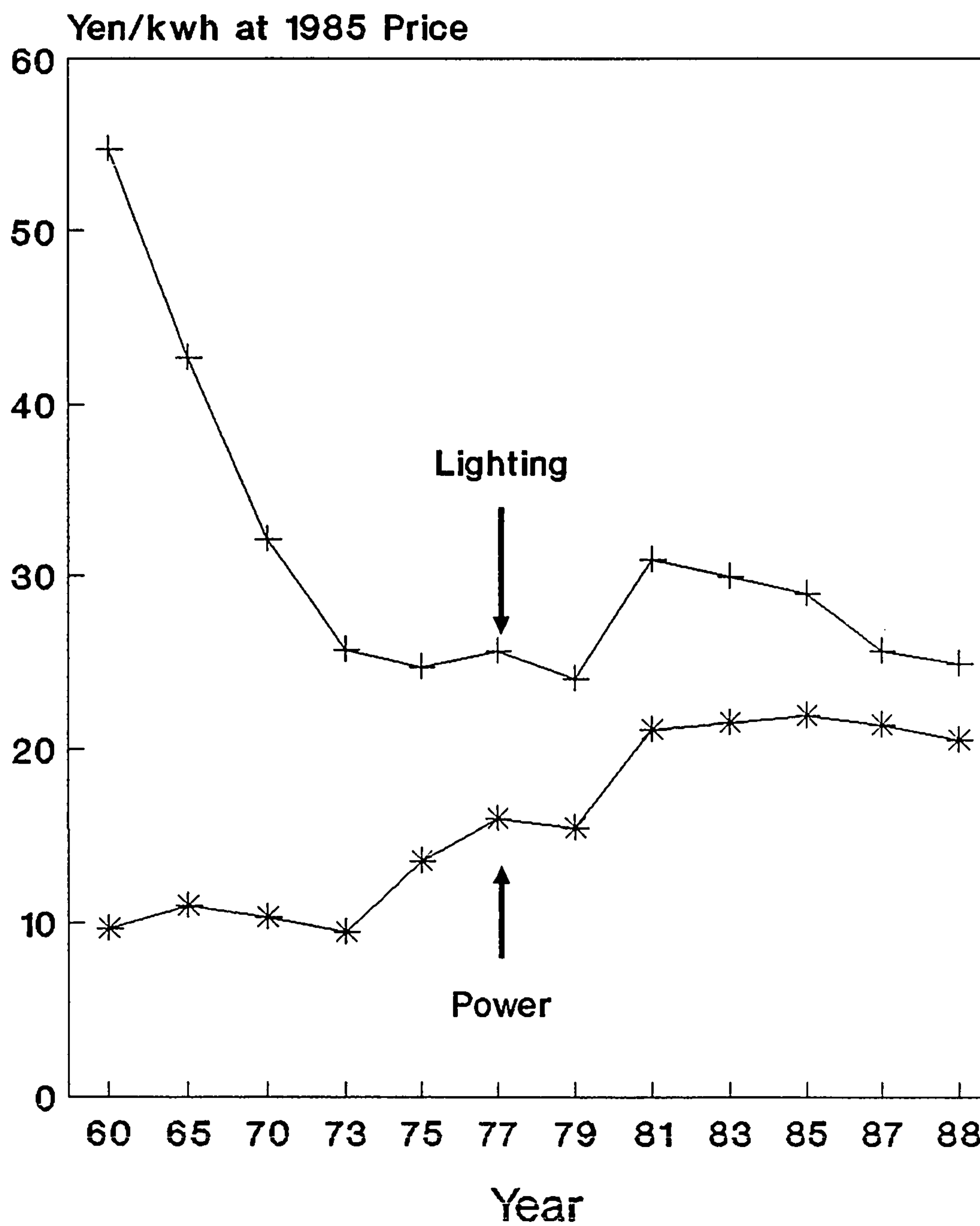
4. Lighting use includes residential and commercial uses, while power use includes industrial use.

Figure 4. Nominal Average Unit Price of Electricity (1960-1988)



Source: Derived from Denkijigyou Rengoukai, various issues.

Figure 5. Real Average Unit Price of Electricity (1960-1988)



Source: Derived from DenkiJigyou Rengoukai, various issues and Keizaikikaku Chou Chousakyokyu, 1989

Table 7

Total Generating Capacity and Total Generation in Japan by Owner in 1988

(Percent)

Owners	Capacity	Generation
Nine privately-owned Cos.[a]	76.3	73.7
Okinawa Electric Power Co.	0.5	0.4
Electric Power Development Co.[b]	5.9	4.7
Other electric utilities[c]	8.0	9.7
Self-generators	9.3	11.5
Total	100.0	100.0

Source: Derived from Denkijigyou Rengoukai, 1989.
a. Nine electric power companies are Hokkaido Electric Power Company (EPCO.), Touhoku EPCO, Tokyo EPCO., Hokuriku EPCO., Chubu EPCO., Kansai EPCO., Chugoku EPCO., Shikoku EPCO., and Kyushu EPCO..
b. Electric Power Development Company is a semi-governmental company and wholesaler to nine electric power companies.
c. Other utilities include municipal utilities and joint-ventured companies.

from generation to distribution with defined supply territories in which they have a legal obligation to provide electricity to retail consumers since 1951, when the basis of the industry structure of electric power supply was established. Only nine electric companies are allowed to sell electricity to retail customers. Other utilities are wholesalers who cannot sell electricity to the public. Table 8 shows basic data on the nine electric power companies.

Another major electric utility is the Electric Power Development Company (EPDC). EPDC is a semi-governmental organization as a wholesaler which initially involved large-scale hydro power development. It is now putting an emphasis on large-scale coal-fired plants with environmental protection equipment such as deSOx and deNOx.

Besides electric utilities, there are many private generators which account for about 10% of total generating capacity and total generation. The scale of generating facilities owned by private generators is small compared to those owned by electric utilities. However, companies installing their own generating facilities have been steadily increasing recently while existing private generators have been boosting their capacity factors because of lower fuel costs.

Nine electric companies are interconnected by trunk

Table 8

Profiles of Nine Electric Power Companies

(As of March, 1989)

Company	Total Asset (billion yen)	Installed Capacity (MW)	Energy Sale (billion kwh)	Customers (1000)	Employees
Hokkaido	1351	4415	18	3041	6364
Tohoku	2265	10057	47	6068	13473
Tokyo	10253	42335	190	21435	39544
Chubu	3998	20969	88	8140	20510
Hokuriku	947	3940	19	1611	5436
Kansai	5395	29426	107	10675	24743
Chugoku	2158	9212	38	4375	11348
Shikoku	1035	5401	18	2376	6780
Kyushu	2937	12908	48	6574	14503
Total	30339	138662	574	64293	142701

Source: Denkijigyou Rengoukai, 1990.

transmission lines such as 500kv, 275kv and 187kv for the purpose of economical and emergency exchange between them which is called the wide-area coordination system corresponding to the power pooling system in U.S. In this connection, the power system in Japan is divided into two frequency zones, 50hz and 60hz, which is unique to Japan.

These major electric utilities and other minor electric utilities as well as private generators are under pervasive public regulations. Specifically, the Agency of Natural Resources and Energy under MITI has been regulating the electric power industry through authority given by the Electric Power Industry Law of 1964 (Shigen Enerugii Chou, 1988) and the well-known Gyousei Shidou (administrative guidance). Among other things, rate-of-return regulation is a central measure to control franchised electric utilities as in the U.S.

However, Japan does not have a law corresponding to the U.S. Public Utility Regulatory Policies Act (PURPA) of 1978 which mandates electric utilities to purchase from Qualifying Facilities (QFs) that are cogenerators and small power producers which meet some qualifications such as efficiency standard. Nor does there exist a law akin to the Public Utility Holding Act of 1935 governing the electric utility industry.

Unlike in the U.S. electric power industry, deregulation of non-utility generators is as yet very limited in Japan. Only recently, it has become possible for private cogenerators to sell electricity as far as the electricity sale is confined inside one building. Therefore, movement toward deregulation or the competitive market for power is very slow in comparison with the U.S. electric power industry in which competitive pressure, represented by the entry of independent power producers into the wholesale market, has been recently mounting.

Until the beginning of the 1960's, a primal power source was hydro. However, to meet the rapidly growing demand since then, electric utilities urgently needed to develop large-scale power sources. Therefore, they introduced thermal power plants, in particular, oil-fired thermal power plants, which did not require a long lead-time compared to development of the hydro-power source. In addition, thermal power plants burning coal were converted to oil-fired plants. The decision regarding a shift to oil-fired power plants also reflected the fact that the price of oil was declining in real terms during this period.

Since the first oil crisis, electric utilities have sought to diversify their energy sources and reduce oil consumption through the development of nuclear, coal-fired and LNG-fired power plants. Consequently, the share of output generated by oil-fired power plants declined by almost 50% between 1973 to 1988, while the share of nuclear and LNG-fired power generation has risen markedly.

Accordingly, the role of each power source in the power supply system has changed. Oil-fired power plants as base-load facilities in the past have become middle-load and peaking units. Meanwhile, nuclear and large-scale coal-fired units have been playing the role of base-load facilities and LNG-fired units are the middle load facilities. In addition, the pumped-storage hydro helps meet a portion of peak load.

According to long-term resource planning, the role of thermal power generation will shift further to meet the middle and peak load because the share of nuclear power generation in total electric power generation is targeted to increase from 26.6% in 1988 to 43% in 2010 (Denkijigyou Shingikai Jikyuu Bukai, 1990). LNG-fired power plants are expected to become a power source for the middle and peak load, while oil-fired facilities will meet only peak-load. The role of coal-fired power plants is going to change from base-load facilities to base-load and middle-load facilities. Table 9 presents the principal features of these fossil-fueled steam generation technologies (oil-fired, LNG-fired and coal-fired).

Remarkable progress has been realized in thermal power

Table 9

Comparison of LNG-, Coal- and Oil-Fueled Power Sources

	LNG	Coal	Oil
1) Construction Period (year)	10	12	n.a.
2) Fuel Procurement	* take or pay contract (long-term contract, 20 years)	* medium-term contract and spot market available.	* short-term contract (within one year) except for Chinese oil
	* price is pegged to oil prices.	* price is expected to increase	* uncertain
3) future role in generation mix	* middle and peak	* base and middle	* peak
4) start-up (hours)	* 2	* 5	* 2
5) environment	* relatively clean	* dirty	* cleaner than coal

Source: Denkijigyou Shingikai Jukyuu Bukai, 1990.

generation during the last thirty years. Maximum thermal efficiency, for example, has improved from 29% to 43% by new technologies that allow expansion of unit capacity, installation of supercritical steam-pressure units and introduction of combined-cycle systems. Yet, there are some theoretical limits regarding improvements of thermal efficiency in conventional fossil-fueled steam power generation systems. Specifically, heat systems are basically governed by the second law of thermodynamics. Therefore, marginal gain in thermal efficiency from increasing pressure diminishes (Hirsh, 1989).

Advances have also been made in the field of control technologies, which corresponded to increased size of the generating plant. These technological changes evolved from the decentralized monitoring and control system in the 1950's, through the centralized operation and control system in the 1970's, to the automatic operation and control system in the 1980's. These technological changes have resulted in considerable labor saving in the thermal power station (Japan Electric Power Information Center, 1989b).

Nuclear power started in 1966 in Japan when the first commercial gas-cooled reactor by the Japan Atomic Power Company was commissioned. Thereafter, electric utilities have adopted light water reactors (LWRs) that are boiling water reactors (BWRs) and pressurized water reactors (PWRs).

These LWRs are expected to contribute to the generation of nuclear power until fast breeder reactors (FBRs) come into use. Therefore, electric utilities have been making efforts to develop technologies which improve economic efficiency of LWRs such as capacity factor, extension of the plant service life and high performance fuels. The government is strongly committed to the eventual introduction of FBRs to meet Japan's long-term nuclear needs. Toward this policy, the Power Reactor and Nuclear Fuel Corporation is constructing "Monju", a prototype reactor, planned to reach criticality in 1992 and the Japan Atomic Power Company is planning to build and operate its first demonstration reactor (Japan Electric Power Information Center, 1989a).

Development of alternative technologies was initiated by the government of Japan after the first oil crisis, although most of these technologies have not as yet been commercialized. There are two major national projects called the Sunshine Project and the Moonlight Project which aim at developing renewable technologies and new conservation technologies, respectively (Agency of Industrial Science and Technology, 1987a, 1987b). These projects include generation technologies such as solar energy, geothermal, and ocean thermal energy conversion in the Sunshine Project, and fuel cell power generation and ceramic gas turbine in the Moonlight Project. The electric utility has been actively cooperating with the government for developing and commercializing these technologies in light of the fact that Japan depends on imports for most of her energy resources.

4. Problem Statement

Before the first oil crisis in 1973, performance of the electric utilities in Japan was generally satisfactory for consumers. This is particularly so because electricity rates were very stable. However, circumstances surrounding the electric power industry have changed drastically since the first oil crisis. Electric power utilities became subjected to rapid inflation, higher interest rates, and higher fuel prices immediately following the first oil crisis. In particular, the skyrocketed oil price weakened the financial position of electric power companies. This was because the oil-fired generating facilities had already been the dominant power source in the generation mix by 1973. Hence, it was natural that the electric power industry became very vulnerable to turmoils in international oil markets. The price of fuel oil for electricity generation, for instance, tripled between 1972 and 1974, which raised the share of fuel costs in total expenditure during the same period from 19.5% to 39.2%. Electric power companies therefore had to increase electricity rates several times between 1974 and 1979 to assure their financial standing, and again in 1980 and 1981 due to soaring oil prices brought about by the Iran-Iraq War. This was because electricity generation is characterized by very limited substitution between inputs and between fuels and a long gestation period to construct a power plant, which implies that the possibility of offsetting cost increases through substitution is very limited. As a result, nominal average unit prices increased by 244% for lighting use and 409% for power use between 1973 and 1985, although electricity rates were revised downward several times after 1986 due to lower fossil fuel prices caused by the oil glut in the world market and Japanese yen's appreciation due to its huge trade surplus.

Besides the above-mentioned exogenous factors which affected the electric utility industry adversely, a major concern for the power sector has been a decline in load factor[5] on the demand side. Figure 6 shows a downward trend of the load factor during 1970-1988. The gap between off-peak and peak load has been widening year after year, mainly due to increased demand for air-conditioning in summer, which forces the electric power utility to operate power plants inefficiently. According to a long-term demand forecast,the load factor is expected to lower further

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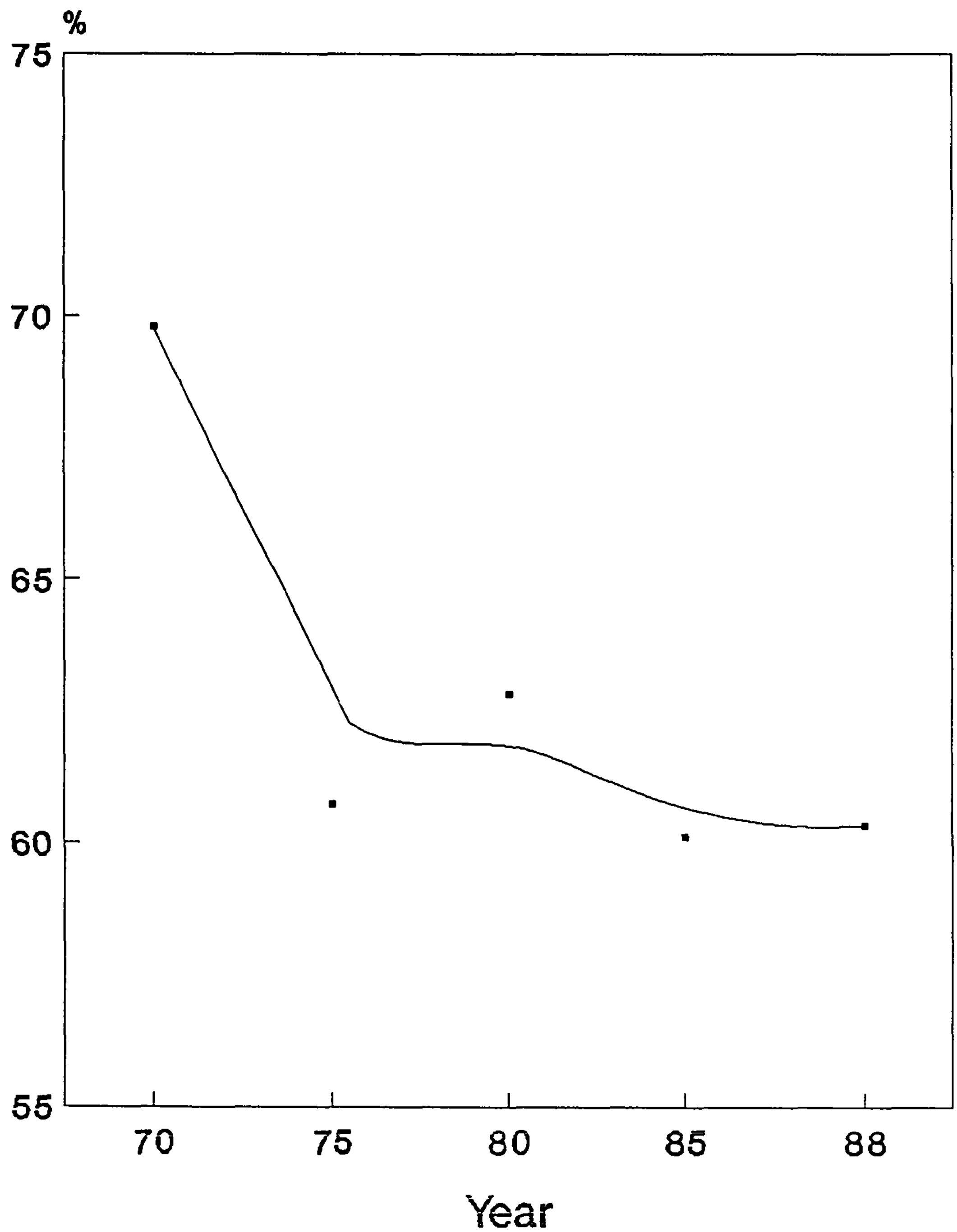
5. Load factor = average demand/peak demand

Figure 6. Load Factor (1970-1988)



Source: Derived from Denkijigyou Rengoukai, various issues.

(Denkijigyou Shingikai Jukyuu Bukai, 1987). This projection is plausible in that the weight of energy-intensive industries characterized by high load factor is expected to decline while residential and commercial sectors with low load factors will be increasing their proportions in the total electricity demand.

Moreover, the growth of electricity consumption slowed down after the first oil crisis due to: (1) sluggish production in electricity-intensive industries such as steel and chemical, (2) permeation of conservation efforts and development of energy-efficient electrical equipment, and (3) higher electricity rates. However, electricity consumption did not slow down as much as other types of energy did, which was attributed to the following factors:

1. Conservation efforts centered on reduction of energy consumption for heating and steam uses in the industrial sector (Institute of Energy Economics, 1986).

2. As people's income increased and the economy became more service-oriented, attributes of electricity such as controllability, safety and cleanness came to be crucial in the choice of specific energy among various end-use energies.

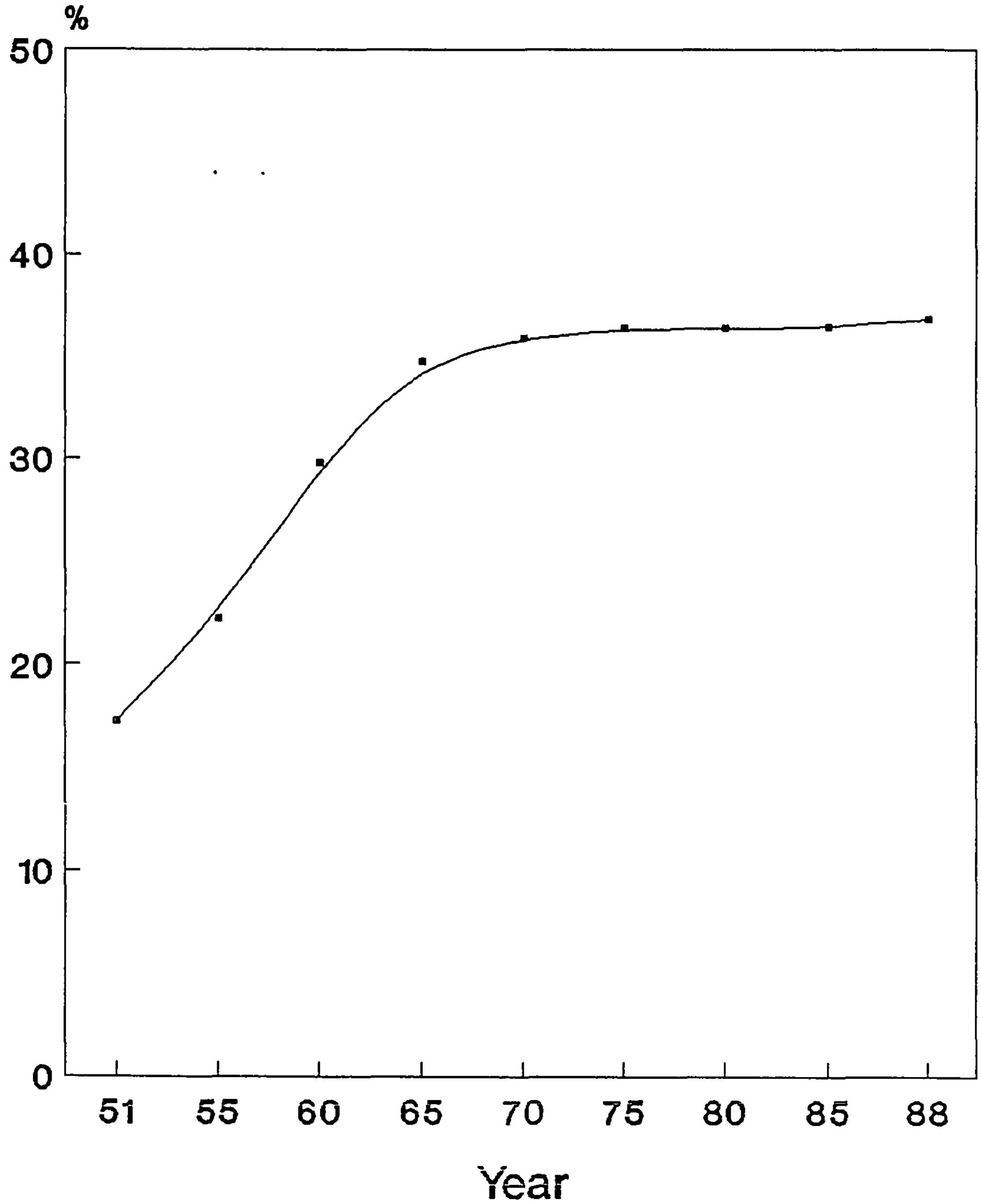
But the growth rate of electricity consumption, as well as overall energy demand, has increased markedly during 1987-1988 due to a steady growth in demand from large industrial customers, including the material and commercial sectors, and increased use of large household appliances. To meet this uptrend, electric utilities are now rescheduling their power development programs and reopening their idle thermal power plants. In particular, the case of Tokyo Electric Power Company (TEPCO) is noticeable, which reflects a recent unusual concentration of economic activities in Tokyo areas. In the summer of 1990, TEPCO faced a serious shortage of its electricity supply capability due to a heat wave coupled with increased demand in all sectors. Therefore, TEPCO had to ask the public as well as large customers to conserve electricity to avoid possible blackout along with purchasing emergency power from other electric utilities.

Another major concern for the electric utilities is the erosion in historical rates of productivity improvement on the supply side. A study by the Central Research Institute of the Electric Power Industry in Japan (Uchida, Ito and Sekiguchi, 1984) clearly indicates that total factor productivity of electric utilities slowed down for the period of 1973-1980. Although it is difficult to pinpoint the sources of productivity growth, economies of scale and technological progress are generally associated with productivity improvement as the history of the electric power industry reveals (Joskow, 1987). In this respect, the thermal power generation segment in Japan's electricity supply system may have already entered the stage of diseconomies of scale. Thermal efficiency, as a major efficiency indicator for thermal generation, did not exhibit any improvements after early 1970's, either (figure 7).

Recent stagnation in thermal efficiency improvements coupled with increases in electricity consumption imply another serious problem, viz. degeneration of our ecosystem. As is well-known, electric utilities are major emitters of CO_2 because they are a principal consumer of fossil fuels. It is estimated that Japanese electric utilities are responsible for at least 20% of CO_2 emitted in Japan and account for approximately 1% of the total quantity of CO_2 in the world. Therefore, increases in electricity consumption would lead to a larger quantity of CO_2 emitted from thermal power plants, given the current level of thermal efficiency and non-availability of technologies to scrub CO_2. Accordingly, enhanced efficiency of thermal power plants burning fossil fuels is a key to preserving the environment as well as the depletable natural resources.

The above discussion has highlighted the vulnerability of the Japanese electric utilities to external shocks and the inherently uncertain electricity demand and other challenges facing the electric utility industry in Japan. These problems have manifested themselves in the generating

Figure 7. Thermal Efficiency (1951 - 1988)



Source: Derived from DenkIjigyou Rengoukai, various issues.

sector, especially in the case of thermal power generation. Therefore, it is important to analyze the thermal power generation sector and understand the nature and scope of problems in this sector.

5. Objectives

The basic objective of this study is to determine the technological characteristics which were responsible for productivity changes in thermal power generation in Japan over the period of 1964 - 1988.

Specific objectives are:

1. To estimate the magnitude of economies of scale,[6] the rate of technological change,[7] capacity factor effect[8]

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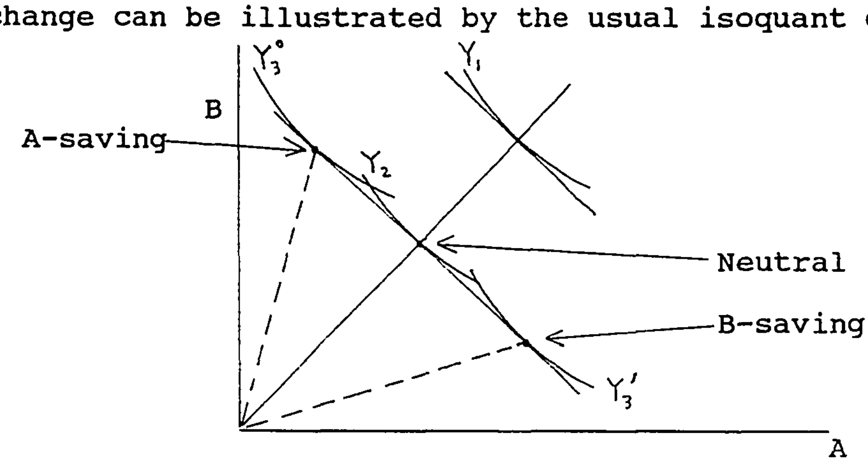
6. Economies of scale are said to exist when an increase in output at constant input prices leads to a less than proportionate increase in total cost.
7. Technological change can be generally classified into neutral and non-neutral or biased technological change. The difference between neutral and non-neutral technological change can be illustrated by the usual isoquant diagram.



and factor substitution between inputs[9] for thermal power generation.

2. To estimate movements in total factor productivity[10] and clarify contributions of economies of scale, technological change and capacity factors.

Suppose that each isoquant represents the same level of output. Neutral technological change is then shown as a parallel shift of the isoquant toward the origin, e.g., from Y_1 to Y_2 - neutrality means a homothetic inward shift of the isoquant. Meanwhile, technological bias is shown as a change in the position of isoquant such as Y_1 to Y_3. To measure the bias, change in the relative share of the inputs is generally used. There are several definitions of technological change. The Hicksian definition measures the bias at a constant input ratio. Harrod's definition measures the bias at a constant capital-output ratio. Solow's definition measures the bias at a constant labor-output ratio. In this study, the Hicksian definition is used to categorize technological change. Technological change can be also classified into embodied and disembodied technological change. "Embodied" means that new inputs are more efficient than old inputs because of technological innovation (Nadiri, 1970). For instance, technological change embodied in thermal power plants such as higher thermal efficiency brings about less fuel consumption given output. Therefore, embodied technological change is the notion that explicitly aims at capturing technological innovation in some input.

8. Capacity factor in this study is defined as follows.
Capacity factor = (actual generation)/(installed capacity x 8760 hours)

9. Factor substitution means replacement of some inputs with other inputs in production process as a result of change in relative input prices.

10. Total factor productivity measures the rate at which inputs are transformed into outputs. The change in total factor productivity from one period to the next is roughly equivalent to the change in cost per output holding input price constant.

3. To derive policy implications for the electric power industry regarding the role of thermal power in future electricity generation.

6. Justification

The share of thermal power in the electrical energy generation mix has been decreasing since the oil shocks. Yet it still accounted for two-thirds of the total generating capacity in 1988. The long-term electric power development program of electric utilities also indicates that the thermal power segment would continue to occupy half of the total generating capacity at least until the year 2010 (table 10).

Nuclear power may be able to replace some portion of thermal power. Yet nuclear power, as is well-known, has been facing enormous uncertainties despite the fact that policy makers have been actively promoting it with an emphasis on the necessity of nuclear power from the standpoint of energy security and also environmental concerns relating to CO_2 emission from fossil-fueled power plants. However, there are far too many problems for nuclear power to play as dominant a role as coal and oil played in the history of the energy economy. Problems involving back-end and decommissioning are formidable economically and technologically. In addition, it would be

Table 10

Projection of Electricity Generation Mix

(10MW)

	1988 (actual)	2000	2010
Nuclear	2870(17.4)[b]	5000(22)	7200(27)
Thermal	9981(60.5)	13110(58)	13320(50)
Coal	1112 (6.7)	2960(13)	4000(15)
LNG	3306(20.1)	5030(22)	5300(20)
Oil & LPG	5563(33.7)	5120(22)	4020(15)
Hydro	3613(21.9)	4450(19)	5170(19)
Geothermal	18 (0.1)	100(0.4)	350(1)
Others[a]	-	110(0.5)	670(2.4)
Total	16482 (100)	22770(100)	26700(100)

Source: Denkijigyou Shingikai Jukyuu Bukai, 1990.
a. Others include fuel cell, solar thermal, wind and methanol.

b. Figures in parenthesis show percentage share.

more difficult to get future public acceptance as a result of incidents at the Three Mile Island and Chernobyl. Recent movements in Sweden and Italy, where nuclear power is supposed to be phased out, have also been promoting such an atmosphere. Hence, the choice of nuclear power cannot be without doubt determined solely by economics, but must be determined within a much broader context.

Hydro power as well as other renewable energies cannot be substituted for fossil-fueled thermal power. The promising hydro sites have already been exploited in Japan. The remaining sites are limited and do not offer potential as major sources of energy. Other renewable energy sources are still not economically viable despite the fact that the government of Japan has been spending large amounts of money on developing alternative technologies in the Sunshine Project and energy conservation technologies in the Moonlight Project. Accordingly, thermal power must continue to play a key role in meeting electricity demand until another important energy source emerges.

The electric power generation sector as well as the transmission and distribution sectors are heavily regulated by MITI, while vertically integrated electric utilities are protected from potential competitors who may want to enter the market for power.

Economic rationality of regulation is to gain from the efficiency of natural monopoly, while protecting consumers from monopoly power. Traditionally, the necessary and sufficient condition for a natural monopoly was an existence of economies of scale. As Kahn (1988) argued:
"The critical and - if properly defined - all embracing characteristic of natural monopoly is an inherent tendency to decreasing unit cost over the entire extent of market."

Recent development of the contestable market theory, however, replaced the existence of increasing returns to scale with the more general idea of subadditivity as a condition of natural monopoly (Baumol, Panzar and Willig, 1988; Sharkey, 1982). An industry is said to be a natural monopoly if, over the entire relevant range of outputs, the firm's cost function is subadditive, viz. at given output level y for a single-product case, an industry is a natural monopoly if:

$$C(y) < \sum_{j=1}^{m} C(y_j)$$

for any $m \geq 2$ and positive $y_1, \ldots, y_m$ such that

$$\sum_{j=1}^{m} y_j = y$$

Therefore, even a single firm in the stage of decreasing returns to scale can be a natural monopoly provided that it can produce at a lower cost than two or more firms can. Yet the subadditivity criterion of natural monopoly has not led to a reexamination of the traditional core, public utilities, of natural monopoly theory (Vogelsang, 1988). This is because public utilities involve substantial sunk costs. Theoretically, it may be possible for the electricity market to be a contestable market if we can create a market in which entry and exit are free. However, such a market is very implausible in the light of the electric power industry having a large sunk cost. Mere application of the contestable market would perhaps bring about an unreliable and unstable supply to the public.

In the electric power industry, economies of scale could arise from all segments, namely the generation, transmission and distribution segments as well as the vertically-integrated system itself. Therefore, diseconomies of scale in one segment do not necessarily imply diseconomies of scale in the overall supply system. In other words, constant returns to scale or decreasing returns in one sector does not imply that vertical disintegration is a more economical alternative than vertical integration if economies of scale derived from the vertically-integrated system outweigh the diseconomies of scale in one sector and/or other sectors. Therefore, the mere evidence of diseconomies of scale in the generation segment does not warrant competition in this sector (Joskow, 1983; Zardkoohi, 1986).

Nonetheless, to the extent that the era of stable electricity supply has ended, as exemplified by repeated revisions of electricity prices after the oil shocks, it is meaningful to analyze productivity changes of the electric utility and clarify causes of its movements. From this viewpoint, economies of scale are an extremely important factor to be examined. This is particularly true of the generation segment which accounts for about 50% of total operating cost and approximately 40% of total fixed asset for electricity supply.

Significance of technological effects on productivity growth or the cost structure requires little explanation. Recent stagnation in technological progress represented by the slowdown in thermal efficiency improvement is an oft-cited cause of poor performance in the electric power sector (Hirsh, 1989).

Changes in the capacity factor may also be an important determinant of productivity growth, which all of the earlier studies in Japan have neglected. Capacity factor of the thermal power sector has been declining in Japan over the years mainly because of the changed role of thermal power generation in the generation mix and the deterioration of the load factor: In light of this, it is important to examine the effects of capacity factor on total generation costs.

Quantifying attributes characterizing the production structure of thermal power, viz. scale economies, technological change and capacity factor, could therefore help clarify sources of productivity changes: Such clarification could help develop new policies to improve efficiency in not only the thermal power sector but also in overall electric supply.

CHAPTER II

REVIEW OF LITERATURE

There exist a number of studies on production technologies for thermal power generation in the U.S. This is due to the fact that thermal power has been the most important power source in the generation sector of the U.S. electric utility industry. These studies have focused largely on economies of scale and technological change because these attributes of production technology are related to much broader issues, such as validity of the institutional structure of the electric power industry.

Equally important is the availability of extensive data relevant for empirical studies for the electric power industry. Appropriate data derived from accounting and reporting practices of the electric utilities have facilitated applied econometricians to estimate the production technologies of this industry. Even in Japan where the degree of information disclosure is not as high as in the U.S., data on the electric power industry are relatively voluminous. However, the number of economic studies using these data are not as numerous as in the U.S. The U.S. studies have also contributed to methodological innovations in the field of applied econometrics. The application of the dual cost function to estimate the production function by Nerlove's pioneering work (1963) is a representative example.

Cowing and Smith (1978) provided an excellent evaluation of 13 studies on thermal power technologies in the U.S. conducted in the 1960's and 1970's. The authors categorized these studies into: (1) production and input requirement function studies, (2) input demand models, (3) cost equation studies and cost function models and (4) profit function studies. They generalized from the research results as follows:

1. There are significant scale economies in steam generation at small and intermediate generating units. However, these studies could not succeed in assessing factor bias in scale effects.

2. Evidence supports substitutability among inputs in the ex-ante technology. Since ex-post substitution is very small, it is best characterized by Leontief or fixed proportion in measuring factor substitution in the ex-post technology.

3. Technical change in the electric power industry is labor- and fuel-saving. The vintage model seems to be a best specification for technical change.

Among studies Cowing and Smith evaluated, Christensen and Greene's work (1976) was drawn upon by many later researchers. It would be, therefore, worthwhile to discuss their study in some detail here.

The Christensen and Greene study was inspired by Weiss (1975) in which he suggested that introduction of competition into the traditional generation market would result in a more efficient electricity supply system. The question was whether benefits stemming from the more competitive generation market could outweigh costs by sacrificing scale economies. Therefore, they examined economies of scale at the firm level in order to assess reorganization of the industry structure.

Methodologically, they made use of duality theory and the translog function, which is a more flexible functional form developed by Christensen, Jorgenson and Lau (1971, 1973), than the Cobb-Douglas function used by Nerlove's study using the same 1955 data. Their study was the first application of the translog cost function to estimate thermal power technology. The estimation model consisted of the translog cost function and two cost share equations. Explanatory variables included in the model were prices of labor, capital, fuel and output generated. The sample consisted of cross-sectional data for 114 electric utilities for 1955 and 1970. Their findings are: First, the technology is nonhomothetic. Second, the cost of producing electric power fell during 1955-1970, which was not due to scale economies but technological change because the 1970 average cost curve was simply a downward vertical shift of the 1955 curve. Third, the 1955 sample showed that scale economies were lower at low levels of output but persisted over a wide range of output implying constant returns to scale. Meanwhile, the 1970 data indicated that scale economies were lower than in 1955. Furthermore, their estimates suggested that the 15% of firms with annual production in excess of 20 billion kwh had capacity beyond the 19.8 billion kwh necessary for realizing economies of scale. Since the seventeen firms in this category accounted for over half of the 1970 production of 1,534 billion kwh, they concluded that the industry could be restructured with no significant increases in average costs.

There have been more recent studies on production technologies in the U.S. electric power industry since Cowing and Smith published their review; Stevenson (1980) set forth a model which he considered to be useful both in categorizing technical change and in testing for induced technological bias. His estimation model was unrestricted and restricted truncated third-order translog cost functions. This model made it possible to test for price-induced technological input bias and the Schumpeter-Galbraithian hypothesis that large firms have a more rapid rate of technological advancement than small firms. It should be noted that he incorporated capacity utilization in his estimation model which most earlier studies had neglected. In light of deterioration of the load factor that many electric utilities in industrialized countries are facing, incorporation of this variable is a distinct improvement over the previous models. Data used in the estimation model were firm level data of eighty-one privately-owned utilities in the U.S. for the two years 1964 and 1972. His conclusions based upon his findings were:

1. The results do not confirm the Schumpeter-Galbraithian hypothesis.

2. The rate of technological advancement has declined substantially over time.

3. Economies of scale and capacity utilization reflecting demand structure are important determinants for productivity measurements.

A 1981 study by Gollop and Roberts is one of the most comprehensive and rigorous works in terms of model specification and data construction. They examined productivity improvement and its source in vertically integrated electric power companies in the U.S. Specifically, the primary objectives of their study were to decompose productivity growth into seven source components including scale economies and the rate of technological change and to allocate the rate of technological change among components associated with individual inputs. The estimation models were the translog cost function, cost share equations and the Törnqvist index to estimate a general model and a factor-augmentation model of production and technical change. The sample was annual data for eleven utilities for 1958-1978 which relied mainly on coal-fired plants. Data regarding prices were constructed following the Törnqvist price index. In this respect, their selection of electric utility was legitimate because they chose the eleven electric utilities under similar technological, market and regulatory conditions. Their major findings regarding scale economies, technological change and total factor productivity are as follows:

1. All estimates of scale economies were less than one which implied that the technology was in the stage of increasing returns to scale. Yet, scale economies declined sharply between 1972-73 and 1974-75.

2. Technological change was labor-saving, fuel-saving and capital-neutral.

3. The combined net effect of relative price changes lowered the rate of technical change and scale economies in the period of the first oil crisis.

4. The overall productivity growth has slowed down significantly over the 1958-1975 period, for which technical change was mainly responsible.

Cowing (1982) developed a general methodology to incorporate regulatory effects on behavior of competitive firms. His research clarified an important property of regulated cost function. Namely, the neoclassical cost function subject only to underlying technologies is homogeneous of degree one in input prices, while the regulated cost function cannot be homogeneous of degree one in input prices. Incorporation of the regulatory effect in the neoclassical framework dates back to the well-known Averch-Jhonson theorem (Averch and Johnson, 1962). Yet the value of his study was that he successfully incorporated rate-of-return regulation in flexible translog cost functions with the property of nonhomogeneity in input prices. Drawing upon this methodology, he estimated the production technology of thermal power plants using 96 steam-electric generating plants constructed between 1947 and 1965. Estimation models consisted of the restricted translog cost function and three cost share equations and the competitive model including the unrestricted translog cost function and two cost share equations. His conclusion is that the competitive model generally yields biased estimates in terms of substitution elasticity.

Gollop and Roberts (1983, 1985), in addition to the above-mentioned study, analyzed and quantified the effect of sulfur dioxide emission regulations on productivity growth in thermal power generation. The uniqueness of their model is credited to incorporating the following regulatory intensity variable "R".

$$R = \left(\frac{E_t^* - S_t}{E_t^*}\right)\left(\sum_{i=t-1}^{t} 1/2 \frac{E_i^* - E_i}{E_i^* - S_i}\right)$$

where S_t = legal standard, E_t = the actual emission rate, and E_t^* = desired or unconstrained emission rate. These variables are defined as pounds of SO_2 per million BTU in period t. In this equation, the first term captures the extent of legal constraints while the second term measures the degree to which a firm's actual emission reduction corresponds to the required emission reduction. The estimation model was the translog cost function incorporating R and low sulfur and high sulfur fuel prices in addition to basic inputs prices, time variable and four cost share equations. The sample was taken from fossil-fueled generation costs of 56 privately-owned electric power companies over the period 1973-79. Their prime findings were: (1) Sulfur emission control regulation resulted in significantly higher generating costs and (2) the average rate of productivity growth was reduced by 0.59% per year for electric utilities restricted by emission control standards. Extending this study, they calculated marginal abatement costs of the same firms and found that marginal costs varied among regions due to differences in the fuel prices and regulatory tightness. They therefore concluded that it was possible to save the resource cost equivalent to 47% of the actual cost through emission trading.

Nelson and Wohar (1983) estimated technical change, economies of scale and regulatory biases associated with total factor productivity growth in thermal power generation of fifty investor-owned utilities over the period 1950-78. Their estimation model was the translog cost function incorporating a variable representing rate-of-return regulation in addition to variables of prices of capital, labor and fuel and the time variable. Their major findings are: First, scale economies accounted for about 13% of increase in productivity over the period 1950-78. Second, reduction of demand growth rate would reduce both the contribution of scale economies to productivity growth and productivity itself. Third, regulatory biases may have existed in the 1970's. Among these three findings, the second finding has a very important implication in terms of current policy formulation in the U.S. Reduction of electricity demand through demand side management in so-called Least Cost Planning, as discussed in many recent studies (Cicchetti and Hogan, 1989; Joskow, 1990) and the U.S. government reports such as Interim Report on the

National Energy Strategy (U.S. Department of Energy, 1990), may be an alternative source for new generating facilities. Yet, reduction of demand would reduce total factor productivity growth as Nelson and Wohar concluded. Therefore, we must take into consideration the tradeoff between conservation and productivity in developing integrated resource planning.

Joskow and Rose (1985) analyzed the technological, regulatory and organizational factors which influenced the costs of building coal-burning steam-electric generating unit over the past twenty years. Their study concentrated on the capital costs of coal-fired generating unit to estimate economies of scale in construction costs, learning effects associated with utilities and architect-engineers, and the cost of environmental regulations. The results suggested significant economies of scale associated with the costs of building coal units. They also put forward a hypothesis that the most advanced thermal technology, supercritical technology, is not necessarily economical over sub-critical technology because of poor reliability and high maintenance and replacement costs.

Nelson (1984, 1986, 1987) examined the effects of capital vintage on the rate and direction of technological change. Researchers have traditionally used a time variable to estimate the rate of technological change. However, this index assumes that new technology is introduced at a constant rate, which may capture the effects of any variable that moves smoothly over the years. The empirical study by Kopp and Smith (1985) also indicates that the time variable may fail to provide a consistent description of the direction of technological change. Nelson therefore suggested explicit incorporation of a vintage index in addition to a time variable in the model, because use of the vintage index has the advantage that we do not need to assume that new technology is introduced at a constant rate across firms. The vintage index was computed as the average age of plants. This formulation allows us to decompose technological change into vintage-related (embodied) technological change and time-related (disembodied) technological change. The objective of the 1984 study was to assess the effect of regulation on vintage-related technological change and time-related technological change, while studies of 1986 and 1987 aimed at comparing performance of a time variable with that of a vintage index. Specification of the estimation model was same for three studies. Namely, Nelson incorporated a vintage index, a time variable and allowed rate-of-return in addition to basic three input prices in a translog cost function. Data for the 1984 study were taken from a sample of 40 privately owned firms over the period 1951-1978. Meanwhile, data for the 1986 and 1987 studies were taken from a sample of 22 primarily coal-burning privately owned electric utilities over the period 1961-1978. The findings in the 1984 study were that disembodied or time-related technological change was the primary source of cost reduction during 1951-70 and that regulation seems to have had a negligible effect on the rate of technological change in the electric power industry. The 1986 and 1987 studies concluded that the multiple index models, which could disentangle the effects incorporated in the time variable, are to be preferred to single index models. Overall, his suggestion regarding incorporation of the explicit technological index may be legitimate if the objective of the study aims at disentangling the effects represented by the time variable. Yet, the vintage index is also arbitrary index since newer capital does not necessarily embody the same degree of improvements in technologies. Moreover, the vintage index may capture other effects such as capacity utilization which reflects the vintage of the plant.

Baltagi and Griffin (1988) developed a model using a more general index of technology. The primary objective of this study was to show that the model incorporating a general index of technical change has many advantages over the traditional time trend representation of technical change. The sample consisted of firm level data for 30 electric utilities in U.S. for the 1951-78 period. The estimation model was a translog cost function incorporating a time-specific dummy as a general index of technical change. Their major finding was that the productivity decline of 1970's can be attributed to environmental control and declining capacity utilization due to rapidly increasing peak demand.

As for production technologies for Japanese electric utilities, Izawa (1981) examined economies of scale in thermal power generation technologies. His model exactly followed Christensen and Greene's specification. Therefore, his model did not incorporate any variables representing technological change. Data were taken from firm level of nine electric power companies over the 1978-80 period. It should be noted that the price of capital was derived by using bookvalue of the thermal power facilities and installed capacity, which is not the service price of capital but stock price. His finding suggested that the thermal generation sector of Japanese electric utilities was still in the stage of decreasing average cost.

Uchida, Ito and Sekiguchi (1984) investigated the movement of total factor productivity in nine electric power companies over the period 1964-1980. They estimated total factor productivity based upon the theorem developed by Caves, Christensen and Diewert (1982), which does not require computation of the translog parameters in the case of constant returns to scale and decreasing returns to scale. They ran a multiple regression to determine the factors which brought about changes in total factor productivity. The explanatory variables were load factor, load density, total loss factor, thermal efficiency, average unit size, and dummy variables representing the share of thermal power plants in generation mix and electric power companies. They found that total factor productivity growth slowed down after the first oil crisis and recorded negative growth after the second oil crisis. Multiple regression results indicated that thermal efficiency was a dominant source of improvement in total factor productivity. All of load factor, load density, average unit size and dummy variables had positive correlations with total factor productivity growth, while the share of thermal power generation and total loss factor was negatively correlated with total factor productivity growth.

Awata, Ito and Nakanishi (1987) estimated scale economies in the thermal power sector. The estimation model for the thermal power sector was a translog cost function, in which two input prices and output were included as explanatory variables. They normalized input prices and the dependent variable by the price of capital. Data were taken at the firm level for nine electric power companies over the period 1969-1984. It should be noted that These data were the average of nine electric utilities, so that the number of observation was only 16. Their study results show that the thermal generation sector was in the stage of decreasing returns to scale over the sample period. Their model, however, did not include a variable representing technological change despite the fact that data covers long period. Hence, the result may not be reliable because dropping the technological variable would bias parameters. In addition to the above study, they also computed scale economies of coal-fired power units. The estimation model was a multiple log-linear regression. In this model, the regressand was construction costs of 40 coal-fired units in operation and regressors were the installed capacity, the year of commission, dummy variable representing whether the unit is the first unit or not in the plant, GNP deflator, dummy variable representing environmental protection measure and the variable representing learning-by-doing. The estimated parameter related to scale economies show that economies of scale exist at the unit level but units with above 400MW and commissioned after 1975 are in the range of increasing costs.

Nakanishi and Ito (1988) estimated economies of scale in the generation sector and the vertically integrated system. This study was unique in the sense that they tried to estimate economies of scale derived from the vertically integrated system and the whole generation sector. Yet they excluded the fuel used in nuclear power facilities in the generation sector which is a serious flaw of their study and therefore undoubtedly biased the regression results. Moreover, they did not address the aggregation problem despite the fact that the generation technologies in Japanese electric utilities are not homogeneous. The sample was taken from the aggregate firm level and the generation sector of nine electric power companies during the 1960-1980 period. The estimation model was of the Christensen and Greene type with the time variable. The conclusion of this study was that there still existed economies of scale in the vertically-integrated system, but economies of scale in the generation sector had been already exploited after the first oil crisis.

Shinjou and Kitasaka (1989) estimated scale economies in thermal power generation, nuclear power generation and the integrated power system of nine electric power companies. The estimation model drew upon Christensen and Green's model without any variables other than basic input prices and output. Their study may be the first for estimating nuclear power technologies. It seems that the model is theoretically consistent. Yet there is a problem concerned with data construction viz. data regarding costs incurred by nuclear power generation did not include back-end and decommissioning costs which are still in controversy, in analyzing economics of nuclear power generation. Data were taken from nine electric power companies over the period 1978-1985. The authors concluded that scale economies for the thermal power generation sector of three companies (Tokyo, Kansai and Chubu electric power companies) were already in the stage of decreasing returns to scale, while those for the remaining six companies were still in the range of decreasing average cost. In the case of nuclear power generation, they found that the threshold of decreasing returns to scale was 28 billion kwh. Meanwhile, their findings show that the larger firm had been enjoying economies of scale at the aggregate firm level while relatively small companies were in the stage of decreasing returns to scale.

Mori (1989) examined economies of scale at the plant level of coal-fired and nuclear power plants using data of 20 coal-fired plants and 29 nuclear plants over the period 1977-1986 and 1974-1986, respectively. The estimation model was a multiple log linear regression, in which the dependent variable was construction costs of plants and explanatory variables were installed capacity and the year of completion. The results indicated increasing returns to scale both at thermal power plants and nuclear power plants.

As is clear from the above, the approach, scope and data sample are diverse. The studies for the U.S. electric power industry have focused mainly on scale economies, technological change and regulatory effects with different weight. Some studied the vertically-integrated system while some others analyzed specific technologies in the generation sector, in particular thermal power generation. The choice of sample data reflects the differences in these approaches.

With respect to the nature of production technology, recent studies in Japan as well as in the U.S assumed cost minimization drawing on the duality theory. Also, most of their functional forms in order to mimic the actual technology were of the translog cost function type. Differences in specifying the models for the U.S. studies revolved around incorporation of noncompetitive factor, such as cost-of-service regulation and environmental regulation, and other important variables represented by technological changes into the competitive model. Meanwhile, Japanese models on thermal power generation incorporate only three input prices and output.

Recent study results on the U.S. electric power industry reveal that the major causes of slowdown in total factor productivity growth were declining scale economies, stagnant technological improvement and decreased output and that regulatory effects could not be ignored. Meanwhile, results of the studies regarding thermal power generation in Japan, which aimed mainly at estimating scale economies, are not consistent in terms of the study results. Izawa's study indicated existence of increasing returns to scale while the Awata-Ito-Nakanishi study showed that electric utilities have already exploited economies of scale. The Shinjou-Kitasaka study also showed that the larger firms were in the stage of increasing average cost although returns to scale for smaller firms were found to be increasing.

In summary, the studies reviewed here have contributed greatly to clarifying the nature of the production technology which are viable information for supporting actual policy formulation and to develop the advanced methodology in the field of applied econometrics in U.S. But, as suggested by Cowing and Smith, further development based on the actual physical and behavioral constraints is needed. This is particularly so in light of more competitive markets for power in recent U.S. electric power industry.

Similarly, the Japanese studies call for improvements in the estimation model. A critical point is what other factors, in addition to basic economic variables, should be taken into account to model Japanese thermal power technology more accurately. Incorporation of non-competitive factors commonly seen in the most recent U.S.

studies may improve the model if those factors are actually affecting behavior of the electric utility and construction of accurate data representing them are feasible. If not, however, such variables in the model may lead to biasing other parameters.

The Japanese studies regarding thermal power generation incorporated only three inputs and output as explanatory variables. No study on thermal power generation in Japan has taken into consideration other factors such as technological progress and the change in the role of thermal power generation in the overall generation mix over the years. Furthermore, the studies conducted in Japan so far have tended to aim at merely quantifying parameters. Quantification itself may be of value for its own sake, but the value of these studies may be limited for policy makers.

CHAPTER III

METHODOLOGY

1. Basic Model

In order to achieve the objectives of this study, we at first assume that a regular production function exists, $Y = f(\mathbf{X})$, where Y is output and **X** is the vector of inputs, $\mathbf{X} = (X_1 \ldots X_n)$.

A production function is regular at a positive X_i if it satisfies the following conditions.

$$f(X_i) > 0, \quad i = 1 \ldots n \tag{3.1}$$

$$f_i(X_i) = \frac{f(X_i)}{X_i} > 0 \tag{3.2}$$

$$(-1)^i |H_i| = \begin{vmatrix} 0 & f_1 & \cdot & f_i \\ f_1 & f_{11} & \cdot & f_{1i} \\ \cdot & \cdot & \cdot & \cdot \\ f_i & f_{1i} & \cdot & f_{ii} \end{vmatrix} > 0 \tag{3.3}$$

Namely, $f(X_i)$ is positive, finite, continuously twice differentiable, strictly monotone and quasiconcave at X_i.

Corresponding to a regular production function, a minimum cost function, $c(Y,\mathbf{P})$, satisfies the following conditions by the duality theorem.

> $c(Y,\mathbf{P})$, where **P** is the vector of input prices, is finite, positive, continuously twice differentiable, and strictly monotone in $(Y,\mathbf{P})$, and linear homogeneous and concave in **P**.

As is well-known, the duality theorem, which was originally proved by Shephard (1970), established a one-to-one relationship between input-conventional production possibility sets and input-conventional cost structures (Uzawa, 1964; Diewert, 1971; McFadden, 1978). More concretely, the duality theorem tells us that a relationship, under some regularity conditions, between input quantities based upon profit maximization can be represented by a relationship between input prices based upon cost minimization or vice versa. This theoretical result allows us to estimate the characteristics of some production technologies by applying a dual cost function which contains all the information in production possibility sets.

Moreover, the use of the cost function has several advantages over the use of the production function on both theoretical and statistical grounds. This is indicated by the fact that a number of recent empirical studies, as reviewed in chapter 2, modeled production technologies in the electric power industry by the dual cost function rather than the production function. The advantages of the cost function include (Binswanger, 1974a):

1. A cost function is homogeneous of degree one in input prices regardless of homogeneous properties of the production function.

2. Although an electric power company in Japan is a regional monopoly, markets for input factors, i.e. capital, labor and fuel, are competitive since the electric utility must compete with other industries to procure such factors. Therefore, input prices can be treated as exogenous variables. Meanwhile, input factors in the production function are endogenous because firms determine the use of input factors based upon input prices.

3. A cost function can easily incorporate variables representing returns to scale and technical change.

4. High multicollinearity among explanatory variables often arises in the production function approach while multicollinearity between factor prices in the dual cost function is generally limited.

5. Partial elasticity of substitution between inputs can be derived directly from the parameters in estimated cost functions.

The appropriateness of a cost function is further enhanced if we consider the importance of technological and institutional characteristics of the electric power industry for model building, viz.

1. Present technologies do not permit us to store electricity for use. Therefore, electric utilities must meet electricity demand instantaneously, which implies

that the level of output is considered to be primarily exogenous.

2. The hypothesis that the electric utility maximizes profit is implausible because utilities are regulated in terms of revenue through electricity rates.

Accordingly, a cost function is a more attractive model for the study of the electric power industry rather than a production function.

We therefore assumed the following factor minimal cost function as the basic model in order to characterize the thermal power generation technology in Japan.[11]

$$C = c(Y, P_K, P_L, P_F, U, T) \qquad (3.4)$$

Where

C = annual total cost for thermal electric generation

c = cost function

11. We initially set forth the four factor model; that is prices of capital, labor, oil and composite of LNG and coal, which aimed at capturing the effect brought about by a change in generation mix over the years. Yet we could not obtain significant results. Specifically, this model violated basic regularity conditions. The reason for insignificant result may be that electric utilities diversified the sources of electricity generation because of energy security rather than substitution between fuels as a result of a change in relative prices between fuel input prices. Moreover, the four factor model must assume that present technologies permit us to use two fuels interchangeably, which is not a legitimate assumption.

Y = annual output generated by thermal power plants

P_K= service price of capital

P_F= price of fuel per calorie

P_L= wage of employees working in the thermal sector

U = average capacity factor of thermal power plants

T = time variable

In this study, a maintained hypothesis is that the electric power industry minimizes the cost of generation subject to the production function. Most of the recent studies on the U.S. electric power industry have assumed that an electric power company minimizes cost subject to both production function and regulation on rate of return. This specification of the model is derived from a supposition that the firm under regulatory constraint such as rate of return results in inefficient resource allocation, which is the well-known Averch-Johnson (A-J) theorem (Averch and Johnson, 1962). The A-J theorem implies that electric power companies tend to have excess capacity under cost-of-service regulation when the regulation is binding because the firm can increase the allowed profits by using more capital.

In Japan, electric power companies have been operating under pervasive regulations as in the U.S. such as regulations on rate of return through electricity rates. One important difference between Japan and the U.S. is that regulations governing the electric power industry in the U.S. seem to be literally aiming at protecting public interest from monopoly power as stated in the Federal Power Act of 1920 and the Public Utility Holding Company Act of 1935 at the federal level. The prudence review by state public utility commissions, which did not allow many electric utilities to recover costs involving construction of nuclear power plants in 1970's and 80's, is a typical example of a regulatory action aiming at protecting public interests. Ironically, however, due to this review, investor-owned electric utilities are now reluctant to construct large-scale base-load facilities in order to avoid financial risk, which is bringing about a serious problem viz. possible shortage of electricity generating capacity in some parts of the U.S. (U.S. Department of Energy, 1990).

Stigler (1962) stated that "the innumerable regulatory actions are conclusive proof, not of effective regulation, but of the desire to regulate. Whether the statutes really have an appreciable effect on actual behavior can only be determined by examining the behavior of people not subject to the statutes." His statement might be valid in the 1960's. Yet, recent regulatory actions represented by the prudence review are in fact having considerable impacts on decision making in the U.S. electric power industry, in particular on investor-owned electric utilities. Moreover, what recent state regulators are reviewing is the ratebase rather than the level of rate of return.

Joskow also questions the effectiveness of rate of return regulation by pointing to empirical evidence that regulatory reviews on allowed rate of return were implemented in the U.S. only when an electric power company applied for a rate increase (Joskow, 1974). He argues that the regulatory agencies did not care about the rate of return unless prices were increased.

Meanwhile, regulators in Japan seem to lean toward protecting the electric power industry as a basic industry within the context of industrial policy, not as a mere utility, although there are statements related to protection of public interest in the Electric Power Industry Law of 1964 (Shigen Enerugii Chou, 1988). The contents of regulatory measures are almost the same as those in the U.S. since the Japanese public utility regulatory system emulated the U.S. system. Therefore, rate of return regulation is a central tool to govern the electric utility. Yet Joskow's argument exactly characterizes rate of return regulation in Japan. When the cost of service was probably constant or decreasing until the first oil crisis due to economies of scale, technical innovations and low fossil fuel prices, electric power companies never applied for rate revision or reduction, while the regulator never reviewed it. Only recently did electric power companies decrease electricity rates due to the appreciation of the Japanese Yen, plummeted oil prices and pressure from energy-intensive industries. Discussion on rate revision generally centered only on prices. It rarely touched on the validity of the level of rate of return. This is evidenced by the fact that the allowed rate of return had been maintained at 8% since 1960 when rate of return regulation was adopted. It was for the first time reduced to 7.2% in 1987. Consequently, exclusion of the Averch-Johnson effect in the model does not give an negative effect.

Another issue, pointed out by Joskow and Schmalensee (1983) and Zardkoohi (1986), is whether power interchange between electric utilities affects parameters estimated. As correctly pointed out by them, pioneering econometric studies by Christensen and Greene (1976) did not take into consideration pooling, although later they (1978) tried to estimate with incorporating pooling unsuccessfully. In light of the fact that in the U.S. substantial quantities of electricity are moving between electric utilities and regions (U.S. Federal Energy Regulatory Commission, 1988a), exclusion of pooling would bias the estimate. However, quantities of electricity interchanged between electric utilities in Japan are only a small percentage of total output generated. Limited coordination among electric utilities in Japan reflects that:

1. Load pattern is the same throughout Japan except for the Hokkaido area; peak demand is recorded in summer, while off-peak is in winter.

2. There is no time difference between regions in Japan.

3. The composition of electricity generation plants for major electric utilities is almost the same. Thus, power interchange between electric utilities is not a major determinant of generation costs.

In this study, capacity factor (U) and a time trend (T) are incorporated as an explanatory variable in addition to the four basic variables, output (Y) and prices of capital (P_K), fuel (P_F), labor (P_L). Given input prices, high capacity factor reduces generating costs per unit while low capacity factor increases the cost. Capacity factor is generally determined by the role of the plant in the overall electricity generation mix and load factor. If the plant were operated only for meeting peak demand, then its capacity factor is low and production cost is high compared to base-load facilities with high capacity factor. Present thermal power facilities in Japan consist of base-load, intermediate and peaking units. In the past when the price of oil was low, thermal power, in particular oil-fired facilities, was base-load facilities. As nuclear power increased its share in the composition of generating sources, the role of thermal power generation as base-load facilities has been decreasing. Vintage of the plant is also a determinant of the role in the generation mix. Generally, old plants are costly so that they become peaking and/or emergency units. Therefore, capacity factor also reflects vintage of the plant. In addition, the pattern of load affects capacity factor of plants. When the gap between off-peak and peak demand is large, quite a few plants must remain idle during off-peak periods. Thus in order to characterize the production technology for Japanese electric utilities, the model incorporating capacity factor is a more accurate specification of the production technology.

Incorporation of the variable representing technological change requires little explanation in light of this study covering a long period. However, a time variable to represent technological has some shortcomings as Nelson (1984) and Kopp and Smith (1975) pointed out correctly. The index of vintage may be an alternative candidate for a time variable. Yet this index has also a drawback because the use of this index must assume that technological progress is always embodied in newer capital, which is not necessarily correct. In addition, this study does not aim at explicitly capturing effects of embodied technological change in some specific input. Accordingly, we use a time variable to represent both embodied and disembodied technological change. But use of a time variable can be defended only on pragmatic grounds. Therefore, we must be cautious regarding interpretation of estimates (Nelson, 1984, 1986).

As for measurement of productivity, there are as many models as there are factors of production. The earliest approach to productivity measurement was the partial productivity measure. This is simply the average product of labor, capital and fuel in the case of the electric power industry. This approach, however, cannot make it possible to identify factors accounting for productivity changes (Nadiri, 1970).

A more comprehensive approach is total factor productivity. The index of total factor productivity is: (1) the rate of change of an index of outputs divided by an index of inputs, or (2) a rate of shift in a production function (Solow, 1957; Jorgenson and Griliches, 1967). Recent methodologies on measurement of total factor productivity are divided into four groups as Diewert (1981) categorized: (1) econometric estimation of cost and production function, among other things translog functions, (2) Divisia Index, (3) Exact Index Numbers and (4) Non-Parametric Methods. Because of inadmissibility of negative technical change for non-parametric methods and of continuous-time formula of the Divisia approach, econometric estimation or the exact index numbers approach has been usually used in empirical studies.

2. Estimation Model

Historically, various functional forms were developed for achieving the objectives of production studies, such as: distribution, scale, substitution, separability, technical change, technological flexibility, efficiency, homotheticity and aggregation problem (Fuss, McFadden and Mundlak, 1978). Cobb-Douglas (C-D) (Cobb and Douglas, 1928), Constant Elasticity of Substitution (CES) (Arrow, Chenery, Minhas and Solow, 1961), Transcendental Logarithmic Functions (Christensen, Jorgenson and Lau, 1971, 1973) and Generalized Leontief Functions (Diewert, 1971) are among the most well-known. The evolution from the C-D function to the flexible functions such as the translog function reflects a history of searching for general and flexible forms embodying few maintained hypotheses. The underlying objective of the search for the flexible forms is to impose the fewest restrictions on the parameters of the model.

C-D and CES models are highly restrictive. As is well-known, the Cobb-Douglas production function assumes a priori that the elasticity of substitution between inputs is unity.

The CES model also assumes that substitution between inputs is constant and rules out the possibility of complementarity between inputs.

Meanwhile, the translog is a flexible model which places the fewest a priori restrictions on the nature of the underlying technology. The translog function can be interpreted as the second-order Taylor series approximation to some true but unknown production or cost functions. This function does not impose a priori restrictions on returns to scale, homotheticity, or elasticity of substitution between input pairs. Moreover, both C-D and CES belong to a set of the translog technology. Hence, the translog function is well-suited for quantifying some parameters related to the objectives of this study. Moreover, the translog function is easier to use compared to other flexible functional forms as written below.

Regarding flexible functional forms themselves, various forms other than translog forms have also been developed. Generalized Leontief functions (Diewert, 1971), generalized Box-Cox (GBC) forms (Berndt and Khaled, 1979) that contain the translog, generalized Leontief (GL) and generalized square root quadratic (GSR) forms as special cases are a partial list of those forms. It is not clear, however, how we should choose among them since true technology is unknown. There are several papers which have discussed the choice among flexible functional forms. Appelbaum (1979a) found that GL and GSR is the best model for the technology using the U.S. manufacturing data. The study by Berndt and Khaled (1979) rejected GSR but did not reject GL form and was inconclusive concerning the translog function. Caves and Christensen (1980a) found that the translog function is well-behaved over a wider range of observations when true partial elasticities have similar large value while the GL is well-behaved over a wider range of observations when true partial elasticity of substitution have small values or have dissimilar values. Yet, these results of evaluating performance of flexible forms are conclusive neither posteriori or a priori.

The functional form chosen for estimation in this study is the translog cost function, specified as follows.

$$\begin{aligned}\ln C = {} & \alpha_0 + \sum_i \alpha_i \ln P_i + \frac{1}{2} \sum_i \sum_j \alpha_{ij} \ln P_i \ln P_j + \beta_1 \ln Y \\ & + \frac{1}{2} \beta_2 \ln Y^2 + \sum_i \beta_{iY} \ln P_i \ln Y + \tau_1 \ln U + \frac{1}{2} \tau_2 \ln U^2 \\ & + \sum_i \tau_{iU} \ln P_i \ln U + \tau_{YU} \ln Y \ln U + \mu_1 T + \frac{1}{2} \mu_2 T^2 \\ & + \sum_i \mu_{iT} \ln P_i T + \mu_{YT} \ln YT + \mu_{UT} \ln UT \qquad (3.5)\end{aligned}$$

where i, j = capital (K), labor (L) and fuel (F) and ln is a natural log operator.

Applying Shephard's Lemma (Diewert, 1971), we differentiate equation 3.5 with respect to input prices in order to derive cost share equations:

$$\frac{\partial \ln C}{\partial \ln P_i} = \frac{\partial C}{\partial P_i} \frac{P_i}{C} = \frac{P_i X_i}{C} = M_i \qquad (3.6)$$

$$M_i = \alpha_i + \sum_j \alpha_{ij} \ln P_j + \beta_{iY} \ln Y + \tau_{iU} \ln U + \mu_{iT} T \qquad (3.7)$$

where X_i are inputs demanded at a cost minimizing level. M_i is the cost share of input X_i in total cost, so that it must sum to unity.

The above translog cost function is well-behaved only if it satisfies the following three conditions.

1) Homogeneous Degree of One in Input Price

Linear homogeneity is defined as follows:

$$\ln C(Y, rP_i, U, T) = \ln rC(Y, P_i, U, T) = \ln r + \ln C \qquad (3.8)$$

where r is scalar.

Rearranging eqation 3.8, we get:

$$\ln C(Y, rP_i, U, T) - \ln C(Y, P_i, U, T) = \ln r \qquad (3.9)$$

Using equation 3.5, we obtain the following:

$$\ln C(Y,rP_i,U,T) = \alpha_0 + \sum_i \alpha_i \ln rP_i + \frac{1}{2} \sum_i\sum_j \alpha_{ij} \ln rP_i \ln rP_j$$

$$+ \beta_1 \ln Y + \frac{1}{2} \beta_2 \ln Y^2 + \sum_i \beta_{iY} \ln rP_i \ln Y + \tau_1 \ln U + \frac{1}{2} \tau_2 \ln U^2$$

$$+ \sum_i \tau_{iU} \ln rP_i \ln U + \tau_{YU} \ln Y \ln U + \mu_1 T + \frac{1}{2} \mu_2 T^2$$

$$+ \sum_i \mu_{iT} \ln rP_i T + \mu_{YT} \ln YT + \mu_{UT} \ln UT \qquad (3.10)$$

Expanding equation 3.10, we obtain the following:

$$\ln C(Y,rPi,U,T) = \alpha_0 + \sum_i \alpha_i (\ln r + \ln P_i) + \frac{1}{2} \sum_i\sum_j \alpha_{ij} (\ln r +$$

$$\ln P_i)(\ln r + \ln P_j) + \beta_1 \ln Y + \frac{1}{2} \beta_2 \ln Y^2 + \sum_i \beta_{iY} (\ln r + \ln P_i) \ln Y +$$

$$\tau_1 \ln U + \frac{1}{2} \tau_2 \ln U^2 + \sum_i \tau_{iU} (\ln r + \ln Pi)(\ln U) + \tau_{YU} \ln Y \ln U +$$

$$\mu_1 T + \frac{1}{2} \mu_2 T^2 + \sum_i \mu_{iT} (\ln r + \ln P_i) T + \mu_{YT} \ln YT + \mu_{UT} \ln UT \qquad (3.11)$$

Subtracting equation 3.5 from eqation 3.11, we get:

$$\ln C(Y,rP_i,U,T) - \ln C(Y,P_i,U,T)$$

$$= \sum_i \alpha_i \ln r + \frac{1}{2} \sum_i\sum_j \alpha ij (\ln r^2 + \ln r \ln P_i + \ln r \ln P_j) + \sum_i \beta_{iY} \ln r \ln Y +$$

$$\sum_i \tau_{iU} \ln r \ln U + \sum_i \mu_{iT} \ln r T \qquad (3.12)$$

Hence, we must impose following restrictions to maintain homogeneous degree of one in input prices.

$$\sum_i \alpha_i = 1$$

$$\sum_i \alpha_{ij} = \sum_j \alpha_{ij} = \sum_i\sum_j \alpha_{ij} = 0$$

$$\sum_i \beta_{iY} = 0 \qquad (3.13)$$

$$\sum_i \tau_{iU} = 0$$

$$\sum_i \mu_{iT} = 0$$

2) Monotonicity

This condition means that the function must be a nondecreasing function of input prices as shown below.

$$\frac{\partial \ln C}{\partial \ln P_i} = \alpha_i + \sum_j \alpha_{ij} \ln P_j + \beta_{iY} \ln Y + \tau_{iU} \ln U + \mu_{iT} T \geq 0 \qquad (3.14)$$

3) Concavity in Input Prices

This implies that the matrix formed by the following must be negative semidefinite within the range of input prices, which is the second order condition.

$$\frac{\partial^2 C}{\partial P_i \, \partial P_j}, \; i, j = K, L, F \qquad (3.15)$$

An econometric model in this study is formed by the translog cost function equation, 3.5 and cost share equations, 3.7. Based on parameters derived from the econometric model, we can obtain the parameters we are seeking, namely, returns to scale, technological change, capacity factor, elasticity of substitution between input pairs and the translog index of total factor productivity.

Returns to Scale

We at first define homogeneity and homotheticity of the production function. A production function is homogeneous of degree r when all inputs are increased (decreased) by the same proportion, output increases (decreases) by the rth power. Formally, if a production function, $f(\mathbf{X})$, is homogeneous of degree r, then $f(t\mathbf{X})=t^r f(\mathbf{X})$. Specifically, if the function has constant returns to scale, then it is homogeneous degree($r = 1$). Similarly, increasing returns to scale and decreasing returns to scale are the cases of $r > 1$ and $r < 1$, respectively.

A homothetic function is a monotonic transformation of a homogeneous function:

$F[f(\mathbf{X})]$, where $f(X)$ is a homogeneous function and F shows monotonic transformation of $f(\mathbf{X})$.

A homothetic function and a homogeneous function as a subset of a homothetic function have an important property that the slopes of the level curves are the same along every point of a given ray out of the origin.

In order to quantify returns to scale, we differentiate the translog cost function partially with respect to output.

$$\frac{\partial \ln C}{\partial \ln Y} = \frac{\partial C}{\partial Y} \frac{Y}{C} = \epsilon_Y = \beta_1 + \beta_2 \ln Y + \sum_i \beta_{iY} \ln P_i + \tau_{YU} \ln U$$

$$= \epsilon_Y = \beta_1 + \beta_2 \ln Y + \sum_i \beta_{iY} \ln P_i + \tau_{YU} \ln U + \mu_{YT} T \qquad (3.16)$$

where ϵ_Y is the ε

output and can be interpreted as inverse of the scale elasticity as Hanoch (1975) proved. If ϵ_Y is unity, then the cost increases in proportion to changes in output, which implies constant returns to scale. If ϵ_Y is less than unity, then it indicates increasing returns to scale. If it is more than unity, decreasing returns to scale exists. Following Christensen and Greene (1976), scale economies (SCE) can be defined as follows:

$$SCE = 1 - \epsilon_Y \qquad (3.17)$$

If SCE is positive, then economies of scale exist. If it is zero or negative, it implies constant returns to scale or decreasing returns to scale, respectively.

Homotheticity and homogeneity can be tested by imposing the following restrictions statistically. As is well-known, the translog cost function does not a priori constrain the production structure to be homothetic and homogeneous.

homothetic : $\beta_{iY} = \tau_{UY} = \mu_{tY} = 0$ (3.18)

homogeneous: $\beta_2 = 0$ and $\beta_{iY} = \tau_{UY} = \mu_{tY} = 0$ (3.19)

Technological Change

To capture the effect of technological change on total costs of thermal generation, we differentiate partially the translog cost function with respect to the time variable. Then, we obtain the following:

$$\frac{\partial \ln C}{\partial T} = S_t = \mu_1 + \mu_2 T + \sum_i \mu_{iT} \ln P_i + \mu_{YT} \ln Y + \mu_{UT} \ln U \tag{3.20}$$

Namely, the rate of technological change equals the rate of growth of total cost with respect to time, holding output, input prices and capacity factor constant.

The rate of technological change (S_t) can be decomposed into four components: (1) pure technological change ($\mu_1 + \mu_2 T$), (2) non-neutral technological change or biased technological change ($\Sigma\mu_{iT} \ln P_i$) which affects factor proportions among inputs, (3) scale-augmenting technological change, which is related to the famous Schumpeterian hypothesis and (4) technological change which may affect capacity factor (μ_{UT}).

Following Nelson (1986), technological bias (B_i) can be derived by differentiating cost share equations with respect to the variable representing technological change, T.

$$B_i = \frac{\partial M_i}{\partial T} = \mu_{iT} \tag{3.21}$$

If B_i is positive, then it implies that technological change is ith input-using. Similarly, if $B_i < 0$ and $B_i = 0$, it implies that technological change is ith input-saving and ith input-neutral, respectively.

We can test the hypothesis of no technological change by imposing the following restrictions.

$$\mu_i = \mu_2 = \mu_{it} = \mu_{Yt} = \mu_{Ut} = 0 \tag{3.22}$$

<u>**Capacity Factor**</u>

Partial derivative of total cost with respect to capacity factor measures effect of a change in capacity factor on total cost.

$$\frac{\partial \ln C}{\partial \ln U} = S_U = \tau_1 + \tau_2 \ln U + \sum_i \tau_{iU} \ln P_i + \tau_{YU} \ln Y + \\ + \tau_{tU} T \tag{3.23}$$

where S_U is the elasticity of the cost with respect to the capacity factor, holding input prices, output and technological change constant. Generally, cost decreases when capacity factor increases. As the equation shows, effects from changes in capacity can be decomposed into four components as the case of the rate of technological change, viz. (1) pure effect on generation costs from a change in capacity factor, (2) the effect of capacity factor on factor proportions, (3) the effect of capacity factor on scale and (4) the effect on the rate of technological change.

Elasticity of Substitution

As for elasticity of substitution between inputs, the Allen partial elasticity (Allen, 1938) can be derived from the cost function as Uzawa (1964) proved.

$$\sigma_{ij} = \frac{CC_{ij}}{C_i C_j}, \quad i, j = L, K, F; \; i \neq j \tag{3.24}$$

Where C = total cost,

$$C_i = \frac{\partial C}{\partial P_i}, \text{ and } C_{ij} = \frac{\partial^2 C}{\partial P_i \, \partial P_j}$$

For the translog cost function in this study,

$$\sigma_{ij} = \frac{\alpha_{ij} + M_i M_j}{M_i M_j} \tag{3.25}$$

$$\sigma_{ii} = \frac{\alpha_{ii} + M_i(M_i-1)}{M_i^2} \tag{3.26}$$

The own- and cross-price elasticity of demand for the ith factor is:

$$\epsilon_i = \sigma_{ii} M_i \tag{3.27}$$

$$\epsilon_j = \sigma_{ij} M_j \tag{3.28}$$

Total Factor Productivity

To derive total factor productivity, we first differentiate the cost function in equation 3.4 logarithmically with respect to time. Then, the rate of increase of total cost can be decomposed into such factors as: (1) scale elasticity, (2) cost elasticity with respect

$$\frac{d\ln C}{dT} = \frac{\partial \ln C}{\partial \ln Y}\frac{d\ln Y}{dT} + \frac{\partial \ln C}{\partial \ln P_K}\frac{d\ln P_K}{dT} + \frac{\partial \ln C}{\partial \ln P_L}\frac{d\ln P_L}{dT} + \frac{\partial \ln C}{\partial \ln P_F}\frac{d\ln P_F}{dT} + \frac{\partial \ln C}{\partial \ln U}\frac{d\ln U}{dT} + \frac{\partial \ln C}{\partial T} \tag{3.29}$$

to prices of inputs, (3) cost elasticity of capacity factor, and (4) changes in total costs due to technological change.

Using equations 3.6, 3.16, 3.20 and 3.23, we can rewrite equation 3.29 as follows:

$$\frac{d\ln C}{dT} = \epsilon_Y \frac{d\ln Y}{dT} + \sum_i M_i \frac{d\ln P_i}{dT} + S_U \frac{d\ln U}{dT} + S_t \tag{3.30}$$

Rearranging equation 3.30 holding input prices constant, the rate of growth of total cost or the Divisia index number (D) can be rewritten:

$$D = \epsilon_Y \frac{d\ln Y}{dT} + S_U \frac{d\ln U}{dT} + S_t \tag{3.31}$$

where

$$D = \frac{d\ln C}{dT} - \Sigma M_i \frac{d\ln P_i}{dT} \tag{3.32}$$

Namely, the Divisia index number is equal to the sum of contributions of scale economies, technological change, and effects of capacity factor.

However, the above model is a continuous form while actual data are of the discrete type. Therefore, we need the form which can deal with discrete data. The Törnqvist index is one which is a discrete approximation to the Divisia index and corresponds to the production technology based on second-order approximation (Diewert, 1976). As Diewert proved, if and only if the quadratic function, f(z), is defined by the following,

$$f(z) = a_o + \sum_{i}^{n} a_i z_j + \frac{1}{2} \sum\sum_{ij}^{nn} a_{ij} z_i z_j, \qquad (3.33)$$

where z is a n-dimensional vector and the a_i and a_{ij} are constant and $a_{ij} = a_{ji}$, then

$$f(z_1) - f(z_0) = \frac{1}{2} [\nabla_z f(z_1) + \nabla_z f(z)](z_1 - z_0) \qquad (3.34)$$

where ∇_z is the gradient vector.

Applying the above quadratic approximation lemma to the translog cost function with using equations 3.6, 3.16, 3.20 and 3.23, we can derive the following:

$$\ln C(P_i t, Yt, Ut, t) - \ln C(P_i t^*, Yt^*, Ut^*, t^*)$$

$$= \frac{1}{2} \sum_i (M_i t + M_i t^*) \ln \frac{P_i t}{P_i t^*} + \frac{1}{2} (\epsilon_Y t + \epsilon_Y t^*) \ln \frac{Yt}{Yt^*}$$

$$+ \frac{1}{2} (S_U t + S_U t^*) \ln \frac{Ut}{Ut^*} + \frac{1}{2} (S_t t + S_t t^*)(t - t^*)$$

(3.35)

where the superscript * refers to observations in period t^*. From equation 3.35, we do not need to estimate the translog function if we can assume that returns to scale are unity and capacity factor effects are assumed to be zero. In this case, we can derive technical change as the residual without econometric estimates. However, scale elasticity is not assumed to be one in this study. Furthermore the variable representing capacity utilization is an important factor to be estimated. Consequently, it is necessary to rely on parameters estimated by translog cost function 3.5 and derived cost share equations 3.7 in order to compute the rate of total factor productivity growth and decompose it into sources of returns to scale, technological change and capacity factor. The estimated index of total factor productivity growth in this study is therefore:

$$\overset{\circ}{TFP} = - S_t + (1 - \epsilon_Y) * \overset{\circ}{Y} - S_U * \overset{\circ}{U} \qquad (3.36)$$

where ∘ refers to time derivative.

3. Estimation Procedures

In this study the estimation model consists of the translog cost function and cost share equations. There are other estimation procedures. One way is to estimate the translog cost function directly by applying the ordinary least squares method. However, this procedure, in light of many explanatory variables in the translog cost function, is less efficient than a multivariate regression including cost share equations since incorporation of cost share equations increases the degree of freedom. Another procedure is to estimate cost share equations as a multivariate regression system. Yet, estimation by a system of cost share equations neglects the important information regarding returns to scale included in the translog cost function. Therefore, in this study the translog function and cost share equations are jointly estimated as a multivariate regression system with adding error terms to respective equation. Estimation procedure employed is Zellner's (1962) Seemingly Unrelated Regression permitting simultaneous estimation of the translog function and cost share equations, which is more efficient and do not lose the information included in the translog function. However, summation of error terms of three cost share equations is zero because cost shares sum to unity, which in turn implies that the covariance matrix of error terms is singular. In this connection, Barten (1969) has proved that maximum-likelihood estimates of a system of share equations with one equation deleted are invariant regardless of which equation is deleted. Therefore, we can drop one of cost share equations arbitrarily to avoid the problem of singularity. Furthermore, iteration of the Seemingly Unrelated Regression until convergence leads to maximum-likelifood estimates as Kmenta and Gilbert (1968) has proved, which is an efficient method. We therefore employ Iterative Seemingly Unrelated Regression procedure in this study.

4. Data

Data required to achieve objectives of this study are as follows:

1. Annual output generated in the thermal power sector

2. Annual total cost which includes costs of capital, fuel and labor incurred in the thermal power segment

3. Prices of capital, fuel and labor

4. Cost shares of capital, fuel and labor

5. Average annual capacity factor of thermal power plants

These data are at the firm level because the firm determines input levels as the work by Nerlove (1963) emphasizes. It should be noted, however, that we cannot say *a priori* whether data at firm level are more relevant than data at the plant level or the unit level. The choice of data level depends upon the objectives of the study. For instance, if we estimate *ex-ante* substitution between input pairs, then plant or unit level data are more appropriate (Fuss, 1978). This is because the possibility of substitution between inputs may exist to some extent before the configuration of the plant or the unit is fixed. However, once the configuration is determined, the possibility of substitution between inputs becomes very limited. The only permitted substitution after plant or unit configuration may be interfuel substitution in the case of dual or triple-fired power plants in the short-term (Atkinson and Halvorsen, 1980). Yet, interfuel substitution is generally only permitted for fuel oils in the short-term; that is, interfuel substitution is possible between crude oil and heavy oil, while substitution between oil and coal is not feasible technologically in the short-term.

Samples used in this study are pooled cross sectional data for the period of 1964-1988 for nine electric power companies. The data required are covered mostly in annual reports published by Shigen Enerugii Chou (Agency of Natural Resources and Energy), Denkijigyou Rengoukai (Federation of Electric Power Companies) and Oukurasho Insatsukyoku (Printing Office of the Ministry of Finance).

Specifically, data on electricity generation is obtained directly from Denkijigyo Binran (Handbook of Electric Power Industry) published annually by Denkijigyou Rengoukai. Total costs of thermal power generation are available in Yuukashouken Shouken Houkokusho Souran (Comprehensive Statement of Finance and Account) submitted annually to minister of finance. Total costs include capital cost, fuel cost and labor cost. Capital cost includes depreciation costs, maintenance costs, property tax, rental costs, costs of insurance, financial costs including interest payments and dividend and other miscellaneous costs, of which we can obtain all components except financial costs. Financial cost was derived by multiplying total financial cost for the firm by the ratio obtained from dividing original costs of the thermal power facilities by original costs of total fixed asset for the firm. Fuel cost in the thermal generation segment is obtained directly from either Denkijigyou Binran or Yuuka Shouken Houkokusho Souran. Note that fuel cost includes some environmental protection costs related to coal-fired thermal power generation. Fuels used in thermal power plants are heavy oil, crude oil, naphtha, LNG, coal, and LPG. Calorific value per unit and quantity consumed are reported in Denryoku Jukyuu no Gaiyou (Outline of Electricity Demand and Supply) published by Shigen Enerugii Chou. The data on capacity factors of thermal power plants are also obtained directly from Denryoku Jukyuu no Gaiyou published by Shigen Enerugii Chou. In this study, input prices were derived based upon the following:

Price of Capital

In the neoclassical framework, a capital input is defined as the quantity of service flow obtained from its input, not quantity of its stock. In most similar studies in Japan, the capital price used in their models was the stock price viz. asset price per kw. Use of the stock price may be acceptable if there is a proportional relation between capital flow and capital stock. However, it seems that the service price of capital is a more accurate price of capital in light of heterogeneity of capital and accounting practices of Japanese electric utilities.

The price of capital in this study is therefore the service price of capital which is the rental value of a capital input. A flow of capital service can be decomposed into price as the rental rate and quantity of capital used per unit time. The problem is that the rental market for capital does not exist. Therefore, we need to impute the rental value of capital.

The service price of capital in the absence of taxes can be imputed based upon the following.

$$P_k = (r + \delta)q \quad (3.37)$$

Where P_k = imputed rental price of capital

r = rate of return

δ = rate of depreciation

q = the asset price measured by bookvalues divided by the installed capacity

The above relation is obtained from the following basic relation between the price of a new capital good and the discounted value of all the future service derived from this capital good (Hall and Jorgenson, 1967).

$$q(t) = \int_t^{\infty} e^{-r(s-t)} P_k(s) \; e^{-\delta(s-t)} ds, \qquad (3.38)$$

where, $q(t)$ = the price of asset

P_k = cost of capital services

r = discount rate

δ = the rate of replacement

t = the time of acquisition

s = the time at which capital service is supplied

From equation 3.38 and assuming P_k is constant,

$$q(t) = P_k \frac{1}{r + \delta} (1 - e^{-r(s-t)} e^{-\delta(s-t)}). \qquad (3.39)$$

As $t \longrightarrow \infty$, $e^{-r(s-t)} e^{-\delta(s-t)} = 0$.

Hence, rearranging equation 3.39, we get equation 3.37 under static expectation.

The above derivation assumed away the tax system which may affect the cost of capital. Incorporation of the tax system may be more accurate in constructing data on the service price of capital as Hall and Jorgenson (1967) developed. As in the U.S., electric utilities in Japan are subject to various taxes. Specifically, the major taxes on electric utilities are corporate income tax, enterprise tax, property tax and promotion tax of electric power development. Meanwhile, electric utilities in Japan are allowed to hold some reserves internally such as the reserve for future payments for retired employees without tax being imposed. This system is a sort of government subsidy and unique to the Japanese tax system. Therefore, in order to construct the service price of capital, we need to take into consideration not only various tax but also subsidies.

However, these taxes and subsidies are imposed on and provided to the firm itself. It is not of significance nor legitimate theoretically to allocate these costs into various components of the firm because the aggregate firm itself is affected by taxes and subsidies. The accounting practice of electric utilities is, therefore, of such format that the firm's total cost is decomposed into costs of thermal generation, internal combustion, nuclear generation, transmission, distribution and general administration. And data on costs in each component is decomposed into salary, fuel and capital, such as depreciation. Yet, there is no decomposition of taxes and reserves in the firm's financial statements. These costs and benefits are reported only as those to the aggregate firm. In light of this study focusing on only thermal generation, we assume away these costs and benefits rather than allocate arbitrarily those into the thermal power sector.

Regarding the rate of return, the actual rate of return is not disclosed to the public. Therefore, we estimated the rate of return by the following formula which many electric utilities in U.S. use (Kolbe, Read and Hall, 1984).

$$r = \frac{IR + DI + IP}{CA + LD}, \qquad (3.40)$$

where r = the rate of return

IR = internal reserve

DI = dividend paid to equity

IP = interest paid to long-term debt

CA = capitalization excluding long-term debt

LD = long-term debt

As for rate of depreciation, it was derived by dividing actual depreciation in the thermal power generation sector by the original costs of the fixed asset in its sector. In this connection, the accounting system in Japan is based upon the principle of the original cost.

Price of Fuel

Total fuel cost is obtained directly from Yuuka Shouken Houkokusho Souran. Data regarding calorific values of each fuel are reported in Denryoku Jukyuu no Gaiyou. Using these data, we constructed P_F as follows.

$$P_F = \frac{FC}{FV}, \tag{3.41}$$

where P_F = price of fuel per calorie

FC = total fuel cost

FV = total fuel consumption measured by calorific value

Labor Price

Data on total wages paid to employees and the number of employees in the thermal power sector are derived directly from Denkijigyou Binran and Denkijigyou Youran.[12] The price of labor was constructed based on the following.

$$P_L = \frac{TW}{NL}, \tag{3.42}$$

where P_L = labor price

TW = total wage including welfare costs of full-time and part-time employees working in the thermal power sector

NL = the number of full-time and part-time employees working in the thermal power sector

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12. Data on the number of employee in the thermal power sector is available, while there is no data of wages concerned with part-time employees. However, the share of part-time employees in total employees in the thermal power sector is negligible. Therefore, derived labor price will not be inaccurate.

CHAPTER IV

STUDY RESULTS

1. Parameter Estimates

Parameter estimates for the estimation model described in the previous chapter are presented in table 11. These parameters were derived from a multivariate system of the translog cost function and two cost share equations of capital and fuel arbitrarily dropping the labor cost equation. The program for computation was the SHAZAM system command with various restrictions implied by linear homogeneity in input prices as well as symmetry conditions across the equations. These estimates are parameters from which estimates concerned with the objectives of this study are derived.

Asymptotic t ratios presented in the table suggest that most of the coefficients are significant at the 99% level of confidence. Only three coefficients out of twenty-eight coefficients are not significant. Therefore, regression results seem to show that the model is acceptable.[13]

As explained in the previous chapter, some regularity conditions must be satisfied in order that the translog cost function is well-behaved. To check the concavity condition,

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13. R^2s for total costs, capital, fuel and labor equations are 0.99, 0.93, 0.93 and 0.63, respectively. However, the R^2 statistics lose much of their meaning in the simultaneous equation context.

Table 11

Parameter Estimates of The Translog Cost Function

Parameter	Estimate	Asymptotic t Ratio[a]	Parameter	Estimate	Asymptotic t Ratio
α_0	3.0296	3.104	β_{YK}	0.0043408	2.515
α_L	0.24617	14.105	τ_U	-1.7045	-4.106
α_F	-0.92108	-24.284	τ_{UU}	0.25053	2.535
α_K	1.6749	45.599	τ_{UL}	-0.018078	-5.534
α_{LL}	0.02692	13.063	τ_{UF}	0.24206	29.881
α_{LF}	-0.02474	-16.798	τ_{UK}	-0.22398	-29.300
α_{LK}	-0.0021804	-1.427	τ_{UY}	-0.039901	-2.311
α_{FF}	0.19096	62.488	μ_T	0.066830	4.587
α_{FK}	-0.16622	-61.078	μ_{TT}	0.0007762	3.516
α_{KK}	0.16840	59.786	μ_{TL}	-0.0013105	-7.200
β_Y	1.2054	15.196	μ_{TF}	-0.0031418	-8.553
β_{YY}	-0.0022607	-0.379	μ_{TK}	0.0044523	12.370
β_{YL}	-0.0064674	-8.515	μ_{TY}	-0.0021391	-2.864
β_{YF}	0.0021266	1.174	μ_{TU}	-0.0095441	-2.637

a. Degrees of Freedom = 652

we first differentiate the total cost function with respect to input prices. Then we can obtain the following:

$$\frac{\partial C}{\partial P_i} = \frac{C}{P_i} \frac{\partial \ln C}{\partial \ln P_i} = \frac{C}{P_i} Mi \qquad (4.1)$$

Differentiating equation 4.1 with respect to input prices again and using equation 3.7, we can obtain the following:

$$\frac{\partial^2 C}{\partial P_i{}^2} = \frac{\frac{\partial C}{\partial P_i} P_i - C}{P_i{}^2} M_i * \frac{C}{P_i} \frac{M_i}{P_i}$$

$$= \frac{CM_i - C}{P_i{}^2} M_i * \frac{C}{P_i} \frac{\alpha_{ii}}{P_i}$$

$$= \frac{C}{P_i{}^2} (M_i{}^2 - M_i + \alpha_{ii}) \qquad (4.2)$$

Similarly,

$$\frac{\partial^2 C}{\partial P_i \partial P_j} = \frac{C}{P_i P_j} (M_i M_j + \alpha_{ij}) \qquad (4.3)$$

To satisfy the condition of concavity in input prices, the following Hessian matrix formed by equations 4.2 and 4.3 must be negative semidefinite. It should be noted that this condition is global concavity. Yet, the translog log function must be viewed as a local approximation to the true technology, so that the translog function do not necessarily provide a good approximation over a range of data.

$$H = \begin{bmatrix} \alpha_{KK} + M_K(M_K - 1) & \alpha_{KL} + M_K M_L & \alpha_{KF} + M_K M_F \\ \alpha_{LK} + M_L M_K & \alpha_{LL} + M_L(M_L - 1) & \alpha_{LF} + M_L M_F \\ \alpha_{FK} + M_F M_K & \alpha_{FL} + M_F M_L & \alpha_{FF} + M_F(M_F - 1) \end{bmatrix} \quad (4.4)$$

The above condition implies that the curvature of the isoquant which represents the combination of two inputs, given output, are convex to the origin. This condition, that micro economics usually assumes, is based upon the empirical reason that the reverse situation, that is concave to the origin, is inconsistent with the actual firm's or consumer's behavior (Silberberg, 1978). Sufficient condition for monotonicity is that fitted cost share equation is non-negative as defined by equation 3.14. Overall, the conditions for concavity and monotonicity were met at the mean values.

Before computing the parameters related to the objectives of this study, several hypotheses regarding the structure of the production technology were tested with implied restrictions. Hypotheses tested were:

a) homotheticity

b) homogeneity

c) no technological change, and

d) no capacity factor effect

These hypotheses were tested based upon the likelihood ratio tests because parameters obtained by the Iterative Seemingly Unrelated Regression are maximum-likelihood estimates. Denoting the determinants of unrestricted and restricted estimates of residual covariance matrix by $|\Omega_u|$ and $|\Omega_r|$, the likelihood ratio(ϕ) can be written as:

$$\phi = \left(\frac{|\Omega_r|}{|\Omega_u|}\right)^{-n/2}$$

where n is the number of observations. And $-2\ln\phi$ is distributed as chi-squared with degrees of freedom equal to the number of restrictions (Theil, 1971).

Tables 12-15 present estimated parameters with various restrictions implied by the models and table 16 presents test statistics. In this connection, the comparison of parameter estimates in tables 11-15 reveals that some estimates are instable, which seems to be due to the problem of multicollinearity. There exists some degree of multicollinearity in every regression. This is particularly the case for the translog cost function including the first-order and second-order terms of the same variable. The time

Table 12

Parameters Estimates with Restriction of Homotheticity

Parameter	Estimate	Asymptotic t Ratio	Parameter	Estimate	Asymptotic t Ratio
α_0	3.5764	3.959	β_{YK}	...	...
α_L	0.22192	12.973	τ_U	-1.8602	-4.514
α_F	-0.90508	-24.289	τ_{UU}	0.21258	2.210
α_K	1.6832	46.446	τ_{UL}	-0.02329	-7.258
α_{LL}	0.02278	11.367	τ_{UF}	0.24254	30.719
α_{LF}	-0.02584	-17.612	τ_{UK}	-0.21925	-29.428
α_{LK}	0.00306	2.186	τ_{UY}	...	...
α_{FF}	0.19260	66.155	μ_T	0.06690	4.759
α_{FK}	-0.16676	-64.986	μ_{TT}	0.000494	2.492
α_{KK}	0.16370	62.502	μ_{TL}	-0.0012445	-6.849
β_Y	1.1535	27.259	μ_{TF}	-0.0031294	-8.645
β_{YY}	-0.017145	-3.933	μ_{TK}	0.0043739	12.322
β_{YL}	...	...	μ_{TY}	...	...
β_{YF}	...	...	μ_{TU}	-0.014018	-4.386

Table 13

Parameter Estimates with Restriction of Homogeneity

Parameter	Estimate	Asymptotic t Ratio	Parameter	Estimate	Asymptotic t Ratio
α_0	4.3764	4.972	β_{YK}	...	...
α_L	0.22436	13.124	τ_U	-1.8565	-4.505
α_F	-0.90818	-24.377	τ_{UU}	0.20923	2.176
α_K	1.6838	46.465	τ_{UL}	-0.02323	-7.240
α_{LL}	0.02275	11.353	τ_{UF}	0.24221	30.679
α_{LF}	-0.02582	-17.602	τ_{UK}	-0.21898	-29.393
α_{LK}	0.00308	2.196	τ_{UY}	...	...
α_{FF}	0.19239	66.095	μ_T	0.069064	4.917
α_{FK}	-0.16657	-64.924	μ_{TT}	0.000323	1.668
α_{KK}	0.16349	62.437	μ_{TL}	-0.001246	-6.857
β_Y	0.98757	302.73	μ_{TF}	-0.003130	-8.646
β_{YY}	...	...	μ_{TK}	0.004375	12.326
β_{YL}	...	...	μ_{TY}	...	...
β_{YF}	...	...	μ_{TU}	-0.013933	-4.360

Table 14

Parameter Estimates with Restrictions of

No Technological Change

Parameter	Estimate	Asymptotic t Ratio	Parameter	Estimate	Asymptotic t Ratio
α_0	6.7087	9.465	β_{YK}	0.007387	4.377
α_L	0.23954	15.152	τ_U	-3.4446	-13.651
α_F	-0.97399	-27.547	τ_{UU}	0.61113	11.146
α_K	1.7344	52.106	τ_{UL}	-0.012243	-4.087
α_{LL}	0.01768	10.512	τ_{UF}	0.26548	36.883
α_{LF}	-0.02494	-17.000	τ_{UK}	-0.25324	-36.950
α_{LK}	0.00726	6.804	τ_{UY}	-0.034599	-2.963
α_{FF}	0.17897	64.844	μ_T	...	...
α_{FK}	-0.15404	-66.278	μ_{TT}	...	...
α_{KK}	0.14678	64.134	μ_{TL}	...	...
β_Y	1.2749	17.415	μ_{TF}	...	...
β_{YY}	-0.01240	-2.681	μ_{TK}	...	...
β_{YL}	-0.00568	-7.521	μ_{TY}	...	...
β_{YF}	-0.00170	-0.960	μ_{TU}	...	...

Table 15

Parameter Estimates with Restriction of

No Capacity Factor Effect

Parameter	Estimate	Asymptotic t Ratio	Parameter	Estimate	Asymptotic t Ratio
α_0	-2.0809	-8.970	β_{YK}	-0.006560	-3.900
α_L	0.18836	17.647	τ_U	...	...
α_F	0.11455	6.553	τ_{UU}	...	...
α_K	0.69709	40.513	τ_{UL}	...	...
α_{LL}	0.02670	12.982	τ_{UF}	...	...
α_{LF}	-0.02279	-15.827	τ_{UK}	...	...
α_{LK}	-0.003917	-2.583	τ_{UY}	...	...
α_{FF}	0.16816	56.950	μ_T	0.028603	5.315
α_{FK}	-0.14537	-55.243	μ_{TT}	0.002705	17.879
α_{KK}	0.14929	54.620	μ_{TL}	-0.000976	-5.821
β_Y	1.0614	21.000	μ_{TF}	-0.007704	-23.404
β_{YY}	-0.0091376	-1.636	μ_{TK}	0.008680	26.495
β_{YL}	-0.0074495	-9.987	μ_{TY}	-0.002759	-5.516
β_{YF}	0.014010	7.945	μ_{TU}	...	...

trend variable also tends to correlate strongly with output generated because both variables grow smoothly over the years pointed out. However, dropping some variables causes another serious problem, viz. specification error. Furthermore, in light of the fact that most of parameter estimates are fairly stable in regressions conducted for hypothesis testings, parameter estimates in table 11 appear to be reliable.

As table 16 shows, all the hypotheses were rejected at the 1% level. Therefore, non-homotheticity and non-homogeneity incorporating variables representing technological change and capacity factor are required to model the thermal power generation technology in Japan.

Table 16

Test Statistics for Hypotheses

Hypotheses	no. of restrictions	chi-square	critical chi-square at the 1% level
Homotheticity	4	76.09	13.28
Homogeneity	5	85.32	15.09
No Technological Change	6	143.40	16.81
No Capacity Factor Effects	6	342.90	16.81

2. Empirical Results

Scale Economies

As shown in the previous section, hypotheses of homogeneity as well as homotheticity were rejected. Hence, scale economies are characterized as a function of output generated, input prices, time trend representing technological change and capacity factor as equation 3.16 shows.

The elasticity of the cost with respect to output can be derived by using parameter estimates in table 11. Table 17 reports estimated average scale economies, as defined by equation 3.17, of nine electric power companies over the period 1964-1988.

All estimates of scale economies, except for Chugoku and Hokkaido in the period 1964-70, are positive, which implies that the thermal power generation technology is at the stage of increasing returns to scale. Another finding is that average scale economies in 1964-70 are less than those in the subsequent four subperiods. Scale economies in the periods of higher oil prices are greater than those in the period of stable oil prices. Moreover, scale economies for most electric utilities have been increasing as a trend over the years. The extent of positive scale economies ranges between 0.003 and 0.05. One percent increase in output, therefore, led to an increase in total costs in the range of slightly less than 1% and 0.95% due to scale economies.

Table 17

Estimated Average Scale Economies, 1964-88

Company	1964-1970	1971-1975	1976-1980	1981-1985	1986-1988
Tokyo	0.009320	0.022694	0.029310	0.038541	0.051303
Kansai	0.004959	0.017994	0.027682	0.027769	0.035627
Chubu	0.003544	0.019845	0.031426	0.038930	0.054087
Kyushuu	0.009557	0.020385	0.026612	0.021838	0.024028
Tohoku	0.009725	0.023035	0.032169	0.033831	0.040078
Chugoku	-0.000630	0.020113	0.033311	0.032219	0.040089
Shikoku	0.004875	0.018321	0.017148	0.021232	0.033023
Hokkaido	-0.003810	0.022820	0.039437	0.038052	0.045830
Hokuruiku	0.005605	0.018307	0.027000	0.018670	0.021327

Factors which brought about changes in scale economies can be explained by the parameters. Effects due to input prices are measured by β_{YL}, β_{YF} and β_{YK}. Effects by changes in output, technological change and capacity factor are associated with β_{YY}, μ_{TY} and τ_{UY}, respectively. Coefficients of input prices are statistically significant at the 99% level for β_{YL} and β_{YK} and at the 95% level for β_{YF}. Positive values of β_{YK} and β_{YF} indicate that increases in these prices would reduce scale economies while the negative value of β_{YL} indicates that increase in the labor price would lead to higher scale economies. Parameter estimates of technological change and capacity factor, μ_{TY} and τ_{UY}, are negative and statistically significant at the 99% level. Therefore, any increases in these variable would lead to higher scale economies. Meanwhile, the coefficient of output is negative contrary to expectation. However, it is not statistically significant, so that effects due to differences in the size of operation are neutral statistically in terms of effects on scale economies.

In order to measure the magnitude of impacts from changes in relative prices between inputs, in particular relative to skyrocketed oil prices after oil crises, we estimated scale economies holding output, technological change and capacity factor at their mean value. As table 18

Table 18

Estimated Average Scale Economies, 1964-88

Company	1964-1970	1971-1975	1976-1980	1981-1985	1986-1988
Tokyo	0.022589	0.027961	0.029638	0.029696	0.031157
Kansai	0.017251	0.021903	0.023465	0.022211	0.024833
Chubu	0.020980	0.026057	0.028149	0.028429	0.031935
Kyushuu	0.017699	0.022630	0.022193	0.023161	0.027871
Tohoku	0.021153	0.027279	0.028488	0.028885	0.033243
Chugoku	0.016545	0.025310	0.025343	0.025554	0.028144
Shikoku	0.013735	0.018702	0.019484	0.021291	0.024028
Hokkaido	0.021440	0.028320	0.027030	0.024460	0.028097
Hokuriku	0.012152	0.019122	0.021742	0.022522	0.028962

Note: the case of holding output, time and capacity factor at the mean value of each company.

reveals, relative price changes increased scale economies during the period 1964-1975. Thereafter, relative price changes slowed the increase in scale economies for most electric companies.

Accordingly, larger scale economies in the period of 1971-1988 may be attributed to scale-augmenting technological change and capacity factor.

Technological Change

As defined by equation 3.20, the rate of technological change is a function of time, input prices, output and capacity factor. All coefficients of variable related to technological change are statistically significant at the 99%. The likelihood ratio test also rejected the null hypothesis of no technological change.

The sign of the parameter estimate indicates how each variable contributes to the rate of technological change. Pure technological change, $\mu_1+\mu_2$, is positive, which implies that this technological change did not contribute to reduction of costs. μ_{YT} which captures output effects is negative, and this implies that the larger the scale of operation, the higher is the rate of technological change. It should be noted here that it is not the electric utility but manufacturers that bring about advanced or new technologies. The primary objective of R&D activities in the electric utility is to keep abreast of the state of the art so that the engineers in the industry can readily use those new technologies. The coefficient of capacity factor (μ_{UT}) is negative, which indicates that technological change bringing about higher capacity factor reduces the cost. One example of such technological change is the so-called load-following technology. Biased technological changes are represented by coefficients of input prices, μ_{KT}, μ_{FT} and μ_{LT}. μ_{KT} is positive, implying capital-using technological change while estimates of μ_{FT} and μ_{LT} indicate fuel-saving and labor-saving technological changes, respectively. These results regarding biased technological change are consistent with engineering economics which suggest that technological change is embodied in new capital requiring smaller quantity of fuel consumption per output generated. New capital generally also requires less labor than old power plants due to the introduction of centralized control system in the plant.

Table 19 reports average technological change estimated by using parameters in Table 11 and actual data at each point of time. The rates of technological change for larger companies such as Tokyo, Kansai and Chubu are higher than for other companies. Technological change clearly slowed down after the period 1971-1975. Moreover, all companies on average recorded negative rates of technological change

Table 19

Estimated Average Annual Rate of

Technological Change, 1964-88

Company	1964-1970	1971-1975	1976-1980	1981-1986	1986-1988
Tokyo	-0.00549	-0.00595	-0.00364	-0.00090	0.005891
Kansai	-0.00427	-0.00478	-0.00328	-0.00299	0.009885
Chubu	-0.00304	-0.00422	-0.00392	-0.00129	0.003722
Kyushuu	-0.00281	-0.00264	-0.00012	0.00544	0.012409
Tohoku	-0.00193	-0.00283	-0.00189	0.003094	0.008492
Chugoku	-0.00044	-0.00262	-0.00188	0.004210	0.011546
Shikoku	0.000375	-0.00010	0.003649	0.006744	0.011120
Hokkaido	0.002884	-0.00049	-0.00042	0.007449	0.011165
Hokuriku	0.000907	0.000841	0.002024	0.008787	0.015125

during 1986-1988. In this connection, negative rates of technological change may be partly because of the assumption that technological change takes place at a constant rate. Given the assumption of a constant rate of technological change, the rate of technological change can be negative if technological change does not actually take place. Another interpretation is that the rate of technological change can be negative since the thermal power generation sector is composed of various power plants with different vintages. The original performance of equipments in thermal power plants cannot be generally maintained or can even deteriorate as vintage increases. Therefore, assuming a constant rate of technological change, increasing share of old thermal power plants in the thermal power sector is likely to bring about negative rates of technological change.

Table 20 reports the magnitude of price effects to the rate of technological change. Only input prices are allowed, in order to compute the price effects, to vary while other variables are held at their mean values for each company.

In contrast with scale economies, changes in relative prices between inputs reduced the rate of technological change in the period 1964-1970 while relative price movements brought about a higher rate of technological

Table 20

Estimated Annual Average Rate of

Technological Change, 1964-88

Company	1964-1970	1971-1975	1976-1980	1981-1985	1986-1988
Tokyo	0.002492	-0.00285	-0.00552	-0.00694	-0.00239
Kansai	0.003739	-0.00171	-0.00460	-0.00459	-0.00149
Chubu	0.003251	-0.00196	-0.00550	-0.00710	-0.00452
Kyushuu	0.005982	0.00696	-0.00110	-0.00366	-0.00278
Tohoku	0.005670	-0.00003	-0.00306	-0.00428	-0.00363
Chugoku	0.005122	0.000351	-0.00159	-0.00241	-0.001126
Shikoku	0.008418	0.003923	0.001060	-0.00209	-0.00123
Hokkaido	0.008951	0.008967	0.005631	0.00233	-0.00088
Hokuriku	0.008951	0.004612	0.001273	-0.00085	-0.00086

Note: the case of holding output, time and capacity factor at their mean value of each company.

change from 1971 to 1985 and again reduced the rate of technological change during 1986-1988. Therefore, it can be argued that combined net effects of relative price changes on the rate of technological change reduced magnitude of slow-down in the rate of technological change during higher fuel prices.

Capacity Factor

As defined by equation 3.23, effects of capacity factor on total generation cost are measured by the elasticity of total cost with respect to changes in capacity factor. Since incorporation of capacity factor in the model is statistically significant as results of both the likelihood ratio test and asymptotic t ratios show, we cannot neglect capacity factor in modeling the thermal power generation technology.

Parameter estimates of the terms related to pure effects by capacity factor are $\tau_1 + \tau_2$. Simple calculation reveals that this term is negative regardless of the rate of capacity factor. Therefore, increases in the rate of capacity factor always contribute to a reduction in total costs of generation as expected. The signs of parameter estimates concerned with the labor price and the capital price are negative so that increases in these prices, given other variables, would lead to a reduction in total costs.

Estimated parameters in relation to technological change and output effects are also negative, which implies that increases in these variables would bring about a reduction in total generation costs. Meanwhile, an increase in fuel prices leads to higher costs.

Table 21 presents estimated average elasticity of the total cost with respect to capacity factor. Estimated values range from -0.20185 to -0.65398, which means that the increase in the rate of capacity factor by one percent would lead to a reduction in total costs in the range of 0.20185 percent to 0.65398 percent. Therefore, magnitude of capacity factor effect is much larger than that of scale economies and technological change. Another finding is that the rate of cost reduction brought about by changes in capacity factor had been decreasing for the period 1964-1980. This finding is consistent with movements of capacity factor over the years. As figure 8 shows, capacity factor has been declining as a trend.

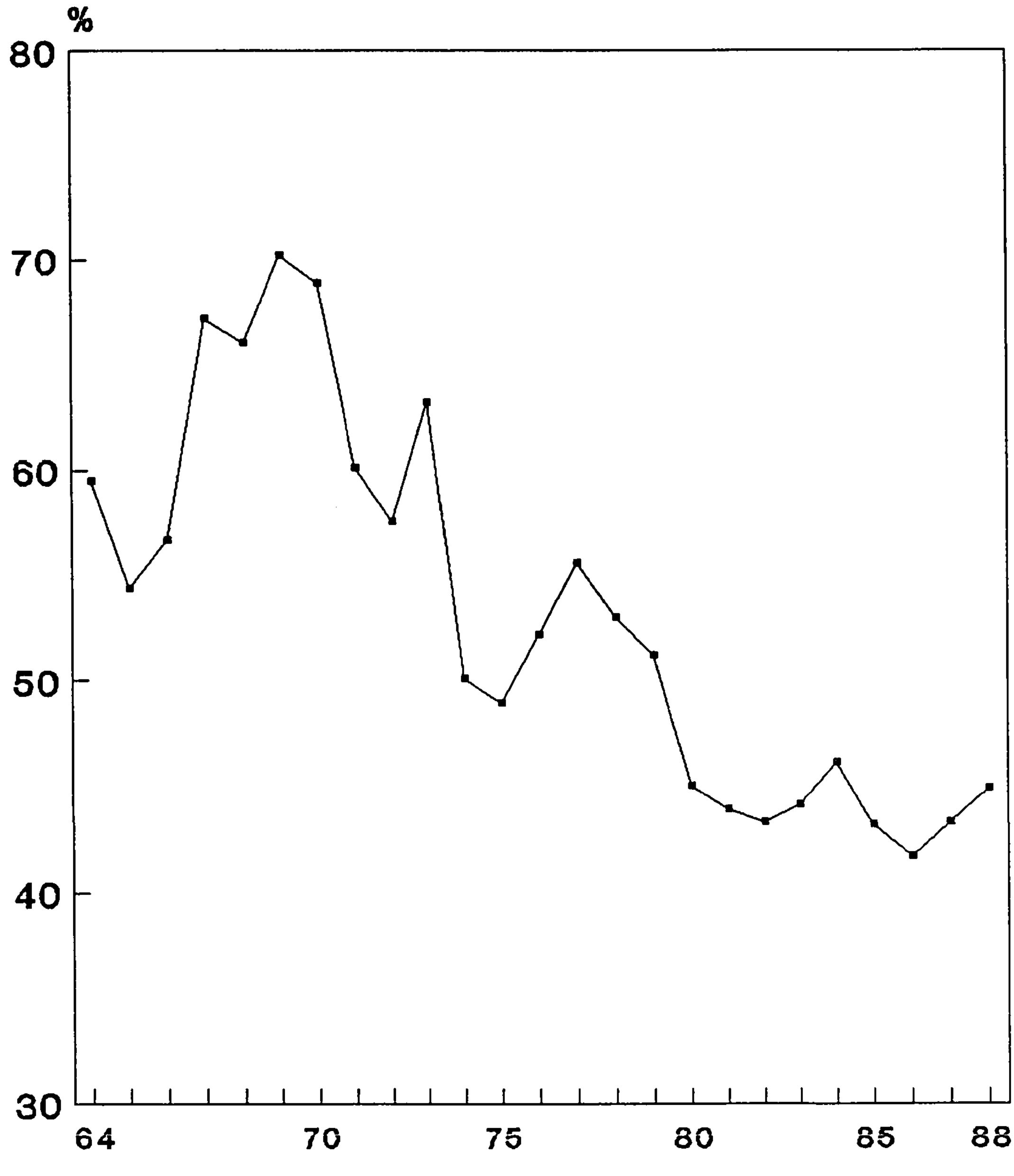
Table 22 presents estimated average effects of capacity factor, holding output, time and capacity factor at their mean values for each company, in order to quantify the magnitude of relative price changes between input prices. The results suggest that the movement of relative prices between input prices slowed down the effect of capacity factor on generation costs after the oil crisis.

Table 21

Estimated Average Effect of Capacity Factor, 1964-88

Company	1964-1970	1971-1975	1976-1980	1981-1985	1986-1988
Tokyo	-0.52785	-0.38215	-0.32796	-0.29559	-0.64595
Kansai	-0.50356	-0.33180	-0.23453	-0.31728	-0.62592
Chubu	-0.52282	-0.36337	-0.23149	-0.20185	-0.45920
Kyushuu	-0.49704	-0.35903	-0.32568	-0.31302	-0.54184
Tohoku	-0.49867	-0.35538	-0.25482	-0.29216	-0.48350
Chugoku	-0.48750	-0.32406	-0.25097	-0.31721	-0.65398
Shikoku	-0.46271	-0.38935	-0.35134	-0.26100	-0.43763
Hokkaido	-0.58163	-0.35916	-0.28364	-0.50714	-0.61722
Hokuriku	-0.41483	-0.33795	-0.25396	-0.28943	-0.49687

Figure 8. Trend of Capacity Factor (1964 -1988)



Source: Derived from Shigen Enerugii Chou Koueki Jigyoubu, 1964-1990.

Table 22

Estimated Average Effects of Capacity Factor

Company	1964-1970	1971-1975	1976-1980	1981-1985	1986-1988
Tokyo	-0.6510	-0.37885	-0.22984	-0.13625	-0.46079
Kansai	-0.64729	-0.36239	-0.19632	-0.17682	-0.42425
Chubu	-0.65095	-0.38850	-0.18835	-0.08810	-0.31465
Kyushuu	-0.67427	-0.40481	-0.27870	-0.12499	-0.25919
Tohoku	-0.66888	-0.38070	-0.21030	-0.13579	-0.24984
Chugoku	-0.60936	-0.36667	-0.23877	-0.18749	-0.46371
Shikoku	-0.65513	-0.43844	-0.26191	-0.08233	-0.21528
Hokkaido	-0.66730	-0.40529	-0.29842	-0.39919	-0.46371
Hokuriku	-0.60424	-0.38955	-0.21133	-0.08314	-0.18666

Note: the case of holding capacity factor, output and time their mean values for each company.

Elasticity of Substitution

Table 23 reports partial elasticity of substitution at mean values of cost shares as defined by equations 3.25 and 3.26. Own and cross price elasticity are presented in table 24. The results show that capital-fuel and capital-labor are substitutes while fuel-labor is complement.

As discussed in chapter 3, substitution possibility is scant between inputs once configuration of generating plants are fixed. However, over the long-run, substitutions between inputs are possible at the firm level. For example, improvements in thermal efficiency and introduction of centralized control technologies in thermal power plants suggest that capital-labor and capital-labor are substitutable. Therefore, the results are consistent with facts that electric utilities have experienced in the past.

Table 23

Estimated Allen Partial Elasticity of Substitution

	Fuel	Capital	Labor
Fuel	-0.11268	0.220770	-0.15169
Capital		-0.48419	0.815047
Labor			-5.34744

Table 24

Estimated Own and Cross Price Elasticity

	Fuel	Capital	Labor
Fuel	-0.07025	0.0175536	-0.00522
Capital	0.137639	-0.16566	0.028082
Labor	-0.09457	0.278867	-0.18424

Total Factor Productivity

Given the parameter estimates related to technological change, scale economies and the effect of capacity factor, we use equation 3.36 to compute the rate of total factor productivity growth and decompose it into contributing factors. Figure 9 presents the movements of average total factor productivity, weighted by output, of nine electric power companies in the period 1964-1988. Table 24 presents the average total factor productivity growth rate of each electric power company over the years. Columns 2-4 show the decomposition of contributing factors.

As indicated in figure 9, there are variations in average total factor productivity growth of nine electric power companies from year to year over the years. However, productivity of all electric utilities on average improved in the subperiod 1965-1970. Subsequently, all of electric

Table 25

Average Total Factor Productivity Growth

(%)

Company & Periods	$\dot{TFP}$	$-S_T$	$-S_U*\dot{U}$	$SCE*\dot{Y}$
(1) Tokyo				
1965-1970	1.7247	0.576	0.9589	0.1894
1971-1976	-0.701	0.594	-1.428	0.1331
1977-1982	-0.017	0.310	-0.372	0.0443
1983-1988	0.3872	-0.3001	0.4935	0.1938
(2) Kansai				
1965-1970	0.8363	0.429	0.2782	0.1281
1971-1976	-0.121	0.496	-0.705	0.0881
1977-1982	-0.038	0.193	-0.231	-0.0008
1983-1988	0.22	-0.7389	0.7607	0.1982
(3) Chubu				
1965-1970	2.6194	0.311	2.1879	0.1198
1971-1976	-0.766	0.432	-1.36	0.1614
1977-1982	0.2977	0.319	-0.083	0.0625
1983-1988	-0.001	-0.1272	-0.081	0.2076

Note: TFP = Total Factor Productivity
S_T = Rate of Technological Change
S_U = Cost Elasticity of Capacity Factor
SCE = Scale Economies
U = Capacity Factor
Y = Output generated

Table 25 (Continued)

Average Total Factor Productivity Growth

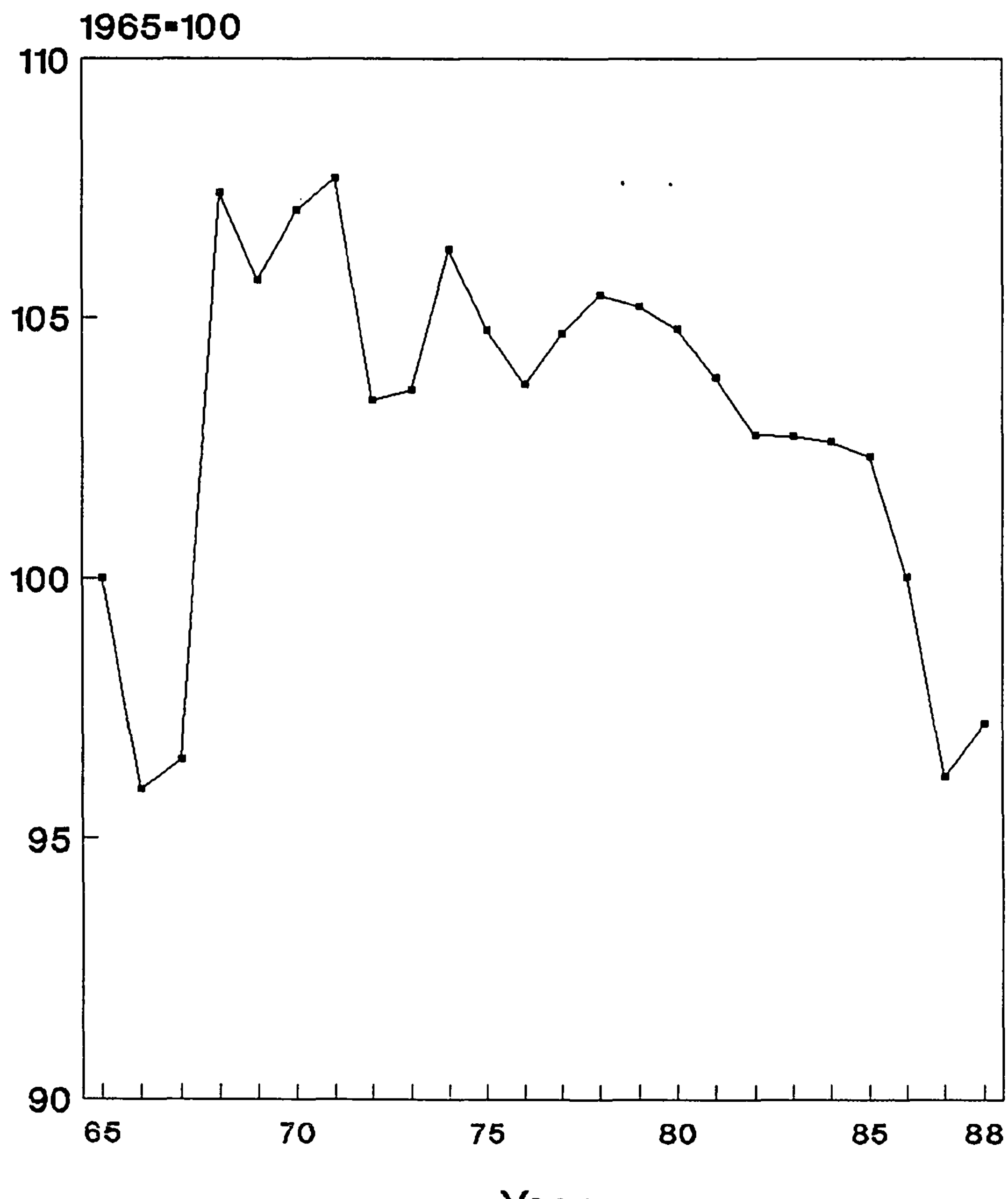
Company & Periods	$\dot{TFP}$	$-S_T$	$-S_U*\dot{U}$	$SCE*\dot{Y}$
(4) Kyushuu				
1965-1970	1.8558	0.319	1.3742	0.1621
1971-1976	-0.890	0.250	-1.341	0.2006
1977-1982	-0.618	-0.0839	-0.590	0.0556
1983-1988	-0.787	-0.9881	0.0922	0.1080
(5) Tohoku				
1965-1970	3.0115	0.226	2.4927	0.2923
1971-1976	-1.465	0.298	-0.1957	0.1936
1977-1982	-0.319	0.068	-0.466	0.0777
1983-1988	-1.083	-0.6504	-0.491	0.0580
(6) Chugoku				
1965-1970	1.5960	0.077	1.4940	0.0240
1971-1976	1.1291	0.287	0.4776	0.3639
1977-1982	-0.256	-0.003	-0.307	0.0543
1983-1988	-0.776	-0.8158	-0.041	0.0807

Table 25 (Continued)

Total Factor Productivity Growth

Company & Periods	$\overset{\circ}{TFP}$	$-S_T$	$-S_U*\overset{\circ}{U}$	$SCE*\overset{\circ}{Y}$
(7) Shikoku				
1965-1970	0.7798	-0.0303	0.5766	0.235
1971-1976	-1.575	-0.0235	-1.822	0.2708
1977-1982	-1.1164	-0.4057	-0.687	-0.070
1983-1988	-0.294	-0.96	0.5693	0.1005
(8) Hokkaido				
1965-1970	4.1807	-0.2377	4.35	0.06
1971-1976	-0.252	0.123	-0.585	0.2095
1977-1982	-0.759	-0.2275	-0.856	0.3243
1983-1988	-1.687	-0.9779	-0.833	0.1243
(9) Hokuriku				
1965-1970	0.7975	-0.1216	0.8044	0.1147
1971-1976	-1.114	-0.1164	-1.229	0.2313
1977-1982	-0.807	-0.3726	-0.414	-0.02
1983-1988	-3.442	-1.2196	-2.218	-0.005

Figure 9. Total Factor Productivity (1965-1988)



Note: Average Total Factor Productivity Growth of 9 Electric Utilities.

utilities registered a decline in productivity. Equation 3.36 indicates how each factor gives rise to fluctuation in productivity. Namely, the rate of total factor productivity growth is affected by the magnitude of technological change, the extent of scale economies, the rate of output growth, the extent of capacity factor effect and the rate of change in capacity factor. In turn, each contributing factor is determined by various factors as defined by equations 3.16, 3.20 and 3.23.

It is apparent that the capacity factor was a dominant force in determining total factor productivity growth before the period 1983-1988. Yet, technological change has been increasing in importance in overall total factor productivity growth while the magnitude of capacity factor effect has been decreasing over the years. Moreover, the rate of technological change has been continuously declining over the years. As a result, a large part of the negative total factor productivity growth during the period 1983-1988 was attributable to technological change. Scale economies were a continuously positive contributing factor to total productivity growth over the years. The magnitude of scale effect is, however, not as much as that of other contributing factors. Therefore, it can be said that scale economies played a relatively small role in productivity improvement. This result may not be consistent with the oft-cited arguments regarding advantages of larger scale of generating units or plants (Nerlove, 1963). However, scale economies in this study are at the firm level where the thermal power sector is composed of various generating plants or units in terms of the role of meeting demand and vintage. Hence, scale economies may not be as important at the level of plants or units. The results of similar studies in Japan and the U.S. are also consistent with our results although direct comparisons may not be meaningful due to differences of the model specification and background of the industry (Awata, Ito and Nakanishi, 1987; Shinjou and Kitasaka, 1989; Nelson and Wohar, 1983; Baltagi and Griffin, 1988).

CHAPTER V

POLICY IMPLICATIONS

1. Japan's Electric Future: Overall Policy Direction

Electrification of Japan has been occurring at a rapid rate in recent years. This trend is expected to continue in the foreseeable future. Therefore, it is very important that the electric utilities generate, transmit and distribute as efficiently and cleanly as possible.

The current installed generating capacity of the electric power industry is approximately 160,000MW. By the year 2010, about 100,000MW will need to be installed additionally to meet growing electricity demand. This is not going to be easy, since it has recently become extremely difficult for electric utilities to find sites for new facilities because of growing public opposition. Public policies therefore call for balancing social requirements with the stable and economical supply of electricity and people's concerns for environmental degradation.

For securing electricity supply at reasonable costs, current regulatory systems governing the Japanese electric power industry appear to be outmoded. Despite the fact that there are many potentially able wholesale generators that could construct and operate power plants at least as efficiently as the electric utilities, current laws basically inhibit those from entering the wholesale market for power. Costly regulation inhibiting the more efficient generating sector must be removed.

Introduction of competition into the generating sector by enactment of the Public Utility Regulatory Policies Act in the U.S. also indicates some benefits for improving efficiency of the generating sector in Japan. The experience in the U.S. electric power industry tells us that traditional electric utilities are not always as competitive as non-utilities such as qualifying facilities and independent power producers. Furthermore, those generating entities seem to be not less reliable than the electric utilities suggest. In the U.S. electric power industry, the generation sector is no longer a natural monopoly.

Meanwhile, it will be necessary to reinforce demand side management to alleviate environmental concerns. Conservative electric utilities are reluctant to promote demand side management in that the effectiveness of that policy is uncertain, which may result in the reduction of revenues. However, to maintain environmental soundness along with meeting electricity requirements, supply and demand options must be examined on equal ground. Moreover, there exists a policy measure to reduce electricity demand in a manner that reduction of electricity consumption does not require sacrifices by providing incentives to both electric utilities and consumers as the State of California has already adopted (California Energy Commission, 1990).

In view of challenges facing the Japanese electric power industry and the recent experience in the U.S. market for power, the received wisdom that in a defined service territory only one electric power company should be allowed to generate electricity for sale, will not ensure an efficient electricity supply. We will need to increase both the supply and demand side options to meet growing electricity demand, which will bring about more flexible, adequate, economical and environmentally sound electricity supply systems.

2. Policy Implications

Scale Economies

The results of this study indicate that scale economies have existed over the years. The extent of scale economies is, however, very small, which means that scale economies played a relatively small role in productivity growth in the past. This result may be inconsistent with the argument that the electric power industry can enjoy economies of scale if it constructs large scale power plants. However, as indicated in the previous chapter, the actual level of scale economies in the thermal power generation sector is influenced by many factors. Economies of scale derived from the construction of large-scale power plants, therefore, do not necessarily improve the overall level of scale economies in the thermal power sector. Accordingly, mere emphasis on the scale of power plants will not be a legitimate policy to improve efficiency of the thermal power generation sector.

In addition, an important policy implication derived from the results is concerned with the fact that the extent of scale economies, as a contributing factor to total factor productivity, is subject to both the level of scale economies and the rate of output. Consequently, the rate of growth in total factor productivity would be reduced if policy makers adopt the policy of promoting conservation which certainly decreases the growth of output generated.

Another important policy issue involving scale economies is one related to the industry structure. It seems that most studies regarding scale economies in the electric power industry were motivated by dissatisfaction with the performance of traditional electric utilities which are vertically integrated and granted legal monopoly status in the defined territory. These studies tend to suggest reorganization of the industry structure based on minimum efficient firm size derived from parameter estimates of scale economies. However, this study is only concerned with the thermal power generation sector which is one of the generating power sources in the overall generation mix.

Whether economies of scale exist or not cannot lead directly to the policy conclusion such as the consolidation of relatively small electric utilities or disintegration of large electric utilities. Scale economies constitute only one factor among many in evaluating the appropriateness of the industry structure.

Technological Change

Econometric results from this study confirm a declining rates of technological change over the years. This may be primarily due to inherent limits of conventional fossil-fueled steam generating systems: We cannot definitely conclude, though, that lack of improvements in thermal efficiency is a major cause of declining rates of technological change because the time variable does not explicitly represent any specific attributes of technological progress. However, considering the engineering status and the perspective of thermal power generation technologies, it appears that the rate of technological change will be deteriorating further so long as we continue to depend on the conventional type of fossil-fueled steam generating system.

There are some new systems which could raise generation efficiency. One in the short-term would be a combined cycle generation system. In the long-term, new technologies such as the "high efficiency gas turbine combined cycle system" could raise thermal efficiency considerably. These high-efficiency generating systems will also contribute to a reduced burden to the environment. Yet, the thermal generating sector is comprised of many vintages. Therefore, it would take a long period to replace old thermal power plants with new technologies even if the efficient new technologies become available commercially. Accordingly, it is necessary in resource planning to take into consideration limitations of thermal power generation technologies even if we have to rely on these technologies in the foreseeable future.

Capacity Factor

The empirical results show that the capacity factor plays a critical role in determining overall productivity growth. Therefore, an obvious policy suggestion would be to improve capacity factor. However, there is as yet no promising development which may improve the level of the capacity factor.

Effects of capacity factor on total costs are determined by the level of capacity factor, output rate, technological change and input prices. Among other things, the level of capacity factor is critical. Yet, the role of thermal power generation as the base-load generating facility is expected to decrease because the share of nuclear power in the electricity generation mix is planned to increase further. If so, the overall capacity factor may be constant or even decreasing, assuming a decline in load factor, which implies sacrifices of efficiency in thermal power generation even if flexible technologies such as load-following were fully developed. Therefore, the question naturally arises as to whether efficiency gain derived from increasing the share of nuclear power could more than offset efficiency loss in the thermal power generation sector due to the low capacity factor. If nuclear energy is the most economical, safe and stable source of power, as policy makers insist, then nuclear energy should play a much larger role as in France where it accounts for approximately 70% of electricity generation. This issue is beyond the scope of this study, but it must be addressed in making policies regarding the choice of electric power sources.

Elasticity of Substitution

A possibility of substitution is a very important element to assure a stable supply of electricity. If the elasticity of substitution is low, reduction in some input availability will have a significant effect on total generation costs. If the elasticity of substitution is high, reduction in some input availability will be less damaging to the electric power utilities. Hence, on the occasion of an external shock such as the oil crisis, the possibility of substitution between capital and fuel or interfuel substitution enhances flexibility of the electric utilities. In this connection, the current crisis in the Persian Gulf will not affect the Japanese electric utilities as much as the oil crises in the past did. The price of fuel oils in international oil markets and the foreign exchange rates are very stable at this time. Moreover, the Japanese electric utilities have been recently importing most of the crude oils (approximately 95%) used for power generation from Indonesia and China (Denkijigyou Shingikai Jukyuu Bukai, 1990).

As noted in the previous chapter, however, the possibility of substitution is very limited in the short-term once the configuration of the power plant is fixed. Interfuel substitution is technically possible in the short-term, but the prices of alternative fuels such as LNG are generally pegged to the price of fuel oils. Therefore, interfuel substitution cannot mitigate the oil price shock by switching to other fuels.

The study results show that capital-labor and capital-fuel are substitutable, which should be interpreted as the elasticity of substitution in the long-term. In the long-term, capital stock such as turbo-generators can be replaced with more efficient capital requiring less fuel and labor if such capital becomes available commercially. But, the possibility of further substitution hinges on technological progress which allows substitution between capital-fuel and capital-labor in the thermal power generation sector. Therefore, it is more important as to how technological progress is brought about in electricity generation.

Total Factor Productivity

The study results show that all electric power utilities experienced declining productivity improvements after the subperiod 1965-1970. The study also shows that many factors affect the rate of total factor productivity growth. The rate of total factor productivity is affected by the extent of scale economies, the rate of output, the rate of technological change, the level of capacity factor and the rate of change in capacity factor. In turn, each contributing factor is determined by various factors as defined by the respective equations.

It is apparent that the capacity factor was a dominant force in determining total factor productivity growth before the period 1983-1988. Yet, technological change has been increasing in importance in overall total factor productivity growth while the magnitude of the capacity factor effect has been decreasing over the years. This is in spite of the fact that the rate of technological change has been continuously declining over the years.

Scale economies have been a continuously positive contributing factor to total productivity growth over the years. The magnitude of scale effect is, however, not as much as that of other contributing factors. Therefore, it may be concluded that scale economies played a relatively small role in productivity improvement. This result may not be consistent with oft-cited arguments regarding advantages of larger scale of plants (Nerlove, 1963). However, scale economies in this study are at the firm level where the thermal power sector is composed of various generating plants or units in terms of the role of meeting demand and vintage. Hence, scale economies may not be as important at the level of plants or units. Overall, total factor productivity may therefore deteriorate further since every factor which may affect total factor productivity growth is not expected to improve.

Overall Assessment

The study results indicate that the outlook for the thermal power generation sector is dim. No promising measure to improve efficiency of the thermal power generation sector exists. Since the electric utilities will continue to rely on the thermal power generation technologies in the foreseeable future, the performance of the electric utilities will probably deteriorate further.

In contrary to the Japanese economy which has increased its flexibility to external shocks, the electric utility has been and continues to be vulnerable to external shocks as long as a large part of electricity is generated by thermal power generating facilities owned by the electric utilities. This is evidenced by the fact that the revisions of electricity rates were implemented whenever the price of fuel oils fluctuated. Although the Japanese electric utilities have succeeded in achieving the diversification of power sources from the viewpoint of securing the quantity of fuels used for power generation, they are still vulnerable to oil price shocks.

The findings in this study regarding the thermal power technology, therefore, suggest the need to develop much broader policy options. A reexamination of the institutional structure, such as regulatory systems prohibiting the entry of potentially able wholesale generators into the wholesale market for power, is needed to increase the flexibility of the generating sector and improve the overall performance of the Japanese electric power industry.

CHAPTER VI

SUMMARY AND CONCLUSIONS

1. Summary

This study has examined the extent of scale economies, the rate of technological change, effects of capacity factor, elasticity of substitution and total factor productivity for thermal power generation of nine Japanese electric power companies during 1964-1988. Estimation models used were the translog cost function and cost share equations. Variables incorporated in the model were time representing technological change and average capacity factor in addition to three input prices, service price of capital, price of fuel per calorific value and annual wage per unit of labor. The estimation procedure was Iterative Zellner's Seemingly Unrelated Regression with restrictions implied by homogeneity in input prices and symmetry conditions. The model was acceptable in terms of regularity conditions. Test statistics, based upon likelihood tests, rejected hypotheses of homotheticity, homogeneity, no technological change and no capacity factor effects.

Principal findings of this study are as follows:

Scale Economies

(1) The study confirmed the existence of economies of scale over the sample period. The extent of scale economies was in the range of 0.003 to 0.05, which means that 1% increase in output led to an increase in total costs in the range of slightly less than 1% and 0.95%.

(2) Average scale economies in 1964-70 were less than those in the subsequent four periods. Moreover, scale economies for most electric utilities have been increasing in 1964-1988.

(3) Estimated parameters showed that increases in the prices of capital and fuel reduced scale economies, whereas higher labor prices increased them.

(4) Technological change and capacity factor are found to be positively related to scale elasticity, viz. any increase in these variables would lead to higher scale economies.

Technological change

(1) The rate of technological improvement clearly declined after the period 1971-1975. In fact, all companies on average recorded the negative rate of technological change during 1986-1988.

(2) The rates of technological change for larger companies were found to be higher than for smaller companies.

(3) Biased technological change was found to be capital-using, labor-saving and fuel-using. Meanwhile, pure technological change, including neutral technological change, did not contribute to the reduction of generation costs.

(4) Combined net effects of relative price changes on the rate of technological change reduced the magnitude of slowdown in the rate of technological change during higher fuel prices.

<u>**Capacity Factor**</u>

(1) Increases in the rate of capacity factor were consistently found to be a contributing factor in reducing generation costs.

(2) Increase in the rate of capacity factor by one percent would lead to a reduction in total costs in the range of 0.20 percent to 0.65 percent.

(3) The rate of cost reduction resulting from changes in capacity factor showed a steady decrease during 1964-1980.

(4) Combined net effects from relative price changes slowed down the effect of capacity factor on generation costs after the oil crisis.

Elasticity of Substitution

(1) The results show that capital-labor and capital-fuel are substitutes, while fuel-labor is a complement.

Total Factor Productivity

(1) The capacity factor was a dominant determinant of total factor productivity growth before 1983-1988. All electric utilities recorded a decline in total factor productivity growth after the period 1965-1970.

(2) The importance of technological change in total factor productivity growth has recently increased.

(3) Scale economies were a positive contributing factor to total factor productivity growth over the years.

(4) The magnitude of scale economies was not as large as that of other contributing factors.

The above empirical results suggest several policy implications.

1. The level of economies of scale in the actual operation of thermal power plants suggests that primary emphasis on the scale of power plants is not justified.

2. As far as the government and electric utilities give priority to nuclear power generation, total factor productivity in thermal power generation is expected to

decline further due to low capacity factor caused by the fixed role of thermal power plants in overall generation mix and a decline in load factor.

3. The rate of technological improvement in the thermal power sector has been declining. In light of the engineering status of thermal power generation and the outlook for thermal power generation technologies, the rate of technological change will continue to decline.

4. Total factor productivity growth is affected by both the level of scale economies and the rate of output. Hence, conservation on the demand side may sacrifice efficiency in the thermal power sector.

5. Overall, total factor productivity will possibly decline further because of no promising developments to improve it.

2. Conclusions

The above results indicate that the outlook for thermal power generation is not bright in terms of efficiency improvements. Nonetheless, the thermal power generation sector must continue to play a major role to meet Japan's growing electricity demand. This is due to the fact that it is not possible to replace the thermal power generation technologies with other conventional electric generating technologies such as nuclear power and hydro power due to various constraints. The study results, thus, suggest the need to consider much broader policy options.

Development of technologies fueled by renewable energies, such as fuel cells, one such option. The problem is that there does not exist the appropriate institution to facilitate the use of these energy sources. The electric utilities are basically reluctant to rely on these sources. Therefore, it may be necessary to enact a law which forces the electric utilities to make use of renewable energy sources or purchase electricity generated by such technologies as the Public Utility Regulatory Policies Act mandates the U.S. electric utilities.

Another policy option is to remove regulatory barriers which prevent a third party from entering the wholesale market for power. Self-generators at present account for about 10% of the total installed capacity and the total output generated. If the barriers are removed, these generators could sell surplus output generated to the electric utilities, with the potential of constructing and operating power plants more economically in order to be competitive in the wholesale market.

Demand side management should also be explored. Traditional management tends to emphasize the need to secure supply capability, given projected electricity demand. However, from the standpoint of least cost planning, cost-effective demand reduction may be competitive with supply addition, which leads to saving scarce resources including energy resources. Load management may be expected to improve load factor which in turn may increase the capacity factor.

The foregoing options correspond to the overall policy direction for the Japanese electric power industry. In other words, there is a need to increase both the supply and demand options to revamp the Japanese electric power industry.

Further Research

Regarding future research, two directions are suggested. One is related to improvements of the specification of the model. In this study, the variable concerned with environmental regulation is not incorporated. Yet, Japanese environmental regulation, which the electric utilities must comply with, is one of the most stringent in the world. Therefore, a model incorporating some variables representing environmental regulations would improve the analysis.

The other need for improvement relates to the scope of the study. In this study, we analyzed the thermal power generation sector. In order to provide a more comprehensive evaluation of the performance of the electric utilities, however, analysis of other sectors such as the transmission sector and the vertically-integrated system is needed. Also, the recently increasing share of transmission costs to total costs of electricity service to end-users is of particular interest in terms of evaluating the industry structure.

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