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Contrasting Catching-up Histories of the Korean and the Japanese

Heavy Electrical Industries in the 1970s-2000s

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degree of Doctor of Philosophy**

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Abstract

The thesis is motivated by contrasting catching-up performances of the Korean heavy electrical industry (HEI) across nuclear power and gas turbine, which have serious ramifications for energy policy as well as catching-up studies. When the opposite performance of Japanese counterparts across the two technologies is compared to the Korean case, the existing catching-up literature based on firm capabilities and sectoral approaches does not offer direct answers. Also, while most of government energy policies are focused on research and development (R&D) efforts, they pay little attention to a wide set of institutions, which might constrain and incentivise a specific technology catching-up.

The idiosyncratic catching-up experiences and potential mismatch between catching-up policies and the institutional factors of the Korean HEI urge comparative and institutional perspectives for a generalisable claim. Therefore, the thesis adopts a partial comparative case study between the Korean HEI and the 'earlier' latecomer, namely Japanese HEI, as a reference case with mostly secondary evidences based on a broad version of national system of innovation system (NSI) approach (Freeman 1987; Lundvall 1988; Lundvall et al., 2002). The adopted NSI framework assumes a potential dichotomy of cross-technology and cross-nation performance attributes to contrasting institutional set-ups. It focusses on two salient institutions of the electricity supply industry (ESI), including business and environmental regulations, and their impact on the catching-up performances across the two technologies.

It finds historically evolved ESI-HEI relationships based on the specific institutional set of ESI substantially influenced the dichotomy of cross-nation and cross-technology catching-up performances, regardless of R&D expenditures and relative technological capabilities of HEI firms. The result supplements the NSI literature by linking the variation of a set of institutions with catching-up performance variations. It also offers strategic implications to catching-up countries, such as the potential necessity for institutional reforms of the ESI in pursuing energy technology catching-up policies.

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List of Acronyms

Acronyms	Name
A&E	Architecture and engineering
ABB	ASEA Brown Boveri
ABWR	Advanced Boiling Water Reactor
ACC	Active clearance control
AEC	Atomic Energy Commission
AF	Air-to-fuel
AKC	Aluminium of Korea Co.
ALWR	Advanced Light Water Reactor
AP1000	Advanced Passive 1000
APR+	Advanced Power Reactor Plus
APR1400	Advanced Power Reactor 1400
APWR	Advanced Pressurised Water Reactor
ATS	Advanced Turbine System
B&W	Babcock & Wilcox
BMI	Basic metal industries
BOF	Basic Oxygen Furnace
BOJ	Bank of Japan
BWR	Boiling water reactor
CAA	Clean Air Act
CAD	Computer aided design
CANDU	Canada Deuterium Uranium Reactor
CC	Conventional cast
CCGT	Combined-cycle gas turbine
CDF	Core Damage Frequency
CDMA	Code Division Multiple Access
CE	Combustion Engineering
CF	Capacity factor
CFHI	China First Heavy Industries
CHP	Combined heat and power plants
CPUC	California Public Utility Commission
CRDM	Control rod drive mechanism
CRIEPI	Central Research Institute of Electric Power Industry
DHIC	Doosan Heavy Industries & Construction
DLNC	Dry low-NO _x combustor
DRAM	Dynamic Random-Access Memory
DS	Directionally solidified
DSS	Daily start and stop
EAF	Electric arc furnace
EC	European Commission
EDF	Électricité de France S.A.

EIA	Energy Information Administration
EPB	Economic Planning Board
EPR	European Pressurized Reactor
EPRI	Electric Power Research Institute
ESBWR	Economic Simplified Boiling Water Reactor
ESECA	Energy Supply and Environmental Coordination Act
ESI	Electricity supply industry
EXIM	Export-Import Bank
FDI	Foreign Direct Investment
FEPC	Federation of Electric Power Corporations
FGD	Flue gas desulphurisation
FIDC	Foreign Investment Deliberation Council
FIL	Foreign Investment Law
FOAK	First-of-a-kind
FSU	Former Soviet Union
FUA	Power Plant and Industrial Fuel Use Act
GATT	General Agreement on Tariffs and Trade
GCR	Gas Cooled Reactor
GEAE	GE Aircraft Engines
GECRD	GE Corporate Research & Development
GENCO	Generation companies
HCI	Heavy and chemical industries
HCO	Hydraulic clearance optimisation
HEI	Heavy electrical industry
HHI	Hyundai Heavy Industries
HII	Hyundai International Inc. (Predecessor of KHIC)
HPC	High-pressure compressor
HPT	High-pressure turbine
HRSG	Heat recovery steam generator
HVDC	High voltage direct current
IAEA	International Atomic Energy Agency
ICC	Ishikawajima-Harima Casting Company
IEA	International Energy Agency
IGA	Inter-granular attacks
IGCC	Integrated Gasification Combined Cycle
IGSCC	Inter-granular stress corrosion crack
IHI	Ishikawajima-Harima Heavy Industries
IMF	International Monetary Fund
IPP	Independent power producer
IPR	Intellectual property right
ISIC	International Standard Industrial Classification
JAIF	Japan Atomic Industrial Forum
JDB	Japan Development Bank
JINED	International Nuclear Energy Development of Japan

JPUC	Japan Public Utility Commission
JSIC	Japan Standard Industrial Classification
JSME	Japan Society of Mechanical Engineers
KAC	Korea Aluminium Company (Predecessor of AKC)
KAERI	Korea Atomic Energy Research Institute
KAIST	Korea Advanced Institute of Science & Technology
KDB	Korean Development Bank
KEPCO	Korea Electric Power Company
KEPRI	Korea Electric Power Research Institute
KFP	Korea Fighter Project
KHI	Kawasaki Heavy Industries
KHIC	Korea Heavy Industries & Construction (Predecessor of Doosan, DHIC)
KHNP	Korea Hydro and Nuclear Power
KIST	Korean Institute of Science & Technology
KLW	Korea Lost Wax
KNF	KEPCO Nuclear Fuel
KNGR	Korea Next Generation Reactor
KOGAS	Korea Gas
KOPEC	Korea Power Engineering Company (Changed to KEPCO E&C in 2010)
KPS	KEPCO Plant Service & Engineering
KSIC	Korea Standard Industrial Classification
KSNP	Korean Standard Nuclear Power
LA	Licence agreement
LNG	Liquefied natural gas
LOCA	Loss of Coolant Accident
LPC	Low-pressure compressor
LPT	Low-pressure turbine
LTSC	Long-term service contract
LWR	Light Water Reactor
MAPI	Mitsubishi Atomic Power Inc.
ME	Ministry of Environment
MER	Ministry of Energy & Resources (Predecessor of MOTIE)
METI	Ministry of Economy, Trade and Industry (Predecessor of METI)
MHI	Mitsubishi Heavy Industries
MHPS	Mitsubishi Hitachi Power System
MITI	Ministry of Trade Industry
MMIS	Man-machine interface system
MOTIE	Ministry of Trade, Industry, and Energy
MTU	Motoren Turbinen Union
NASA	National Aeronautics and Space Administration
NIS	National Innovation System
NISA	Nuclear and Industrial Safety Agency (Predecessor of NRA)
NISTEP	National Institute of Science and Technology Policy
NRA	Nuclear Regulation Authority

NRC	National Research Council
NRIM	National Research Institute of Metals
NSI	National System of Innovation
NSSMC	Nippon Steel & Sumitomo Metal Co.
NSSS	Nuclear steam supply system
OEM	Original equipment manufacturer
OPR1000	Optimized Power Reactor 1000
P&W	Pratt & Whitney
PCC	Precision Castparts Corporation
PG&E	Public Gas and Electricity
PHWR	Pressurised heavy water reactors
POSCO	Pohang Iron & Steel Corporation, Ltd.
PUC	Public Utility Commission
PURPA	Public Utility Regulatory Policy Act
PWR	Pressurised water reactors
PWSCC	Primary water stress corrosion cracking
RCP	Reactor coolant pump
RFB	Reconstruction Finance Bank
RSG	Replacement steam generators
S&L	Surgent and Lundy
SBWR	Simplified Boiling Water Reactor
SC	Single crystal
SCAP	Supreme Commander for Allied Power
SCAQMD	South Coast Air Quality Management District
SCC	Stress corrosion cracking
SCE	Southern California Edison
SCR	Selective catalytic reduction
SGTR	Steam generator tube rupture
SONG	San Onofre Nuclear Generating
SSI	Sectoral system of innovation
STA	Science and Technology Agency
TBC	Thermal barrier coating
TCA	Technology Cooperation Agreement
TEPCO	Tokyo Electric Power Co.
TIT	Turbine inlet temperature
TMI	Three Mile Island
TOU	Time-of-Use
UAE	United Arab Emirates
US DOD	US Department of Defense
US DOE	US Department of Energy
US EPA	US Environmental Protection Agency
US NRC	US Nuclear Regulatory Commission
VIM	Vacuum induction melting
VVER	<i>Vodo-Vodyanoi Energetichesky Reactor</i>

WASP	Wien Automated System Planning Package
WTO	World Trade Organisation

Technical Notes and Disambiguation

BOF: Although Basic Oxygen Furnace (BOF) is only part of Integrated Steel Mill, which also has a blast furnace (BF), BOF is used as a synonym for Integrated Steel Mill in the thesis in order to emphasise its different characteristics from that of electric arc furnace (EAF) that depends entirely on electricity for its thermal energy.

KEPCO: Both the Korean Electricity Power Co. and the Kansai Electricity Power Co. of Japan use the same abbreviation, KEPCO. In order to avoid confusion, the thesis deliberately uses KEPCO for the Korean utility while terms Japanese utilities “Kansai Power” or “Tokyo Power”.

MHI: Although thermal power plant divisions, excluding nuclear power, of Mitsubishi Heavy Industries and Hitachi were merged to Mitsubishi Hitachi Power System (MHPS) in 2014, the thesis uses the term MHI instead of MHPS in order to avoid confusion and maintain consistency. Also, Mitsubishi’s relative capability compared to that of Hitachi is pronounced in CCGT technologies.

NIS and NSI: National Innovation System and National System of Innovation are often interchangeably used in the literature. This thesis also uses both interchangeably, according to the background references.

OEM: Often original equipment manufacturers (OEMs) are recognised as licensed manufacturers of catching-up countries in a few sectors such as electronics and semiconductors. However, the thesis uses the term for a literal original manufacturer, namely licensor rather than licensee, as widely used in the global HEI.

TOU: Electricity supply industries in numerous countries apply Time-of-Use (TOU) prices which impose different prices for electricity at different times of the day in

order to reduce peak load demand and shift the demand to off-peak period. This pricing scheme reduces the generation of peak load power technologies, such as pumped hydro and gas turbine, while increase generation of baseload power technologies, typically nuclear and coal power. The price scheme differentiates the peak-load price and the off-peak price reflecting the level of demand on the electricity network and marginal cost of power generation. Electricity supply industry in a few countries, such as Korea, differentiate the prices further than the differential of marginal cost of power generation between off-peak and peak-load periods.

Chapter 1. Introduction

1.1. Research Problem

1.1.1. Two Low-carbon Technologies in the face of Climate Change

As concerns about climate change grow and mitigation policies are urged upon international organisations and governments, the role of low-carbon technologies is becoming increasingly important in the global power plant market. Nuclear power and gas turbines, alongside renewable energy, represent low-carbon commercial electric power technologies in the world. In particular, the two technologies are the most practical large-scale options as direct substitutes for the existing ‘dirty’ coal power, which still covers the largest share of the existing global electric power supply capacity.

Interestingly, the two technologies contain contrasting economic and technological characteristics while competing directly in liberalised electricity markets, such as those of the UK and the US. Nuclear power requires upfront heavy capital investment with cheap fuel costs, whereas gas turbines require much less capital with relatively expensive fuel costs. Accordingly, the former needs government interventions, including special subsidies or public financing through public utilities, while the latter only needs project financing from private investors in liberalised energy markets. With the liberalisation trend of energy markets and a couple of major nuclear accidents, nuclear power’s global market share has diminished, while that of gas turbines has grown since the 1980s.

In a catching-up economy context, the two energy technologies have more complex ramifications. In terms of domestic energy security, catching-up economies are

under pressure to supply both cheap and low-carbon energy to their rapidly growing, energy-intensive manufacturing industries. In terms of technology development, on the other hand, catching-up countries tend to induce the demand for upstream suppliers through the indigenisation process of the two energy technologies, to enhance technological competence of overall manufacturing industries. Eventually, the latecomers aim to enter the global market of energy technologies once they localise the technologies.

1.1.2. Korea's Nuclear Catching-up Success in Question

Korea's relatively recent nuclear export contract with the United Arab Emirates (UAE) in 2009 surprised the global nuclear community, given that the global nuclear market has been dominated by only a few Western reactor original equipment manufacturers (OEMs), such as Westinghouse and AREVA, for the past half a century. Even Japan, the 'earlier latecomer' that had localised commercial nuclear reactors two decades earlier than Korea, could not export complete reactors, having exported only reactor-related component units of equipment. The Korean government and nuclear engineering community appraise Korea's nuclear export case as a catching-up success story, based on the country's science and technology policy or 'national innovation system'.

Stimulated by the Korean nuclear export case, Japanese reactor suppliers, utilities, and the government established an export consortium, and vigorously sought to export cases right after the Korea-UAE contract. Despite a disruption with the Fukushima nuclear accident in 2011, the Japanese consortium has continued to put the effort of nuclear export through the 2010s. It started from nuclear export agreements with Vietnam and India, but the agreements were eventually abandoned in the mid-2010s. Japanese reactor vendors, including Mitsubishi, Toshiba and Hitachi, attempted separately to export their reactors to Turkey and the UK, but two of them already abandoned the export project due to own financial problems and cost increase, respectively. Hitachi also spent several years for a negotiation with the UK government over financial support of its Wylfa

nuclear project. In this sense, Korea's nuclear export case apparently ignited global nuclear export competition in the past decade.

In effect, the competition is not limited by the two countries. Major developing economies such as China also aim to enter the global nuclear export market, while they are currently building large-capacity of nuclear reactors for their own electricity supply purpose and putting effort into indigenising reactor technologies. China's recent commitment to sharing the financial burden of the troubled 'Hinkley Point C' reactor construction project in the UK in exchange for guaranteeing China's direct involvement in the UK's uncertain future reactor projects indicates their aspiration to enter the global nuclear market. Considering that numerous catching-up economies are showing a propensity to follow Korea's industrial and technological development policies, the Korean nuclear story is worth examining.

It is questionable whether the Korean nuclear catching-up success could be a kind of 'model' for energy technology catching-up to other latecomer countries in two respects. First, the success of the Korean heavy electrical industry (HEI) is limited with regard to nuclear power, which has been diminishing in the global power plant market, while the Korean HEI has not caught-up with emerging technologies, such as combined-cycle gas turbine (CCGT) technology. Second, the Japanese HEI flourished in the domestic and global CCGT market from the mid-1980s, whereas it could not export nuclear reactors for more than three decades, even after it had localised commercial nuclear reactor technologies in the mid-1970s. The dichotomous performances of the two technologies across the two countries in the changing global power plant market raise the necessity for an in-depth analysis, rather than simplistic appraisals of a specific technology success story.

1.2. Aim of the Research

The research aims to shed light on the unquestioned dichotomous catching-up performances of nuclear power and gas turbines across Korea and Japan. The main purpose of the research is, therefore, finding the reasons for the dichotomous catching-up performances, and the political as well as theoretical implications. The research aims to answer the following tentative question:

Why is the Korean heavy electrical industry (HEI) unable to make a shift from its successful catch-up of nuclear technology to that of a globally emerging technology, namely gas turbines, while its Japanese counterpart, an ‘earlier’ latecomer, could do so?

The research has two sub-goals. First, it investigates the policy ramifications of the dichotomy. For instance, was there cross-nation or cross-technology differences in catching-up policies? Or, is the result attributable to their specific capabilities? The second research purpose relates to a theoretical aspect. For instance, to what extent can existing innovation system theories address the puzzling catching-up performances of the two competing technologies across the two countries? It is an important issue for catching-up studies, based on the innovation system theories, considering a well-known fact that both governments of Japan and Korea have been explicitly supporting catching-up of nuclear technology for several decades. Did the efficiency of their catching-up policies or other factors such as institutional structures make the difference?

1.3. Research Approach

1.3.1. Unit of Analysis

Considering the puzzling catching-up performances across the two technologies, the unit of analysis is crucial in improving the quality of the answers to the question. First,

it may be possible to find analyses of the HEI firms' technological capabilities through firm-level approaches. The cross-nation and cross-technology dichotomy, despite the cross-national differential of firm capabilities in terms of technological scope and depth, however, leads the thesis to look beyond firm-level factors.

Second, sectoral-level approaches could be a little better than firm-level approaches, in so far as factors and conditions beyond firms could be analysed. However, the HEI is typically susceptible to heavy-handed government interventions and highly dependent on the user sector, notably the electricity supply industry (ESI). These characteristics led the research to look beyond sectoral-level factors.

Third, national-level approaches might offer a better perspective in terms of the national policies and institutional set-up which shape the dichotomy. Amongst the national-level approaches, a narrow version approach focusses on the micro supporting system for effective coordination between high-technology or advanced science innovation actors, while a broad version approach pays attention to overall socioeconomic factors. The former version might be better suited to Western and advanced economy contexts, where socioeconomic institutions are generally well-established and enable researchers to focus on micro-networks between innovative actors. The research seeks explanations for the dichotomous performances from catching-up contexts which are quite different from those of Western economies and pursues the latter version in order to find differences in socioeconomic factors that can explain the dichotomy.

1.3.2. Catching-up Policies and Institutions

Amongst the various socioeconomic factors in a broad national approach, the thesis focusses on a few core industry policies and institutions which might promote and constrain specific technologies. Considering catching-up contexts, it regards catching-up policies and institutions as competing elements, rather than harmonised or well-established combinations.

In particular, the institutional characteristics of the two catching-up technologies in Japan and Korea are hardly addressed in catching-up studies. Although innovation system approaches such as the national innovation system (NSI) and sectoral system of innovation (SSI) emphasise institutional factors in explaining catching-up performances, their concerns are often either too broad, such as national education systems, or too narrow, such as supporting systems of research networks between firms, universities, and public institutions. Considering that the HEI technologies are heavily affected by growing concerns over environmental impacts and energy prices in numerous nations, the thesis focusses on institutions that govern the two major issues and their impact on catching-up performance.

1.3.3. Historical and Structural Analysis of Institutions

In analysing the institutional impacts of the two technologies in each country case, the thesis adopts a historical approach, in order to find the roots of institutions and their degree of constraining effect on the performance of each technology. As catching-up studies based on the NSI approach often show, the historical approach offers significant advantages when formal or *de jure* rules often confuse researchers and lead them to take institutional factors for granted, or mistakenly consider that institutional factors are identical in a cross-national comparative analysis.

For instance, historical events in the form of external or/and internal shocks to society can decisively shape institutional characteristics, which may be constraining the latecomers beyond nominal or codified rules in each case. Thus, the historical approach offers the research a greater chance to observe the core parts of relevant institutions in each local context. It leads to another advantage that the research could use for rearranging numerous and seemingly undifferentiated institutional factors in a hierarchical framework, given that the institutional factors are accumulated based on historical events and subsequent institutional changes. Through the structural perspective

on institutional factors, the thesis can observe and evaluate the competitiveness and limits of specific catching-up policies in a more systemic way.

1.4. Outline of Chapters

Chapter II: Literature Review and Research Framework compares and discusses several theoretical approaches, including political economy, firm capability, and the National System of Innovation and Sectoral System of Innovation approaches in analysing the specific characteristics of the catching-up HEI. It suggests a user-producer co-evolution framework based on a broad version of the national innovation system approach, to capture richer explanations of catching-up performances from their inter-sectoral relationships, with special attention to the impact of user-sector institutions.

Chapter III: Method outlines the research design and defends a qualitative comparative case study approach against competing quantitative methods, such as Input-Output Analysis, pointing out their limitations in capturing fine-grained inter-sectoral linkages.

Chapter IV: The Case of Korea finds that a set of institutions of the two sectors have been crucial in shaping the country's nuclear power success, while it discouraged gas turbines in the Korean case. By comparison and as a reference case, **Chapter V: The Case of Japan** finds that there has been the dichotomously opposite trend in the case of Japan.

Chapter VI: Comparison of the Cases and Discussions discusses the contrasting catching-up performances of the Korean and Japanese HEIs. The Chapter argues that contrasting the institutional set of ESI, and following interactions between the ESI and the HEI, confirm the efficacy of the research questions. It also discusses the limits of the thesis in explaining the user-supplier relationship and suggests future studies.

Chapter VII. Conclusion answers the research questions, and summaries the contributions of the thesis to knowledge in terms of the theoretical and policy implications of the empirical findings, the limitations and the implications for future research.

Appendix Chapter A. reviews the advanced nuclear and CCGT technology development programmes in the 1990s' US and how the Japanese and Korean latecomers exploited the benefits of the programmes to arrive in the current position in the global market. Although the main case chapters focus on the domestic factors of the latecomers' catching-up process before their commercial success, this Chapter provides the latest catching-up performances from the global perspective.

Appendix Chapter B. briefly addresses the potential and limits of the latecomers' aircraft engine capabilities in the global market context. It supplements the main argument of the case study by clarifying the possible ramifications of the aircraft engine capability to the CCGT catching-up performance.

1.5. Expected Contribution to Knowledge

The research finds a gap in the existing SSI approach, which focusses on the cross-national homogeneity of a sector or technology class and fills the gap through demonstrating how sectoral institutions of user explain the cross-national and cross-technology variation. In this way, the original contribution of the thesis is expected to supplement the scope of the National System of Innovation literature by linking the cross-national variation of the institutional sets with cross-technology catching-up variations.

In empirical terms, the research will have strategic implications to catching-up countries, such as the potential necessity of institutional reforms across related sectors, and the recognition of the trade-off between different technologies in competition within a sector in pursuing specific energy technology catching-up policies.

Chapter 2. Literature Review and Research Framework

2.1. Chapter Introduction

As raised in the Introduction Chapter, the thesis questions the background reasons for the puzzling catching-up performances of the Korean HEI over nuclear power and gas turbine technologies. In searching for answers to the question, the Chapter reviews literature that can better address the question of how and why the catching-up ability has varied so much between nuclear technology and gas turbines within the same sector of the HEI.

Section 2.2 reviews the empirical literature on HEI-specific cases, such as nuclear technology and gas turbines from global and catching-up points of view. The literature of HEI firms in advanced economies shows institutional changes in the electricity supply market induced substantial effects on the HEI firms' technology performance. It also finds that most of the HEI literature lacks attention to catching-up cases, while a handful HEI catching-up literature lacks an integrated view, including inter-sectoral relationships, related institutions, and compatibility with global opportunities, other than sectoral policies, such as public R&D projects of the two technologies.

Subsequently, **Section 2.3** reviews the literature on overall Korean catch-up experiences in other manufacturing industries in order to find the country-specific aspect of the HEI's unbalanced catching-up performances. The literature commonly raises 'catching-up shift dilemma' depicting the structural lock-in of the Korean manufacturing industries within specific technology and product categories and points out the lack of 'user-supplier' or 'producer-specialised supplier' linkages as immediate reasons.

Section 2.4 reviews the system of innovation literature, with special attention to the impact of the inter-sectoral relationship in explaining the dichotomous catching-up performances. It finds that a scope of the national innovation system literature is adequate

as a theoretical base for the thesis, in covering the overall impact of broad institutional factors and ‘user-producer’ linkages on the catching-up issues, rather than focusing on narrow science and technology development efforts. It finds strength and gaps in the firm capability literature, the institutional analysis literature and the literature of regulations and innovations in explaining the specific aspects of the HEI catching-up performances.

Finally, **Section 2.5** constructs a conceptual framework to capture the institutional effects of the user sector on catching-up performances and the user-supplier co-evolution. It employs the firm capability literature in the catching-up context, the institutional analysis literature and the literature of regulations and innovations in order to supplement the broad national innovation system approach.

2.2. Empirical Literature on the HEI

2.2.1. The Literature on HEI Firms in Advanced Countries

In this Section, the literature of the HEI in advanced economies is reviewed on technological stasis of incumbent HEI in the 1970s, and impact of institutional changes of the electric supply industry on the HEI in the 1980s and 90s and competition amongst advanced global HEI firms based on their technological capabilities. In addition, the literature on government’s explicit policy for technology innovation, such as public R&D, and their impact is also reviewed.

‘Stasis’ of Steam Turbine and Emergence of CCGT in the 1970s

Established technological, economic, institutional and social contexts surrounding the heavy electrical industry in the US and Europe began to change in the 1970s. HEI firms had enjoyed continuously growing fuel efficiency of power plants through adopting increasingly larger steam turbines and boilers in the case of coal power, steam turbines

and steam generators in the case of nuclear power, until the 1970s. Electricity supply industry (ESI) shared the benefit of the scale economy. In addition to the fuel efficiency, one large unit of a steam turbine, compared to several smaller units, would reduce accompanied management cost for the same electrical output (Hirsh, 1989; Rosenberg, 1998).

However, diminishing return on scale economy of steam turbines put both ESI and HEI in a difficult position from the 1970s. Although the maximum scale of steam turbines increased above 1,000MW, the large steam turbines' thermal efficiency stagnated below 40% and caused additional maintenance costs mainly due to metallurgical problems (Hirsh, 1989, 1999; Islas, 1997, 1999; Castillo, 2012).¹ Large steam turbine blades for coal and nuclear power were vulnerable to corrosion fatigue and stress corrosion cracking (SCC) and caused substantial costs for repair and maintenance as well as unexpected longer construction lead time (Hirsh, 1989; Barrientos, 2002; Jonas & Machemer, 2008). Although there are numerous large steam turbines above 1,000 MW operating as of 2018 globally, it took several decades for the industry to mitigate the reliability issue effectively. The 'scale-up' issue, in effect, is commonly found in various manufacturing industry sectors and require considerable development efforts in metallurgical, mechanical and dimensional materials properties (Sahal, 1985).

By comparison, gas turbine emerged from auxiliary technology for a niche market to a primary one in the form of a CCGT in the 1970s. CCGT technologies evolved from a small and single-cycle gas turbine for a niche market purpose, namely peak electricity demand, in the 1950s. From the low load-factor niche market, gas turbines gradually adapted to auxiliary part of combined cycle steam and gas turbines, to dominant part of the combined cycle in the contemporary electricity market (Islas, 1997, 1999). As the

¹ Also, as unit size of nuclear power increased, HEI firms and utilities experienced more complex process and much longer construction lead time with huge financial loss in the 1980s (see Hirsh, 1989 and Barrientos 2002 for details).

technology continuously improved, the fuel efficiency of CCGT started hovering around 50% in the mid-1980s (Islas, 1997, 1999; Castillo, 2012). The technological evolution has been accelerated by virtuous circle between development of larger and more efficient CCGTs and a serial development of new natural gas fields, such as those in Malaysia, Indonesia, Brunei, Australia, the Netherlands, the North Sea and North America as well as the Middle East in the 1970s and 80s (Jeffs, 2008).

Institutional Turbulence in the 1970s and 80s

The technological shift from the 'stasis' of large steam turbines to rise of CCGT in the HEI sector was not a smooth and straightforward process. Global HEI faced unprecedented institutional changes in their user sector, namely ESI, in the 1970s' US. The most substantial changes were the Clean Air Act (CAA) of 1970, Power Plant and Industrial Fuel Use Act (FUA) of 1978, and the Public Utility Regulatory Policy Act (PURPA) of 1978. The conflicting interests and prospects on future energy security and environmental issues generated institutional mismatch which hampered overall innovation efforts of HEI for a decade.

Although the CAA of 1970 did not set stringent emission standards compared to other countries such as Japan or later Germany, public interventions during construction and operation processes of coal power plants increased after the legislation. Meanwhile, the Arab oil embargo in 1973 induced an opposite political action, namely the Energy Supply and Environmental Coordination Act of 1974 by the US Congress. The emergency act restricted oil and natural gas use for power generation and promoted coal and nuclear power, on the one hand, interrupted regulatory pressure of the CAA on coal power on the other. FUA of 1978 succeeded the main logic of the temporary act. The US government also legislated a regulatory change to promote energy efficiency of the US electricity market in 1978, namely PURPA. It guaranteed much smaller, non-utility owned, and alternative technologies, such as combined heat and power plants (CHP) and renewables, purchase by vertically integrated utilities at a fair price. The unintended consequence of

PURPA was an erosion of the monopoly status of incumbent electric utilities by independent power producers (Hirsh, 1989, 1999; Winskel, 2002).

The series of conflicting legislations derailed a path of technology change of the American HEI for a decade. CCGT market was virtually shut down while only coal power capacity expanded with limited improvement in emission control technologies in the late 1970s and 1980s (Unger & Herzog 1998; Winskel, 2002). Electric utilities avoided nuclear power despite government's promotion due to enhanced safety regulation, lengthy construction lead time, and expensive retrofitting costs of reactors under construction after Three Mile Island nuclear accident in 1979 (Winskel, 2002; Berthélemy, 2012). The utilities cancelled 93 nuclear reactors under construction or planned between 1974 and 1985, in effect (Williams & Larson, 1988). Depressed demand growth of the US electricity market also added pressure on the HEI firms.

Their European counterparts experienced a similar institutional change. European Commission (EC)'s 'Directive on the use of natural gas in power station' in 1975 shut down CCGT market and put European OEMs, such as ASEA, Brown Boveri, and Siemens, in a difficult position. The restriction on natural gas for power generation continued more than a decade and was abolished in 1990. Although nuclear power was promoted as an alternative to oil and natural gas in the EC member countries, the nuclear market situation was not that much different from the US market. France and the UK could order a few more reactors even after the TMI accident, but they could not sustain new orders anymore afterwards, at least for two decades.

In the UK, political and institutional response to the turbulent 1970s and 80s was more intense than that of US counterpart. The UK government's Energy Act of 1975 implemented the European directive restricting natural gas use for power generation. Incumbent state-owned energy monopolies, including Central Electricity Generation Board, British Gas Corporation, Atomic Energy Authority and the UK government, concerned for energy security and protecting domestic HEI firms. The alliance's scheme

to the Arab oil embargo was to promote nuclear and coal power plants while the prohibited entrance of CCGT or CHP using natural gas into the British electricity market. The preference for nuclear power and coal over CCGT by the incumbents continued even during the privatisation process of electricity and gas industries in the 1980s (Winskel, 2002; Castillo, 2012).

Institutional 'Fixing' in the late 1980s and Effects

The restrictions of natural gas use for power plants across the Atlantic were withdrawn in the late 1980s as the initial misinformation about natural gas reserves were cleared with a series of new natural gas field development around the globe. The FUA in the US and the European Directive were withdrawn in 1987 and 1990, respectively. Once the restrictions were cleared, the global OEMs rapidly returned to CCGT market in the late 1980s. The UK government also revoked the restriction on natural gas for power generation to promote competition in the electricity supply market in 1988 (Unger & Herzog, 1998; Winskel, 2002).²

At the same time, environmental regulations were tightened across the Atlantic. European Commission's Large Combustion Plants Directive of 1988, which required its member countries to reduce sulphur dioxide to a specific level with a specific control technology, such as flue gas desulphurisation equipment. Although the legislation was a decade late compared to its US counterpart, it was detrimental to coal power regarding capital cost and invited CCGTs in the European market. The US Environmental Protection Agency also enhanced emission regulations through CAA Amendment of 1990. Its emission standards of NO_x and SO_x on both of new and existing power plants were

² US emission standards were rather lax and slow in the 1970s, and the amendment of CAA in 1977 only required existing coal power plants installation of scrubbers to reduce SO_x emission. By comparison, its Japanese counterpart set up quite stringent emission standards on SO_x and NO_x emission from both existing and new coal power plants with the promotion of advanced control technologies from the early 1970s. See Popp (2006) and Section 5.2.5 for details.

tightened compared to its 1970 version, and State-level legislation set much stricter standards in the late 1990s (Winskel, 2002; Popp, 2006).

Finally, liberalisation of the electricity and natural gas markets started with the Energy Policy Act (EPAct) of 1992 in the US. Succeeding PURPA of 1978, EPAct allowed competition in the power generation segment of the market. The competition was extended to existing utilities' power generation assets, creating a considerable risk that utilities will not be able to recover costs through electric rate (Stuntz, 1995). Liberalisation of gas supply industry as well as ESI in the UK prohibited British Gas's discrimination against power producers and guaranteed the independent energy suppliers' access to newly developed gas reserves in 1989 (Winskel, 2002). The high capital cost, long construction lead time, and additional equipment for emission control of coal power or safety margin of nuclear power, were more than offset by their cheap fuel cost in the competitive electricity market. Technological improvement of CCGT in terms of efficiency and emission control, by comparison, made CCGT the primary beneficiary of the liberalisation. It was the technological characteristics of CCGT, in effect, which reduced 'minimum efficient scale' of power generation investment from 1,000MW to below 350MW, removed the concept of "natural monopoly" in the power generation segment of the electricity market, and enabled competition in the market (Stein, 2000).

In the overall perspective, the environmental and economic regulations of the ESI and CCGT technology co-evolved and fundamentally changed the landscape of power generation technologies in the developed economies in the 1980s. Although political preference for coal and nuclear power over natural gas in the US and the UK halted the co-evolutionary process for a decade, the temporary political events could not stop the overall force of the change. Nevertheless, the regulatory mismatch originated from the restriction on natural gas use for power generation substantially influenced the survivability of the HEI firms in respective countries. Regardless of political soundness or preference, the coherence of the regulatory framework of the ESI has been crucial to

survival and innovation of the HEI firms in the developed economies. Table 2.1 summarises the institutional changes and their technological effects in the 1970s and 80s.

Table 2.1 Regulatory Change of the ESI and Effects in the 1970s and 80s' US

Emission Regulations	Market Regulations	Restriction on Natural Gas Use		Technology Change
CAA (1970): Preliminary Regulation on Utilities	PURPA (1978): Entrance of Non-Utility Producers	↔	FUA (1978): Blocked a Virtuous Circle	← Emergence of CCGT
				→ Closure of CCGT Market
CAA (1990): Stringent Emission Standards	EPAAct (1992): Competition in the Electricity Supply Market	FUA Withdrawn (1987): Virtuous Circle between Institutional Reforms & CCGT		The revival of CCGT: 'Scale Flexibility', Low-NO _x Technology, Advance in Efficiency

Note: CAA = Clean Air Act, PURPA = Public Utility Regulatory Policy Act, FUA = Power Plant and Industrial Fuel Use Act, EPAAct = Energy Policy Act

Survival Efforts of the American HEI Firms During the Turbulent Decade

During the turbulent period, only a few HEI OEMs with enough technological scope and depth survived while others had to experience mergers or escaped the US market (Watson, 1997; Unger & Herzog, 1998; Winskel, 2002). In particular, competence in turbomachinery played as a criterion of the survivability of the global OEMs in nuclear power and CCGT markets (Thomas, 1988; Watson, 1997; Barrientos, 2002). While the global nuclear OEMs with the competence in steam turbine machines survived longer than other reactor vendors, the competence in gas turbines is recognised as a core capability of the winner in the global CCGT OEMs. Although two American nuclear OEMs, Combustion Engineering (CE) and Babcock & Wilcox (B&W), had dominated the US nuclear steam supply system (NSSS) market thanks to their competence in boiler

technologies until the 1970s, their lack of capability in turbine and generators forced them to exit the nuclear market in the late 1980s, for instance (Thomas, 2005; Barrientos, 2002).³

In effect, CE and B&W outpaced Westinghouse and General Electric (GE) in manufacturing and managing the overall NSSS components regarding design, material choice and piping-work (Thomas, 1988). For instance, CE and B&W supplied 58 and 27 reactor pressure vessels respectively out of 139 in total, commissioned from the 1950s to the 70s in the US nuclear market (Barrientos, 2002). Their lack of expertise in turbine generator, however, made them vulnerable to the depressed US nuclear market in the 1980s while Westinghouse and GE managed to survive with continued steam turbine orders from fossil power projects. CE and B&W were merged by ASEA Brown Boveri (ABB), and Framatome, respectively, in 1989 (Thomas, 2005).⁴

By comparison, gas turbine divisions of OEMs experienced a different path from their nuclear counterparts. General Electric could maintain gas turbine human resources by temporarily transferring them to its jet engine division, whereas Westinghouse did not have such capacity and moved to Japanese gas turbine market and maintained its business with Mitsubishi Heavy Industries (MHI) under a licence contract during the difficult decade. European OEMs had a more difficult decade, and mergers were inevitable choices. ASEA and Brown Boveri became ABB in 1987, and GEC and Alsthom became GEC-Alsthom in 1989 (Watson, 1997; Unger & Herzog, 1998; Castillo, 2012).

The turbulent period squeezed the weaker OEMs and opened a window of opportunity for technology transfer to catching-up countries, such as Japan in the case of

³ NSSS consists of a reactor, reactor coolant pumps, steam generators, a pressurizer and associated piping in a nuclear power plant. The steam, generated by the NSSS, is used to drive the turbine generator unit.

⁴ Although the merger between B&W and Framatome was 50/50 merger initially, the merged firm was consolidated as Framatome Technologies a few years later. B&W's NSSS business was squeezed to supply of a few sets of replacement steam generators in the 2000s for several old B&W design reactors, such as Oconee units and Three Mile Island unit 1. Its business remained only in a marginal market segment, such as maintenance and repair services (IAEA 2008).

CCGT and Korea in the case of nuclear power. Westinghouse's gas turbine division completely shut down its manufacturing base in the US and transferred its CCGT technology to MHI in the late 1970s, as abovementioned. CE transferred its NSSS technology to KEPCO-Korea Heavy Industries & Construction (KHIC) alliance in the 1980s (see Section 4.3.2 for CE's nuclear technology transfer to Korea and Section 5.3.3 for Westinghouse's CCGT technology transfer to Japan).

2.2.2. The Literature on HEI in Catching-Up Context

Amongst the rare contributions to the HEI catching-up literature, Cook and Surrey (1989) comprehensively articulate the overall features of energy technology development and strategies in catching-up countries. They re-define the meaning of R&D in energy technologies as a part of other industrial activities, such as an adaptation of designs, information gathering, or operating practices, rather than a 'source of innovation'. They warn, subsequently, that R&D itself will not build up capabilities without such active demand from the industry, and that establishing of large R&D institutes could exhaust the scarce supply of scientists and engineers, who might be more productive elsewhere.

Cook and Surrey (1989) rationalise such suggestions based on the specific nature of the energy technology progress, which mostly originates from other sectors, even in developed economies, and the importance of clusters of complementary innovation amongst various sectors. It is a crucial point as far as commercial nuclear and gas turbine technology originates from military technologies, such as the Navy's nuclear propulsion system, and the air-fighter jet engine. They identify that energy technology innovation and catching-up is a 'state-of-the-art' *appreciation* of technologies which originate from advanced countries or other sectors, rather than development based on the 'go-it-alone' approach through R&Ds.

After articulating the origin, characteristics, and pre-requisites of progress in energy technologies, Cook and Surrey (1989) emphasise that 'efficiency of technology

transfer' for catching-up countries in the energy sector depends on the closeness and stability of the relationship between licensee and licensor rather than indigenous innovation or governments' restrictive regulation on technology transfer terms. They also emphasise the role of energy suppliers, such as electric utilities, in coordinating the gradual involvement of the domestic equipment industry in new construction projects, and subsequently improving the technical capability of the industry. In addition, catching-up nations need to have overall strategic planning which integrates the development policies of new industries to use the energy, such as aluminium or steel industries (Cook & Surrey, 1989: 436).

In sum, they offer an insight into inter-sectoral aspects of energy technology catching-up, including energy suppliers' roles in managing the capability-building of the domestic energy equipment industry, integrated planning of energy plants considering new energy user industries, and complementary innovation of upstream suppliers. Although their warnings and suggestions are closer to 'rule of thumb' rather than a theoretical argument, the insights based on decades' experience of energy industries could not be dismissed. The next subsections review nuclear and gas turbine catching-up case studies.

Gas Turbine Catching-up Case Literature

As with the nuclear catching-up literature, there are only a few studies on the gas turbine catching-up case, due to the rarity of such cases in the global market where a small number of gas turbine OEMs dominate (Watson, 1997; Kimura & Kajiki, 2008). Kimura and Kajiki (2008) emphasise the role of national R&D programmes through a case study of a sub-project of the "Moonlight Project" (1978–1988) as a main component of a successful gas turbine catching-up performance in Japan. They find that the "High Efficiency Gas Turbine Project" not only offered chances to develop Japanese HEI firms' technological capabilities in different component areas but also offered a technological base to improve their relative status in relationship with foreign gas turbine licensors.

Government's leadership was also crucial in arranging and supporting the cooperative R&D programmes for rapid catch-up and encouraging firms to join in such programmes in the case study.

However, the literature does not address the relative efficacy of the project in relation to the broader gas turbine catching-up process in Japan. The literature, in effect, finds that a leading participant of the project, namely MHI, could have achieved crucial component technologies of the gas turbine, such as ceramic shell moulds, even without the project. Also, public institutes which hosted the project lacked proper infrastructure and had to depend on the leading participant, notably MHI. Although the R&D project seems to shorten the technology catching-up process of MHI, the case study lacks an analysis of the institutional conditions which enabled the commercial success of gas turbines in Japan in the first place (Kimura & Kajiki, 2008).

Regarding the success of the overall Japanese cooperative R&D performances, Porter (1990) points out that Western governments misunderstand the real value of public R&D programmes, sponsored by MITI, as a driver of Japanese success in industrial catching-up. He suggests the actual role of the R&D programmes is to signal the importance of emerging technology areas to participants and to stimulate participating firms' own private R&D initiatives. In effect, Japanese firms participate in the programmes mostly for defensive purposes, such as to maintain a healthy relationship with MITI and/or to manage the potential risks of competitors benefiting from the programmes.

Besides the public R&D projects, other studies suggest that institutional factors, such as regulatory differences between advanced countries and the catching-up countries, contributed to the MHI's gas turbine catching-up success (Watson, 1997; Unger & Herzog, 1998). The literature points out that the temporary ban on the use of natural gas for power generation in the US and Western Europe from the mid-1970s to the mid-1980s was an important factor in the technology transfer from one of the US gas turbine OEMs, namely Westinghouse, to a Japanese latecomer, namely MHI. In addition, Watson (1997) implies

stringent emission standards in Japan also contributed to MHI's successful catching-up of the technology.

Although the precise roles of the institutions relative to the other factors are not differentiated in the overall empirical literature, there have been implications of institutional effects, such as environmental or business regulations on ESI, rather than direct policies, such as public R&D initiatives. Special attention to the effect of the distinctive institutions beyond the specific catching-up policies would represent important contributions to the empirical HEI literature.

Nuclear Catching-Up Literature

Although a few countries, including France, Germany and Japan, caught up with American commercial nuclear power technologies, mostly pressurised water reactors (PWRs), in the 1970s and 80s, since then there has been only one commercial nuclear power catching up: Korea. For instance, France's Framatome, Germany's Siemens and Japan's MHI indigenised PWR technologies under Westinghouse licence. Siemens and Framatome became independent from the Westinghouse after terminations of the licence agreements in 1969 and 1982, respectively, and exported reactors under their brand names. For instance, Siemens delivered Borssele-1 and Goesgen to the Netherlands and Switzerland, respectively, through its subsidiary, Kraftwerk Union, in the 1970s, and Framatome delivered Koeberg unit 1&2 and *Ulchin* 1&2 to South Africa and Korea, respectively, in the 1980s (Thomas, 1988; Inside NRC Statistics Monthly, 2018). Although MHI also localised its PWR technology from the Westinghouse licence in the 1970s and terminated the license agreement with Westinghouse in 1991, it could never export its reactor (see Section 5.3.2). Since then, a reactor technology indigenisation and export case by a catching-up country has not been found other than the Korean case. Thus, it is not surprising that there is limited literature on nuclear power catching-up cases in recent decades.

A handful of literature (Park 1992; Sung & Hong 1999; Choi et al. 2009) commonly suggests strong government commitment, development of human resources, the rapid growth of heavy industries, and technology transfer from foreign firms as main drivers of the Korean nuclear power catch-up in the 1990s. The literature tends to explain the Korean nuclear power technology catch-up as an accumulated result of nuclear policies and R&D programmes in a linear relationship. It claims, in an undifferentiated way, overseas nuclear education and establishment of an “Atomic Energy Department” in the 1950s, a “Machinery Indigenisation Policy” in 1976, a “Master Plan for Technology Indigenisation of Nuclear Power Plants” in the mid-1980s, and public R&Ds in the 1990s as “success factors” (Park, 1992; Sung & Hong, 1999; Choi et al., 2009).

However, such a linear type of explanation needs to be scrutinised. In effect, even the official review of the Korean government’s former Ministry of Energy and Resources (MER), which took charge of the nuclear indigenisation programme in the 1980s, denies the efficacy of the previous nuclear indigenisation policies in the country. It points out that “previous policies and programmes had been fragmented, unsystematic and lacking in proper evaluations” (MER, 1988: 335).⁵ The efficacy of such a linear logic becomes even weaker when Korea’s nuclear technology indigenisation history is compared to that of Japan. Although both started nuclear power programmes in the mid-1950s, it took four decades for Korea to localise commercial nuclear power technologies while Japan did so in two decades.⁶ Japan has formulated more than nine long-term programmes for nuclear science and engineering development through its Atomic Energy Commission since 1956 while Korea started education programmes to train nuclear scientists and engineers

⁵ It should be noted that previous nuclear indigenization programmes had been mostly dealt with by the Science and Technology Agency rather than the MPR.

⁶ Japan’s MHI indigenised its PWR technologies to 95% level in terms of monetary value of equipment through the construction of Mihama unit 2 in 1975 while Korea’s KEPCO/KHIC did so through *Yonggwang* unit 3 in 1995. See Section 4.3.2 and 5.3.2 for details.

including sending about 240 students abroad during 1956-1964 and established overall institutional infrastructure of nuclear energy in 1958 (IEA, 2008; Sung & Hong, 2008).

In addition, the literature lacks unambiguous evidence about the linear relationship between the Korean government's "strong policies" and the process of technology indigenisation. At least, the relative effectiveness of the nuclear policies and programmes should be evaluated in relation to the "window of opportunity", such as technology transfer from a financially troubled American firm, namely CE, amidst the US nuclear market collapse in the 1980s (see Section 2.2.1). Although the government's efforts to indigenise the technology could be defended as a capability building-up process which is a crucial internal factor for successful technology transfer, the four-decades-long government R&D policies and programmes only for capability-building are not easily justifiable. It should be noted that Japan localised the commercial nuclear technologies in two decades even without such a dramatic opportunity as the global nuclear market collapse.

On the other hand, there are a handful of studies that analyse Japan's nuclear power technology catching-up performance. The literature points out problems from the initial stage to catching-up performances in the Japanese nuclear case. The government's early intervention in commercial nuclear catching-up resulted in poor technology choices, such as the Gas Cooled Reactor (GCR), and persistent attempts to develop public R&D programmes for "new reactors" also failed. Although Japanese HEI firms succeeded in indigenising and commercialising the light water reactors (LWRs) in the 1970s, by comparison, it is discounted as a result of the dissemination of American nuclear technologies rather than a victory of market over government intervention (Samuel, 1987; Kitschelt, 1991). This seems to accord with what Cook and Surrey (1989) suggest regarding energy technology catching-up: a stable relationship with licensors is more important than "go-it-alone" public energy R&D initiatives.

Furthermore, the literature ascribes Japan's failure in the export market to the underperformance of its nuclear fleets, emphasising especially its low capacity factor compared to its European counterparts even after a decade of "start-up problems" (Thomas, 1982; Samuel, 1987; Kitschelt, 1991). Although Thomas (1982) implicates Japan's relatively stringent safety culture as a background reason, more unambiguous and systematic analysis of the underperformance of Japanese nuclear fleets is needed.

2.2.3. Research Gap in the HEI Catching-Up Literature

Although a number of HEI studies have identified the nature of the technological and industrial evolution of global HEI firms, little analytic attention has been paid to the catching-up cases of HEI technologies (Thomas, 1988, 2005; Watson, 1997; Bergek et al., 2005). The limited amount of HEI catching-up case literature lacks a systemic analysis of the technological catch-up process beyond the undifferentiated listing of sectoral policies, such as public R&D programmes, with intermittent explanations of external and internal factors, including technology transfer from foreign licensors and growth of domestic heavy industries.

However, a review of the literature confirms that such policies as public R&D programmes would not automatically lead participating firms to successful catching up, including commercialisation (Porter, 1990; Kitschelt, 1991). Also, technology transfer does not spontaneously occur insofar as advanced firms would not allow it given that it could create potential threats to their own market shares in the future (Cook & Surrey, 1989).⁷ Although HEI's interplay with related industrial sectors could be influential, including in terms of (sources of) demand and upstream supplier sectors, the issue is also insufficiently addressed in the literature. The fragmented claims on the "success factors" of catching-up

⁷ Technology transfer could occur in special conditions, other than through a long-term relationship between licensor and licensees, such as where there is a global market collapse and the market becomes the "user's market" for a long period. Nuclear power technology has been the case since the global market collapse in the 1980s.

need to be scrutinised and integrated in a systematic way (Park, 1992; Sung & Hong, 1999; Choi et al., 2009).

Although technology transfer and inter-linkages between HEI and ESI are constrained and incentivised by sectoral institutions, the mechanisms are not sufficiently addressed in the literature. Although the effects of such institutions are partially discussed in the literature, such as in terms of the impact of gas fuel regulations in the US and Europe, the contribution of emissions standards (Watson, 1997; Unger & Herzog, 1998), or the impact of the nuclear safety culture in Japan (Thomas, 1982), they should be investigated in a more integrated and systematic manner.

On the other hand, the literature lacks discussions about the complex relationship between the capabilities of catching-up firms and their catching-up performances in both technologies. Although Japanese HEI has better technological capabilities than its Korean counterpart in terms of technological breadth, depth and history, it was not successful at exporting nuclear power for more than three decades after it localised commercial reactors. By comparison, it took two more decades for the Korean HEI to indigenise the technology, but it entered the export market only fifteen years after the indigenisation. By contrast, Japan's CCGT post-catching-up performance has been far better than for its nuclear power counterpart, whereas Korea is still some way off fully indigenising its commercial gas turbine technology, despite its success in nuclear power.

Overall, the research gap seems to originate from the limited number of studies on the HEI catching-up issue. There is a possibility that some of the research gap is already addressed in other catching-up studies based on various sector cases other than HEI. Whether it directly covers the HEI or not, it may be helpful to understand some common features of Korean catching-up issues when analysing the complex HEI catching-up issue. As such, Section 2.3 reviews other empirical literature on Korea's overall catching-up performance.

Table 2.2 Dichotomy of Cross-National and Cross-Technology Catching-Up

	Japan	Korea
Nuclear Power	Failed in the export market for three decades after indigenisation (1975)	Succeeded in export (2009) relatively soon after indigenisation (1996)
CCGT	Succeeded both in indigenisation and export market (1980s~)	Failed in indigenisation despite repeated catching-up efforts (1990s~)

The preceding review and the identification of the research gap lead to a refinement of the original research question:

Research Question 1: Why did Japanese and Korean HEIs show dichotomously contrasting catching-up performances across their nuclear power and gas turbine industries over the past three decades?

2.3. Empirical Literature on the “Catching-up Shift Dilemma”

2.3.1. Political Economy Approaches in the Early Literature

“Getting the prices relatively wrong” (Amsden, 1989: 139) symbolises the state’s efficient interventions in Korea’s catching-up performances across the heavy and chemical industries (HCI) in the 1970s and 80s. “Reciprocal subsidy” between the Korean state and *Chaebol* firms⁸, preferential loans, and tax credits to *Chaebols* in exchange for improved export performances, have characterised the dynamics of Korean development in the literature. In this reciprocal relationship, the Korean state’s dominance over the market is

emphasised, for example in terms of its disciplined leadership in choosing competent *Chaebols* and punishing weak performers.

The term *Chaebols* indicates typical Korean large conglomerates, owned and controlled by family members of entrepreneurs who founded the groups mostly in the 1950s and 60s. The concept is intertwined with a Korean version of the Developmental State. The Korea government used to target certain industry sectors for export promotion or some “strategic” purposes and incentivise the growth of the sectors by directly linking the provision of subsidised credit at below-market interest rates and export performance. Although the term of “strategic” is not well established in an academic language, it has been used as a synonym of ‘export-oriented’ in Korean industrial policies (Kim et al., 2004). The main beneficiary sectors of the subsidised credit have been changed from light industries in the 1960s, HCI in the 1970s, and some consumer goods and real estate sectors in the 1980s.

However, the approach also has a weak point in addressing failed sectors under the HCI policy, and the implications of such failures. While a few *Chaebols* had been successful in diversifying from globally matured low-end technologies to emerging ones in several sectors, the Korean HEI not only failed under the HCI policies of the 1970s, but also continued to suffer even after nationalisation in the changing global and domestic markets in the 1980s (Rhee, 1994).

The early analysis of the Korean HEI is followed by debates between industry policy and free-market approaches (Auty, 1995; Stern et al., 1995; Chang, 1993, 2000). The free-market literature points out the inconsistency of the state in exerting its authority and limited market reform during the HEI restructuring process in the 1970s and 1980s (Auty, 1995; Stern et al., 1995). In response to the critiques, the political economy literature defends the Korean state’s way of managing industrial adjustment as a driving force of the Korean economic and technological “miracle”. Following the thread of Amsden’s claim, Chang (1993, 2000) defends even the monopolisation and nationalisation of the HEI

during the domestic and global recession of 1980 as evidence of the Korean state's unique competence in calming conglomerates' rent-seeking behaviour. He emphasises that the Korean state was not only good at promoting infant industries but also impartial in restructuring those industries according to their performance.

However, the defence focusses on a political event of nationalisation rather than the broader and in many ways unsuccessful process. It ignores the significant implications of the government's initial grant of monopoly status to a novice *Chaebol* in the HEI sector, and its overinvestment, such as in the world's largest heavy forging and casting facilities. It also neglects the relative lack of success even after the nationalisation of the industry, evidenced in the repeated bankruptcies and bailouts of the nationalised firm in the 1980s (KHIC, 1995, Rhee, 1994; Auty, 1995).⁹

On the other hand, free-market-oriented literature seems to exaggerate the overcapacity issues of power plants and the low capacity factor of manufacturing facilities of Korea Heavy Industries & Construction (KHIC), Korea's previous state-owned HEI firm, in the early 1980s (Auty, 1995; Stern et al., 1995). In effect, the overcapacity or low-capacity factor was ubiquitous in Korea's heavy industries in the 1970s and 1980s, even in dramatically successful sectors such as shipbuilding. The difference is that the successful *Chaebol* in the shipbuilding sector diversified from already matured but low-value ships to higher-value ship products (Amsden & Kim, 1986). Thus, overcapacity *per se* does not reflect the inferiority of the Korean state in dealing with industrial policy.

What both sides miss is the technological implication of the nationalisation that inhibited Korean HEI from responding to the dramatically changing global and domestic

⁹ It should be noted that the energy and industry ministries had consistently opposed *Park Chung-hee* government's monopolisation policy throughout the 1970s (Rhee, 1994; KHIC, 1995). The ministry-level approach seems to be understandable given that awarding a monopoly status to the least-experienced firm in heavy industries and locking out other experienced *Chaebols* from the HEI sector would not have been logical.

power plant markets in the 1980s and 1990s.¹⁰ The nationalisation, instead of market-exit, could be a critical juncture on a path-dependent process by locking the industry into a specific technology capability, such as heavy forging, from which the industry had to escape. Considering the technological rigidity of the HEI firm, the nationalisation rather than the market-exit reduced potential of technological diversification of the country's public sector, such as ESI. It might be the typical case that a single event could generate increasing returns and irreversibility which locks a system into an inferior technology (Arthur, 1988; David, 1985).

When this deficiency in the debates on the role of the state and market began to be recognised, critiques of the debate emerged in the literature. Dervis and Petri (1987) regard the Korean economy's resilience as the 'secret' of its success in the 1970s and 1980s, although its broad outward-oriented industrial strategy is well known and replicable by other catching-up countries. According to Dervis and Petri, the components of Korea's resilience are prominent conglomerates' effectiveness in shifting financial and technological resources into their most profitable applications and the orientation and capability of bureaucracy. They argue that the one-dimensional debate, intervention vs. neutrality, misses the point. Keeping the gap in the state-market debate in mind, the next Section reviews more recent strain of empirical literature on Korean catching-up cases.

2.3.2. Empirical Literature of the "Korean Catching-up Shift Dilemma"

Since the late 1990s, when Korea suffered a financial crisis, a new strain of Korean literature concerning catching-up 'shift' or 'transition' issues has emerged as the

¹⁰ Although it was ESI case rather than HEI, existence of the state monopoly ESI in the 1970s' UK, namely CEGB, seriously locked out development of emerging technologies, such as gas turbine and its up-scaling which was against CEGB's preferred technologies, such as nuclear or coal (Watson, 1997). If a monopoly HEI firm is added to a monopoly ESI, such as 1980's Korean case, it is not difficult to expect systemic and strong technological inertia.

latecomers faced the limits of their earlier catching-up success. This strain of literature focusses on weak aspects of Korean catching-up performances, including the lack of balance in industry structure between *Chaebol* and small firms (Ernst, 1998), the lack of domestic user-producer interaction (Kim, S., 1998; Lee and Lim, 2004), and the lack of product design capability (Hwang, 1998; Hobday et al., 2004). These commonly suggested weak aspects, however, are not easy to overcome, since they form a vicious circle.

Although Korean manufacturers need to diversify into new technologies and products, they are unable to do so due to a lack of qualified domestic upstream suppliers. To nurture specialised suppliers, domestic users need to use the products from these suppliers. Domestic users, however, are reluctant to use the unproven domestic components and equipment due to quality control issues. Thus, the domestic specialists have neither the chance to experience user-supplier interaction nor a market to sell their products. These claims are briefly reviewed below.

First, there is a firm-level capability approach in explaining the Korean catching-up shift issues (Hwang, 1998; Hobday et al., 2004). Hobday et al. (2004) raise the issue of 'catching up in transition' in various Korean firms which intend to move from catching-up status to a leadership position. They suggest that Korean capital goods firms should increase their development capabilities for new products to transit from catching-up status to a leadership position. In this, the firms crucially need a complementary domestic industry partner, which they are not used to from their catching-up period.

In explaining the necessity of a complementary industry partner for new product development, Hobday et al. (2004) introduce the concept of 'producibility' to ensure design for manufacture before the firm decides to continue with potential product design. It is the specialised suppliers who can ensure this 'producibility'. In effect, this is similar to the 'castability' issue in developing a new gas turbine design in a case study of the co-evolution between gas turbine OEMs and precision casters in the US (Rycroft and Kash,

1999). Catching-up capital goods firms need a more intense and direct relationship with the advanced specialised suppliers if they are to move into a leadership position.

As a policy suggestion, Hobday et al. (2004) claim that Korean manufacturing firms need to establish co-development partnerships with advanced foreign specialist firms. For example, *Samsung* had such a relationship with a US-based specialist for core technology of CDMA mobile telephones while *Hyundai* Motors did so with the British engine specialist Ricardo for the development of its own engine (Y. Kim and Lee, 2001). Such relationships with foreign specialists, however, come with certain preconditions, such as that the Korean manufacturers and advanced specialists are not in potential competition with one another. Substantial changes in the global market could also affect potential relationships. It is questionable, therefore, whether such a partnership with advanced foreign specialists can be explained or realised in a firm-level strategy without a specific set of institutions at a sectoral, national or global level.

Second, there is also a sectoral-level approach to a 'catching-up shift dilemma' issue of Korean industries. Although it is not directly concerned with the 'catch-up shift', the literature suggests machine tools as one of Korea's weak industry sectors, suffering from a lack of user-supplier interaction (Lee & Lim, 2001; Y. Kim & Lee, 2008). The literature sees the machine tool industry as a specialised supplier industry, based on Pavitt's taxonomy (1984), in which the tacit knowledge accumulated from the producer-user interface is crucial. It is argued that the poor catch-up performance of the industry is attributable to traditional Korean industry policy, focusing on end products while relying on the imports of core parts and intermediate materials.

Furthermore, the specificities of the knowledge base of the machine tool sector have also placed Korean latecomers in an awkward position. First, the equipment used in production processes is mostly made up of 'general purpose' technologies and the skills accumulated by the labourers are more important than the imported equipment itself. Second, technology licences are limited to a few specific models and cannot enhance the

design capability in the sector, but the sector needs capabilities to modify machine design to meet diverse demand. Third, formal education, study abroad and R&D cannot solve the problems, given that the required knowledge is tacit and only acquired during the product development process (Lim, 1997; Lee & Lim, 2001).

In addition to the original bottleneck issue, the literature points to current obstacles to catching-up in the Korean machinery sector: i) domestic users' mistrust of domestic machinery products, ii) advanced foreign firms' intellectual property rights (IPR) lawsuits against domestic suppliers, iii) advanced foreign firms' price dumping attacks. Therefore, the Korean machine tool sector suffers from a vicious circle between the necessity of user-supplier learning and the low quality of domestic supplier (Y. Kim & Lee 2008).

In overcoming this barrier, Korean machine parts producers consider insufficient R&D funds as the most serious difficulty in the development process. The insufficiency of R&D funds does not only mean the size of the funds themselves but also that there are structural barriers, including the uncertain demand from local users and the involved risks in relation to the size of the firms (Y. Kim & Lee, 2008). The structural issue like unstable domestic demand of the machine tool industry is shared with the specialized suppliers abovementioned.

Finally, there is the national innovation system (NSI) approach to the Korean 'catching-up shift' issue. S. Kim (1998) ascribes the Korean semiconductor industry's successful catch-up and export performances of Dynamic Random-Access Memory (DRAM) in the 1990s to a conjuncture between state, *Chaebol*-governance and a 'window of opportunity' in the global market, rather than to the victory of either a free-market or a state-led target-specific industry policy. She adds a temporal window of opportunity for the Korean *Chaebols* in the global market, namely the US-Japan trade agreement from the late 1980s to the early 1990s, as one of the crucial explanatory variables, while appreciating the "reciprocal subsidies" concept of the earlier political economy literature. She argues

that the state policy, such as the cooperative DRAM R&D project, played only a supplementary role. She suggests that the Korean success in the specific segment of electronics is an idiosyncratic experience and argues for the necessary improvement of the unbalanced relationship between weak domestic user firms and *Chaebol* suppliers of electronics for the next step in catching-up success.

The ‘catching-up shift dilemma’ of the Korean manufacturing industries in the literature commonly demonstrate that some limited but unconventional catching-up strategies, used to be effective and successful in the past, do not work anymore. The stories point out that overall institutional reforms, rather than a few target-specific catching-up policies, need to be considered to address the structural dilemma of the Korean latecomers.

In sum, most of the empirical literature points to either a lack of domestic ‘user-producer’ or ‘producer-specialised supplier’ interactions as the major obstacle to the catching-up shift of Korean manufacturing industries. This raises the question of whether the Korean HEI also shares the common user-producer claim. The research findings of the Korean catching-up dilemma issue in other Korean industry sectors leads to the second research question as below:

Research Question 2: What are the specific weaknesses of inter-sectoral linkages between the Korean HEI and ESI that might explain contrasting catching-up performance between nuclear and gas turbines, compared to their Japanese counterpart?

In addition, there is a nuanced ambiguity as to whether the inter-sectoral relationships in the vicious circle are cause or effect. There is a gap in explaining how those interactions are shaped by the relevant institutions, which could be more decisive factors of a ‘lock-in’ trap in a long-term view. To investigate the research gap of the empirical literature, the theoretical literature in each aggregation level of analysis is

reviewed in the next Section, focusing on the inter-sectoral relationship and institutional factors.

2.4. Theoretical Literature Review

2.4.1. Firm Capability Approaches and Gap

Based on the various elements of the literature that emphasise resources and their implications for firm performance (Penrose, 1959, Stigler, 1961), Briger Wernerfelt (1984) has established the “resource-based view” framework in the field of strategic management. The resource-based view regards a bundle of valuable resources, both tangible and intangible, of firms in a highly imperfect market as the basis of the competitive advantage of a firm (Wernerfelt, 1984: 172). It argues that firms build their strategic distinctiveness on resources that are valuable, rare, and less imitable (Dierickx & Cool, 1989; Barney, 1991). In this way, the distinctiveness of first-mover firms works as a “resource position barrier” to newcomers (Wernerfelt, 1984). In short, the main account of the resource-based literature focusses on the sustainability of already achieved competitive advantages rather than on the creation of advantages by followers or catching-up firms (Barney, 1991, 1995).

On the other hand, the ‘dynamic capability’ approach, another strain of firm-level capability approaches, also focusses more on firms’ competitive survival than on the acquisition of sustainable competitive advantage (Teece & Pisano, 1994). Thus, it is in a more distant area from catching-up contexts. Indeed, the firm-level capability approach assumes that firms are in a developed country context with a modern and sophisticated NSI. In a developing economy context, firms usually not only lack necessary technologies, which should be transferred from foreign countries but also operate within underdeveloped markets and innovation system, such as weak public research institutes (Hobday, 2005). Even when the catching-up firms are in a ‘transition mode’, that is,

between catching up and a leadership position, they still suffer from a lack of sufficient complementary assets, such as upstream suppliers, or a lack of sufficient domestic user-producer interaction as seen in the empirical literature (see Section 2.3.2).

Recognising the gap of the firm capability approach or the resource-based view in addressing technology constraints of catching-up firms, Mathews (2002, 2006) suggests a 'resource leverage' framework, a reversed version of the approaches. In order to overcome such barriers, latecomer firms would strategically exercise linking with advanced technology sources, leveraging of technological opportunities from the linking, and learning from iterations of the linking and the resource leveraging. The latecomers would initially target available resources, which have the least rare, most imitable and transferable characteristics, from advanced foreign technology sources. From this foothold of linking, the latecomers would be able to bargain with the advanced firms for knowledge resources, such as technical know-how through subcontracts of manufacturing. Through numerous iterations of the linking and leveraging, latecomer firms learn how to expand and deepen initially acquired capabilities and turn them into internal competence development. The processes reduce the gap between the latecomer and advanced foreign firms and let the former eventually arrive at leader's position, such as successful semiconductor producers in Korea and Taiwan (Mathews, 2002, 2006).

In explaining the learning process of latecomer firms, he borrows conceptual categories from the organisation and management literature, namely absorptive capacities (Cohen & Levinthal, 1990) and combinative capabilities (Kogut & Zander, 1992). Absorptive capacity is re-defined as latecomer firms' ability to absorb the leveraged resources, including product and process technologies and tacit and explicit knowledge. The capacity can be generated through iteration of rather simple mass production, and eventually can be utilised in conceiving and executing major investments in plant and equipment, and in appreciating a new business area and executing an entry strategy. In this perspective, he specifies the role of R&D expenditures of the latecomers as a means

of acquiring a greater capacity for appreciating and exploiting technological and market “shocks”, chances in other words, rather than a simple means of generating new products (Mathews, 2002).

The combinative capability is defined as an organisational capacity to generate new applications for existing knowledge. It is “the intersection of the capability of the firm to exploit its knowledge and the unexplored potential of the technology” (Kogut & Zander, 1992:391). Although latecomer firms are not expected to generate ‘new knowledge’, they are capable to combine a variety of seemingly fragmented technology sources into a competitive production or process technology (Mathews, 2002).

While Mathews’ alternative approach to the mainstream resource-based view enables an analysis of latecomer firms’ catching-up process in technology constraints, it still lacks explanations of non-firm and crucial factors for the catching-up performances. The shortcomings of technology and market sophistication in catching-up economies cannot be solved just by the latecomer firms and need to be facilitated by national institutions, such as public technology transfer agencies during FDI licensing processes. In this concern, Mathews supplements his approach with the term “institutional resources” and acknowledges the necessity of national-level interventions. “Latecomer firms can be effective in overcoming their disadvantages and exploiting their potential advantages *only if the country in which they are located builds a set of supporting institutions that guide, shape and channel the linkage and leverage processes* (Mathews, 2006: 324, italics added)”.

However, Mathews’ supplementing term “institutional resources” is still too narrow to capture potentially more influential but broader institutional factors to the latecomer’s catching-up performances. The empirical literature reveals that institutional changes of the ESI, including those in economic and environmental regulations, are crucial to the innovation of the HEI technologies in developed economies, and the changes are driven by parliamentary or legal decision makings beyond narrow supporting policies

and incentive systems of energy ministries. The efficacy of narrow supporting institutions would be even weaker in the countries in catching-up transition, such as Korea, where technology transfer from foreign countries is not readily available anymore due to international competition. The firm capability or resource-based view, thereby, could be used only for a partial analysis of the latecomer HEI firms within a broader analytical framework in the thesis.

2.4.2. The Sectoral System of Innovation Approach and Gap

Based on the Schumpeterian classification, Malerba and Orsenigo (1996: 451) suggest that “the patterns of innovative activities differ systematically across technological classes but are remarkably similar across countries for each technological class”. Inspired by various system approaches, Malerba (2002) suggests another kind of system approach, namely the sectoral system of innovation (SSI). In the sectoral system concept, he defines a sector as a set of activities that are unified by linked product groups for a given or emerging demand and that share certain common knowledge.

In its latest version, the literature suggests ‘building blocks’ of SSI consist of i) regimes of knowledge and technologies, ii) actors and networks and the coordination amongst them, and iii) the institutions (Malerba & Nelson, 2008). These elements are assumed to interact to generate variety, subject to selection and co-evolution. The SSI approach reveals that there are certain differences in catching-up patterns and paces in different sectors, even within one country.

While the SSI approach emphasises the sectoral differences by knowledge base and networks of key actors in explaining sectoral variation, it also suggests that there is co-evolution between national institutions and specific sectors (Malerba & Nelson, 2008). Often, the characteristics of national institutions favour particular sectors rather than others. Thus, the sectors that fit the national institutions better may grow and prosper, whereas other sectors that do not match the institutions may be constrained in

development and innovation. The attention to the fitness of sectoral specificities with the characteristics of national institutions is an improvement in Porter (1990)'s account that nations succeed in inter-connected industries rather than in all industries or haphazardly scattered industries.

Despite its contributions to innovation system studies, the approach has three weaknesses. First, it has a gap in explaining the cross-nation and cross-technology variations of a sector. It assumes that each sector is more or less homogenous and thereby succeeds or fails as a whole and that the patterns of innovative activities are similar across countries for each technological class. Although they address different technological trajectories for the same sector across countries (Malerba & Nelson, 2008: 13-14), it considers a variety of business positions of local subsidiaries of multinational corporations, such as a regional marketing centre, R&D centre, or service centre, rather than a variety of technological performances within the same sector.

A second weakness of the approach is in its downscaling setting of sector boundaries regarding cross-technology variation. The literature suggests that different innovation subsystems related to different product groups may coexist within a broad sectoral system (Malerba, 2005). The technologies in the same sector are not mutually irrelevant co-existing entities, however. They often compete with one another under the same or similar set of sectoral institutions, as can be seen in the case of nuclear power and gas turbines in the empirical literature review. Then, the downsizing sectoral boundaries would miss the critical hinge of analysis.

Third, the SSI approach has a gap in explaining inter-sectoral relationships. SSI includes a large number of heterogeneous sectoral elements, including firms, upstream suppliers, users, universities and public laboratories, financial organisations, governments, and actors' networks (Malerba & Nelson, 2008). It is related to the assumption that knowledge and technology, and interdependencies and complementarities from the input (supply) and demand sectors define the 'real

boundaries' of a sectoral system (Malerba, 1999: 5-6). Although the claim offers insights into the clustering effect between supplier and user sectors over certain technology, it also has its own gap.

In effect, the distinctive networks of firms, upstream suppliers, and users are *inter-sectoral relationships* rather than networks of actors in a single sector. This is a serious gap in that upstream suppliers and users also have their own sectoral elements, such as sectoral institutions, and often the institutions of upstream and user sectors have serious influences on technological performances, as we have seen from the empirical literature on HEI.

In effect, the SSI approach to the inter-sectoral linkage issue is inspired by development economics' main theme, namely the impact of inter-sectoral linkages on industrial competitiveness. In his pioneering work of development economics, Hirschman (1958) conceptualised 'backward linkage' and 'forward linkage' as basic components of these linkages. Backward linkage effects mean derived demand and can be translated as the provision of input from other industries for a given activity. Forward linkage effects mean output utilisation; in other words, the outputs from a given activity will induce attempts to use this output as inputs in some new activities of other industries (Hirschman, 1958: 100). His contribution to inter-sectoral co-evolution and national development served as the foundation for the SSI approach. His theory could be abstracted as a combination of Leontief's Input-Output Analysis and Schumpeter's theory of innovation and entrepreneurship (Lundvall et al., 2002).

However, considering the methodological dominance of Input-Output Analysis with the limited measurability of inter-sectoral interactions and sectoral performance only on an aggregate level, the approach could miss fine-grained aspects of inter-sectoral co-evolution and innovation, and lead to the misjudgement of crucial components of national development (Lundvall et al., 2002) (see also Section 3.5.2). Such an approach misses the critical role of the user-producer interactions in the innovation process and could naively

lead to emphasis on upstream sectors as a strategy of developing economies. In contrast, Lundvall et al. (2002) show the opposite case in Nordic countries, where competitive machinery sectors were a result of strong user sectors and a long-term innovative interaction.

This Section has discussed the findings of SSI on the co-evolutionary aspect between specific sectors and national institutions, and the gap in explaining cross-nation, cross-technology variation, boundary setting of sectors, and inter-sectoral relationships. The findings and gap lead attention to the NSI approach.

2.4.3. National System of Innovation and Gap

The literature of NSI reveals the pitfalls of mainstream economics, which explains economic growth as an autonomous mechanism independent of institutional background and does not recognise the relevance of innovation in this growth. It is defined as the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify, and diffuse new technologies (Freeman, 1987:1). It points out the importance of central government leadership, inter-firm and inter-organisational technology exchange and cooperation, and social and educational innovation. It is distinctive from the previous mainstream views that focused on the competence of components and actors themselves in a nation. Instead, it shifts the attention to networks and interactions of components and actors. Furthermore, it demystifies a linear type of innovation idea, which is that basic R&D results in innovation, subsequent commercialisation, and economic growth in an orderly way.

The NSI literature considers complementarities among subsystems or components of the system are a prerequisite in achieving high performance of innovation. Disproportionate progress of the subsystems may lead to mismatch, lack of synchronicity or harmonious integration of them. Thereby, identifying of the mismatch and re-integrating the unfitted subsystems, such as science, technology, economy, politics and

culture, of society would be the primary purpose of innovation policies in the view of NSI (Freeman, 1995). For instance, Freeman (1995) attributes stagnation of the British economy in the late 19th Century and 20th Century to loss of congruence between the five sub-systems of British society. The progress of new science-based technologies and specialised management in large corporations fitted ill with some of the old British political and social institutions.

Since Freeman (1987)'s pioneering work on NSI concepts, there has been a nuanced bifurcation in the literature based on the definition and boundary of institutions, which is a crucial part of NSI (Edquist & Hommen, 2006). In particular, a group of the NSI literature, mainly based on innovation cases in the US, focusses on narrow coordination systems between firms, science-oriented universities, and public R&D centres. The main analytic subjects of this narrowly focused approach are micro supporting systems of the innovative networks such as rearrangements of IPR regulations and financial incentives for venture capitals (Nelson 1993, 2008, Mowery and Oxley, 1995).

Inevitably, the narrow version of NSI has a propensity to focus on the developed economy context, where the production of knowledge and new technology are pronounced based on a well-established NSI. In the developed economy context, it is not only possible but also efficient to 'analyse the details of the specific subsystem without worrying too much about the rest of the innovation system' (Lundvall et al., 2002: 226). Thus, the narrow version NSI literature often concentrates on firms and technology, reducing the analysis of the (national) institutions to a 'left-over category' (Groenewegen & van der Steen, 2003). The narrowly defined institutions, however, do not match the poor components, such as weak public R&D institutes, and networking capabilities of NSI in developing economy contexts (Lundvall 1988, 2007; Lundvall et al., 2002).

As an alternative, Lundvall and colleagues suggest a broad version of NSI and shift the attention to a broader set of institutions that shape competence building in

developing or small economies. The approach accounts for four conceptual building blocks as a theoretical base of the NSI. They include i) economy as a system, ii) the home market effect, iii) the microeconomic approach to innovation as an interactive process, and iv) the role of institutions in shaping innovative activities (Lundvall et al., 2002: 216-217).

Implications of the four concepts need to be discussed for application to this research. First, the approach considers the national economy consists of industry sectors with backward and forward linkages rather than random co-existence of various industries. This implies the necessity of understanding of existing economic structure in innovation studies. Second, the 'home market effect' implies the importance of national context which offers the local demand and subsequently induces technological specialisation. Third, the interactive process implies co-operation between heterogeneous agents including user firms, supplier firms, public institutes, and universities as a crucial factor of innovative performance of firms. Fourth, the institutions are considered as formal and informal institutions that form the contexts in which the inter-active learnings take place (Lundvall, 2002). In addition, they emphasise a historical analysis of the role of the state, the creation and evolution of institutions under which user-producers' learning by interaction evolves, international specialisation, and the co-evolution of major sectors (Lundvall, 1998, Lundvall et al., 2002).

A few crucial points derived from the empirical literature could be accounted for by this approach. ESI-HEI relationship based on specific institutions, such as electricity market regulations and environmental regulations, have been crucial to HEI's survival and performances in the empirical literature. Also, the home market concept could be useful in understanding specific coevolution patterns of the latecomer HEI firms and relevant actors, including ESI. The economic structure concept is also important in understanding the demand conditions of the Korean and Japanese HEI. In this sense, the broad version of NSI and its user-producer concept in relation to institutional and historical perspectives could be used as a theoretical base of the thesis.

Furthermore, the broad NSI's user-producer framework based on the concept of 'quality of demand' is highly relevant to this thesis. In the user-producer approach, the institutions of ESI can shape the quality of demand regarding HEI's catching-up performances, including environmental and economic performance. Although most frequently analysed institutional factors in the NSI literature are concentrated on the education system, industrial relations, and labour market dynamics, Lundvall et al. (2002) suggest broad applications of the NSI concepts, such as energy and environmental policies. The conceptual framework of the NSI, thereby, is chosen as the main theoretical approach of this thesis.

However, the NSI lacks a detail theoretical analysis of how the innovation systems function and how they evolve. The theoretical limit makes it challenging to compare empirical cases of countries in a more systemic fashion (Fagerberg, 2003; Witt, 2003; Balzat & Hanusch, 2003; Groenewegen & van der Steen, 2006). Although the conceptual frameworks of NSI are widely shared by policymakers in various countries, they still need better systemic NSI benchmarks, taking systematically into account the variety of "national idiosyncrasies" (Moreau, 2004; Groenewegen & van der Steen, 2006). In this regard, this thesis adds supplementing theoretical perspectives to the NSI approach. The next Section discusses the supplementing literature to the NSI approach for this thesis.

2.4.4. Supplementing Analytical Approaches to the NSI Approach

This Section devises three supplementing approaches to the broad version of NSI. First, firm-level capability approach could be partially utilised for comparing and analysing the latecomer HEI firms in Korea and Japan in a broad NSI context. Section 2.4.1 already discussed the useful points and limits of the firm-capability approach in this regard. Second, institutional factors need to be analysed more systematically in order to understand the historical background and hierarchical relationships of core regulations

on ESI in the two catching-up countries. Third, core regulations on ESI need to be analysed in order to understand how they function in catching-up of technologies in overall national systems of innovation.

Hierarchical Analysis of Institutional Factors and NSI

In addressing the research questions, there is still a nuanced gap in the analytical concept of institutions. Although the concepts of ‘match’ and ‘mismatch’ between institutions and policies are already reflected in the NSI approach (Freeman, 1987; Lundvall, 1988; OECD, 1997b), overall relationships of the institutions and policies are not systematically addressed. For instance, which will be more influential or enduring among the relevant institutions and policies on the occasion of mismatch? Where should policymakers focus on the occasion of mismatch? Should governments consider all the types of institutions in equal weight?

In this regard, the hierarchical framework for institutional analysis (Williamson, 2000) based on a historical perspective is added to the NSI approach. Although the framework was devised for economic policy discussions rather than innovation studies, the institutional and historical perspectives can account for the ambiguous aspect of the NSI. Based on the concepts of ‘humanely devised constraints’ and ‘endurance’ of institutions (North, 1990), and in answering Kenneth Arrow’s open question, “why economic institutions emerged the way they did and not otherwise? (Arrows, 1987:734)”, Williamson (2000) elaborates an institutional framework for social analysis. The four-level scheme classifies institutional elements by their hierarchical positions in the chain of constraints accompanied by relative endurance including social embeddedness (Level 1), institutional environment (Level 2), institutional governance (Level 3), and resource allocation and employment (Level 4). In this chain of constraints, a higher level imposes constraints on the level immediately below (Table 2.3).

Table 2.3 Economics of Institutions

Level of Institutions	Frequency (years)	Purpose
L1. Societal Embeddedness (informal, customs, traditions, norms)	10^2 to 10^3	Spontaneous
L2. Institutional Environment: Property (polity, judiciary, bureaucracy)	10 to 10^2	Get the institutional environment right
L3. Governance: Contract (aligning governance structure with transaction)	1 to 10	Get the governance structure right
L4. Resource Allocation & Employment (prices and quantities)	Continuous	Get the marginal conditions right

Source: Williamson 2000: 597

According to the scheme, Level 2 and 3 are emphasised as analytical themes while the ‘social embeddedness’ (Level 1) is implied as an entity beyond ‘deliberate choice’ of society. Institutional environment (rules of the game) is shaped by political, judicial, and bureaucratic decision-making, and endure more than a decade if they are not abruptly changed by occasional ‘massive discontents’ such as occupation after WWII or military coup. Although a rare window of opportunity to effect broad reforms is opened at this level, such moments are considered exceptional (Williamson 2000). Due to accompanied costs and complex processes in defining and enforcing the rules of the game at this level, more detailed institutional arrangements for transactions are defined by ‘governance structure’ at Level 3. The possible re-organisation of transactions among governance structures can be re-examined periodically and more frequently within a decade. Resource allocation and employment are routinely dealt with at Level 4. Williamson (2000) suggests that transaction cost economics’ role belongs to Level 3 while neo-classical economics’ role belongs to Level 4.

Although the four-level analysis framework is devised to address economic policy issues, the hierarchical concepts based on historical perspective could be applied, in

conjunction with the NSI approach, to address the research questions. It enables this thesis to systematically address critical institutions of ESI in terms of historical background and the relative degree of constraining effects of different institutions on catching-up performances. Borrowing the analytical scheme of Williamson (2000), this thesis adopts the bottom three out of the four levels. It elaborates a framework which regards relevant institutions of the ESI as decisive factors of 'quality of demand' in a catch-up context. The framework follows a sequence of i) elaborating crucial institutional factors in a historical perspective, ii) finding measurable core institutions of electricity suppliers as decisive factors of 'quality of demand', iii) analysing differentiated impacts on cross-technology or cross-nation catching-up variations.

From a historical perspective, the framework considers major historical, external and domestic events and subsequent institutional changes as origins of the deeply entrenched 'institutional environment' of the ESI in the cases. A few major events in economic and environmental dimensions may directly define ownership of ESI and the legal status of environmental and safety regulations, respectively. At the level of 'Governance', state control or the autonomy of the ESI's business transactions, including pricing scheme and fuel contracts, and environmental and safety standards and criteria are defined. At the level of 'Routinised Operation', routinised business transactions of ESI, such as pricing practices, and routinised regulatory practices on the environmental and safety issues of ESI are observed. At this level, observations are focused on the degree of autonomy or control by the state in routinised business transactions, and the degree of regulatory practices in terms of enforcement of sanctions on the occasion of violations. Finally, the framework interrelates the catching-up performances of technologies to the economic and environmental institutions of the ESI. Although the constraining effects of institutions are proportional to the hierarchical chains, the directly measurable components in the case study are at the level of resource allocation and employment (Table 2.4).

Table 2.4 Historical and Hierarchical Analysis of Core Institutions of ESI

	Economic Dimension	Environmental Dimension
Institutional Environment (property rights)	- Ownership of ESI (private/national)	- Legal change (often with new agency)
Governance (contracts)	- Control or autonomy of business transactions	- Emission & safety regulations (standards, criteria)
Routinised Operation	- Electricity pricing practices - Fuel contracts & transactions	- Regulatory practices (sanctions or exemptions on violations)

Source: Adaptation from Williamson 2000: 597

The Literature of Regulations and Innovation

As observed in the empirical literature on HEI in advanced economies, economic and environmental regulations on ESI profoundly affected HEI firms' innovation activities and their survivability in the 1970s and 80s. The aspect is directly related to technology transfer from the affected advanced HEI firms to the latecomers in Japan and Korea. Therefore, it is rational to look at the corresponding economic and environmental regulations and their functions in the catching-up process in the latecomer countries. In analysing the effects of the economic and environmental regulations on the catching-up performances in the two countries, this thesis needs to supplement the overall NSI approach with the literature on regulations and innovation.

Porter and van der Linde (1995) famously claim that although a stringent environmental regulation may hinder national industries initially, it will induce technology innovations and enhance their global competitiveness with increased export potentials over foreign firms, which will be constrained by the same regulations in respective nations later. A large body of empirical literature testing the hypothesis find a

mostly positive impact of environmental regulations on innovation, at least, from a long-term perspective.

For instance, Popp (2006) finds that US firms increased innovative activities regarding sulphur dioxide scrubbers of coal power plants in response to the US Clean Air Act of 1990, but they did not respond to environmental regulations of foreign countries. Berthélemy (2012) finds that stringent safety nuclear regulation in terms of average outage for inspection alongside new construction of nuclear reactors and public R&D expenditure induced innovation of nuclear technologies in twelve OECD countries between 1974 and 2008. He, however, finds that reactor outages by regulatory decisions in the case of non-compliance to safety standards hamper innovative activities.

Beyond the effects of environmental regulations, there is a large amount of literature that cover the effects of other regulations on innovation. Stewart (2010) and Blind (2012) find that economic regulations have detrimental effects on innovation in general while social regulations induce compliance innovations at large from a broad cross-industry literature review and a quantitative assessment. From the empirical bifurcation, they draw an insight that the former is concerned with resource allocations rather than innovation while the latter is more likely to require compliance innovation to correct negative externalities. According to their definitions, economic regulations include price control, market entry conditions and the regulation of contract terms while social regulations include environmental controls, health and safety regulations (Table 2.5).¹¹

¹¹ These are generally compatible with OECD's taxonomy of regulations which include economic, social and institutional regulations (1997).

Table 2.5 Effects of Regulations on Innovations in the Literature

	Negative Effects	Positive Effects	Empirical Results of Net Effects
Economic Regulations (market entry, price)	<ul style="list-style-type: none"> - Prohibit entry of potential innovators - Reduce innovation activities 	<ul style="list-style-type: none"> - Positive for protection of infant industries - Flexible price schemes increase productivity 	<ul style="list-style-type: none"> - Stifle innovations in general - Positive in case of deregulation
Social Regulations (e.g. safety, environment)	<ul style="list-style-type: none"> - Create compliance costs - Reduce R&D spending on other areas 	<ul style="list-style-type: none"> - Incentives for new environmental tech. e.g. create barriers to non-innovators' entry 	<ul style="list-style-type: none"> - Ambivalent in the short run - Positive in the long run

Source: Adapted from Stewart (2010), Blind (2012)

Despite the efforts in finding causality between individual regulations and innovation effects, a systemic approach which analyses combined effects of the focal regulation with other regulations and policies is seldom found in the literature. A handful of literature pays attention to a narrow range of innovation instruments directly complementing the focal environmental regulations, such as public R&D (Walz et al., 2008; Ambec et al., 2011). Environmental regulations and their complementing policies, however, do not operate in a vacuum condition. For instance, electric utilities and HEI firms are heavily influenced by economic regulations with completely different intents, including price controls, market-entry regulations or sometimes fuel regulations, other than environmental regulations (see Section 2.2.1).

In this regard, Borrás & Edquist (2014) point out a potential fallacy of analysis of the effect of individual regulations on innovation. They articulate three reasons why it is difficult to find a direct causality between individual regulations and innovation effects. First, numerous complex factors, including wider socio-economic and technical factors, may intervene in diverse ways. Second, there could be a considerable time lag between a change of regulation and its eventual effects on innovation. Third, environmental regulations operate in complex interactions with other regulations and policies rather than operate in isolation. They argue that it is more realistic to pay attention to the effect

of regulatory frameworks, rather than the effect of individual regulations, on innovation. Thereby, there is a gap in the literature in capturing the combined effects of core regulations on catching-up performances of the HEI. The gap in the empirical literature and the findings in the review of theoretical literature lead to the third research question:

Research Question 3: To what extent, can a specific set of user sector's institutions explain the contrasting catching-up performances of the Korean HEI, as compared to the experiences of the Japanese?

2.5 Chapter Conclusion

The empirical literature of HEI firms in advanced economies shows that regulatory changes of their user sector, namely ESI, heavily affected the HEI firms' innovation activities and survivability. The regulatory changes and subsequent firms' survival efforts directly resulted in technology transfer from the firms to the two latecomer countries, namely Japan and Korea. In this regard, the corresponding regulations in the two latecomer countries might be important but the literature of catching-up HEI firms lacks the systematic analysis on effects of the regulatory asymmetry between the advanced economies and the latecomer countries.

In supplementing limits of HEI catching-up literature, the literature review on Korea's 'catching-up shift dilemma' in major manufacturing sectors shows lack of user-producer or producer-specialised supplier interactions as a main cause of the dilemma. The literature on the dilemma based on firm-capability approach lacks systemic analysis beyond firm capability given that users' aversion of domestic products or unavailability of technology transfer from advanced foreign firms is the problems beyond the focal firms' capability.

The theoretical literature review shows that the broad version of NSI would be suitable to analyse the cross-nation, cross-technology variation of the HEI latecomers in a specific catching-up economy context. In order to supplement its weak theoretical frameworks in investigating how the innovation systems function and how they evolve over time and in comparing national idiosyncrasies, it needs additional perspectives including the firm-level capability approach (Mathews, 2002, 2006), the hierarchical analysis of institutions (Williamson, 2000), and the regulatory framework perspective on innovation (Borrás & Edquist, 2014).

The supplementary perspectives contribute analytical concepts to explaining the cases, but individually they do not account for the overarching story. The firm capability approach helps to analyse catching-up firms' 'combinative capability' in limited resource conditions but has limits in analysing institutional factors in the catching-up context. The hierarchical analysis of institutions helps to analyse how and why core regulations on ESI evolved and to compare the national idiosyncrasies in a comparative manner but do not explain their relationship with catching-up performances. The regulatory framework perspective can explain the combining effects of core regulations on catching-up performances but lacks a perspective on the historical evolution of the regulations and affected firms' performance.

Thereby, the thesis will use the broad version of NSI as the main theoretical framework to integrate the analytical strength of the three supplementary perspectives while complements their limits (Table 2.6). By employing the broad NSI approach with consideration of firm capabilities, institutional evolution, and regulatory effects, it is possible to investigate comparatively the coevolution of the HEI and ESI sectors in Korea and Japan. The thesis aims to suggest an interpretive history of institutional, economic and technological development in the context of catching-up NSI through this combined framework.

Table 2.6 Analytical Framework based on the Broad NSI Perspective

	Capability of Latecomer HEI Firms	Core Regulations on User Sector (ESI)	Institutional Evolution
Narrow NSI	Linking & Leveraging - Absorptive Capability - Combinative Capability	Supporting Institutions - Public R&Ds - Facilitations of Technology Transfer	Institutions are Left-over Parts in Undifferentiated Contexts
Broad NSI	Latecomers' Adaptation to Domestic Regulations and Global Market Changes	Combined Effects of Environmental & Economic Regulations on Catching-up	Historical Evolution of Environmental & Economic Regulations

At the beginning of Chapter 2, the tentative empirical question was raised: “Why has the Korean HEI been unable to make the shift from its successful catch-up of nuclear technology to that of a globally emerging technology, namely the gas turbine, while its Japanese counterpart, an earlier latecomer, could do so?” The review of the empirical and theoretical literature reveals that the Japanese catching-up of nuclear power was unsatisfactory with its export performances despite its early technological indigenisation of commercial reactors.¹² In this regard, the two countries’ HEIs show dichotomously contrasting catching-up performances across the two technologies in terms of export. Thereby, the tentative question needs to be revised and elaborated further. The three research questions derived from the literature review are revisited here.

Research Question 1: Why did Japanese and Korean HEIs show contrasting catching-up performances between nuclear power and gas turbines in the past three decades?

¹² It should be noted that Japanese nuclear reactor vendors have sought to export their reactors with enthusiastic government support in the 2010s even after Fukushima Daiichi Nuclear Accident in 2011 (see Section 5.3.2 for details).

Research Question 2: What are the specific characteristics of inter-sectoral linkages between the HEI and ESI that might explain the cross-nation, cross-technology variation in catching-up of nuclear and gas turbine across Korea and Japan?

Research Question 3: To what extent, can a specific set of user sector's institutions explain contrasting catching-up performances of the Korean HEI, as compared to the experiences of the Japanese?

In addressing the above research questions, the analytical framework based on the broad version of NSI suggests a series of assumptions. The framework assumes that a regulatory set of a user sector (ESI) influences the catching-up ecosystem of HEI and systemically favours one technology over another through a specific chain of demands. The set of core regulations on ESI evolve through historic economic and social events within a given national context rather than randomly change over time. The technological performances in terms of operation and new construction based on the chain of demand offer domestic conditions for technology transfer from foreign licensors, change the rate of learning by repetition of construction projects, and build a track record for the technology in the global market (Table 2.7).

Table 2.7 Assumptions of User Sector's Institutions and Catching-Up

A Set of Institutions of ESI	Distinctive Inter-Sectoral Relationship	Catching-Up Performances
influences user-supplier relationship to a specific mode	systemically favour specific technology over another through a specific chain of demand	construction, operation, indigenisation, export

Although this thesis does not intend to establish a general theory on HEI firms' catching-up performance, it needs to suggest a theoretical proposition as a foundation for the research design. The research assumes that the cross-national variation of key institutions of ESI shaped the cross-national and cross-technology dichotomy of catching-

up, regardless of public R&D efforts. In this regard, the following research proposition is suggested below:

Research Proposition: Contrasting institutional sets of ESI between Japan and Korea have shaped the dichotomously contrasting catching-up performances of nuclear power and gas turbine technologies across the two countries, regardless of relative firm capability, sectoral arrangement, and public R&Ds in the HEI sector.

However, plausible rival explanations may arise from other theories or conjectures. To validate the credibility of the research design, the research must address these rival approaches before the selection of the research method. First, the cross-technology and cross-nation variation in catching-up performance could be attributable to differences in the technological capabilities of the Korean and Japanese HEI firms. Second, the cross-technology and cross-nation variation in catching-up performance could be argued to be mere coincidence, based on the SSI approach, which considers different technology classes as different sectors. Finally, the cross-technology and cross-nation variation in catching-up performance could be argued as a result of different R&D efforts, including the size of public expenditure and frequency of R&D projects, as a practical rival proposition. These three rival explanations can be formulated as rival propositions:

Rival Proposition 1: The cross-technology and cross-nation variation in catching-up performances is a result of different firm capabilities, including specialised supplier's capabilities.

Rival Proposition 2: The cross-technology and cross-nation variation in catching-up performances is a mere coincidence, given that the two technologies are different, and each has an independent sub-sector.

Rival Proposition 3: The cross-technology and cross-nation contrast in catching-up performance is a result of different R&D efforts, including the size of public expenditure and frequency of R&D projects.

In addressing the three rival propositions, the research will i) thoroughly gather and analyse the relevant data regarding the impact of capabilities of HEI firm and supporting industries, sectoral contexts including institutions and policies, and R&D efforts, and ii) demonstrate cross-national and cross-technology dichotomous catching-up performances which might verify the firm capability, sectoral system, practical approaches' claims throughout the comparative case study. The three rival propositions are addressed in the discussion and conclusion chapters.

Chapter 3. Research Method

3.1. Chapter Introduction

This Chapter develops a method based on the framework introduced in Chapter 2, describing the broad NSI framework in which the investigation of firm capabilities, institutional evolution, and regulation effects on catching-up will be conducted. This Chapter establishes a method to observe and measure i) the pattern and extent of the set of key institutions and ii) their impact on user-supplier interactions, which eventually enables iii) a catching-up of a specific HEI technology compared with other technology, for instance, nuclear power compared with the gas turbine.

In order to focus on the discussion, this Chapter centres on impact of inter-sectoral institutions regarding new construction and operation performances of the two technologies, given that the performances i) can be indicated by ‘track-record’ in each export market, ii) increase technological capability through learning by repetition of new build projects, and iii) offer adequate domestic market conditions for foreign advanced licensors to transfer technology.

As this Chapter explains, this research applies a qualitative comparative case study based on Korean and Japanese cases to highlight institutional impacts on user-supplier relationships regarding specific technology catching-up performance patterns. The Japanese case, however, is used as a reference case rather than a part of a full-blown case study considering the asymmetric nature of the two cases. In other words, the Japanese latecomers have superior technical capabilities in both technologies in terms of a few decades’ earlier technology localisation histories. Thereby, a few crucial periods of the catching-up process will be highlighted while the early localisation history will be only briefly reviewed. Thus, the research on the Japanese case mainly takes the form of

extensive desk research on previous case studies, technology reviews, local literature, archival records, statistics and interviews with a few key informants.

This measurement of the pattern and degree of an institutional set of a user sector and their impacts on the catching-up performance of the two technologies depends mainly on a qualitative comparative case study with supplementary descriptive statistics.

3.2. Methodological Review and Discussion

3.2.1. Quantitative Methods

Input-Output Analysis and Its Limitations

One of the typical methods for dealing with a specific industry's backward and forward linkage effects is Input-Output Analysis (I-O Analysis). Based on an 'inter-industry relation table', a given input is enumerated in the column of an industry, and its outputs are enumerated in its corresponding row. This format shows how influential and dependent each industry is a relation to all others in a nation, both as a customer of the nation's outputs and as a supplier of its inputs.

The most appealing contribution of input-output matrices concerns the impacts of economic activities on sectoral distribution and trade. For instance, 'leakages' due to imports from other countries may prove to be important for policy-making. Similarly, the impact of sectoral demand may prove to be important, particularly if it is considered that some sectors must be stimulated to accelerate the overall national growth rate. However, the efficacy of this approach lies in the broadness of the research scope (i.e. aggregation level) and the availability of an appropriate dataset. Its dataset is based on national standard industrial classification, which covers only large-scale industrial sectors.

However, economic output statistics are not always disaggregated enough to reveal the technological aspects of inter-sectoral trade, such as the extents of shifts from

lower to higher-value products (Williams & Larson, 1987). For example, the United Nation's International Standard Industrial Classification (ISIC) or national standard industrial classifications do not distinguish specialty products from commodity products, even in its finest classification units, namely four-digit classes. Thereby, Input-Output Analysis (I-O analysis) based on such statistics cannot capture inter-sectoral relationship beyond the broad aggregation level of the dataset. Its broadness of aggregation level itself makes it difficult to discern specific technologies from such a broad technology group. It has fundamental limits on distinguishing each detail in an industry sector, as well as the relevant technologies and products of the HEI and ESI.

For example, in the Japanese Input-Output Table, the 'Engines' sector (Column Code 3011-03, Row Code 3011-031) broadly defines 'the production activities for internal combustion engines' listed under Industry Number 2613 and 'Miscellaneous Engines and Turbines' listed under Industry Number 2619 of the Standard Industrial Classification for Japan (JSIC). Thereby, the sector includes various heterogeneous technologies, including 'atomic power reactors, water wheels, windmill engines, compressed air engines, parts, fixtures and accessories for general purpose internal combustion engines', as well as general purpose gasoline engines, kerosene engines, and diesel engines (Chapter VI. Concept, Definition and Scope by Sector, 2005 I-O tables of Japan).

Another example of basic sector classification of the Japanese Input-Output Table is 'Electric power facilities construction' (Row Code 4132-021). This basic sector is broadly defined as 'Electric business activities.... and facility construction work activities... relating to power generation, transmission and distribution.' Also, facilities replacement and repair work are included in this sector (2005 I-O tables of Japan). Thus, it is also impossible to capture technology-specific construction activities, such as nuclear power or gas turbines, from the input-output tables of Japan.

Similarly, in Korean input-output tables, sectoral categories face the same problems. For instance, at its basic industry level—which is the most disaggregated

industry grouping level in Korean Standard Industry Classification (KSIC)—the ESI is divided into nuclear power, fossil-fuel power, hydropower, and other power. Thus, it is impossible to directly compare the linkage effects of nuclear power to those of gas turbines with I-O analysis. Furthermore, the ‘construction of power plants’, which is the closest to the HEI sector, is not distinguished from the broad category of the construction industry. Even in its basic industry level categories, there is only an electrical construction category, which does not distinguish power plants from transmission and distribution network equipment. Thus, it is virtually impossible to distinguish and compare individual power generation technologies in terms of HEI performance.

Because the Input-Output Table does not provide detailed groups of technologies and products, it is difficult to compare the catch-up performance of the two technology cases with this tool. Although, in theory, one can decompose the basic level sector and re-group it into more fine-grained levels to investigate nuclear power and gas turbine’s inter-sectoral linkages, this approach requires a large-scale research project to cover a large amount of elementary data and proprietary information, which firms are unlikely to disclose. In this regard, I-O analysis cannot be used as a method to investigate inter-sectoral linkages between the two sectors of concern in this thesis. The excerpt below emphasises the problem:

...one could implement an input-output model with thousands of sectors or a world model with all of the approximately two hundred countries represented as potential trade partners. While the advantages of additional detail and disaggregation are evident, it should be recognised that there are also drawbacks. ... Clearly the availability of adequate data becomes much more problematic. (Duchin & Steenge, 2007:29)

Thereby, one cannot expect the I-O analysis to capture the detailed interactions between the two sectors, namely HEI and ESI, surrounding nuclear power and gas turbine catching-up performances.

Regression Analysis and Its Limitations

In measuring the effects of users' institutions on different technologies' catch-up performances, a multiple regression analysis can be considered. In a similar vein, a regression analysis needs a detailed and fine-grained time-series data set, which shows the catching-up or innovation performances of the HEI in relation to the other two sectors. The availability of such a data set, however, is limited to rather a small batch and large technology products of the HEI sector, namely nuclear power and gas turbine. Although such detailed data set in the ESI sector is available in the form of time-series data such as electricity price and power generation, regression analysis has limits in explaining the relationship between ESI and the HEI's catching-up performances due to the limited data of HEI.

3.2.2. Qualitative Methods: Comparative Case Study

Amongst several qualitative methods, including phenomenological research, grounded theory research, ethnographic research and case study research, case study research offers more utility in analysing the two sectors' interactions surrounding the catching-up process of the two energy technologies, while others are limited in their capacity to capture these interactions. A comparative case study contrasting technological catch-up performances between the two countries could increase explanatory power.

Multiple case studies have a replication logic which is analogous to that used in multiple experiments (Yin, 2009): 'The logic of multiple case studies is based on a careful choice of cases so that it either i) predicts similar results which imply "a literal replication" or ii) predicts contrasting results but for anticipatable reasons, which means "a theoretical replication". Subsequently, the framework needs to state either the conditions under which a particular phenomenon is likely to be found or the conditions when it is not likely to be found.' (Yin, 2009: 54). If two cases are selected based on their contrasting situations

and the subsequent findings support the hypothesised contrast, the results represent a robust step towards theoretical replication, which greatly strengthens the findings, as compared to those of single case studies (Eilbert & Lafronza, 2005; Yin, 2009).

However, the full-scale comparative case study on two countries with embedded units, such as two sectors and each sectoral institution, and their impact on dichotomous catching-up performances across the two technologies, is not feasible in this PhD thesis. As such, this thesis chooses the Japanese case as its reference point and carries out the Japanese case study mainly based on secondary sources of information, such as industry journal, technology review, historical archives, local literature, statistics, and interviews with a few available key informants.

Data Collection

This study's data collection depended mainly on in-depth interviews, archival records, technology reviews, industry journals, literature in local languages, sales records, published public expenditure and descriptive statistics during fieldwork. Following the main concepts of the abovementioned framework, the data collection focused on sectoral institutions and policies as well as technology indigenisation and the output of the two technologies, as described below.

Technology Catching-Up Policies

- HEI: Archival records, government reports, and technology R&D reports
- BMI: Archival records, local literature, and technology R&D reports
- ESI: Technical reports, electricity supply plans and electricity market statistics, and government policy reports

Sectoral Regulations

- ESI: Business and environmental regulations including emission standards, nuclear safety inspection standards, and electricity price and fuel cost statistics

- HEI: Archival records and government reports

Data of Technology Catching-Up Performances

- HEI: Domestic sales and export data, technology reports, corporate & trade journals, and technology review reports
- ESI: Construction and operation statistics

Participatory Observations

In addition, participatory observation results from the author's participation at industrial and governmental energy policy conferences are included. The author participated in a series of government energy policy conferences and workshops, including South Korea's conference 'The Second Basic Energy Demand and Supply Plan' process and subsequent workshops between June and December 2013, namely, 'Demand-Management Expert Working Group' for 'The Seventh Basic Plan for Long-term Electricity Supply and Demand's ' meetings between March 2014 and April 2015, as a panel and working group member. Those conferences and workshops offered the author invaluable chances to directly observe public comments from director-level government officials, manager-level industry leaders, and university professors during and after official meetings.

3.3. Research Design

3.3.1. Basic Concepts

Technology Catching-Up of HEI

This thesis defines technology catch-up of HEI by overall user-supplier interactions involved in construction, operation, indigenisation and modification of power generation technologies, in overcoming given constraints (or maximising given incentives), rather than specific R&D activities and technology indigenisation process.

This broad definition enables the research to include the innovative activities of latecomers in overcoming given institutional and technological constraints with their limited technological capabilities, as compared to their more advanced foreign counterparts. This conceptual perspective is consistent with the literature review. The broad version of NSI literature suggests a more realistic framework in a catching-up economy context, compared to the narrow version of NSI which assumes advanced networking capabilities between well-established NSI components. The empirical literature also points out a lack of user-producer relationship as a base of ‘learning by doing’, rather than narrowly focused research efforts, as the main cause of ‘Korean catching-up shift dilemma’.

Heavy Electrical Industry and Supporting Industries

As a central theme of the thesis, Japanese and Korean HEIs maintain both the business of nuclear power and gas turbines. Unlike Western HEI firms—which are specialised either in turbo-machinery, including steam turbine and gas turbines, or stationary structures, including boilers or steam generators—these two latecomer industries have attempted to catch up of both technological areas. As can be seen in Table 3.3, the two HEI technologies can be divided into the Steam Generator (2513) and Engines & Turbine (2518) classes in the ISIC (Rev. 4). Most of public R&D for the catching-up of nuclear and gas turbine technologies are focused on the HEI, while specialised supporting industries are involved in such R&D as upstream technology suppliers. The HEI firms are constrained not only by their own sectoral institutions, such as trade and entry regulations but also by those of the ESI sector.

Although the thesis is focused on inter-sectoral issues rather than firm-level ones, it is inevitable to narrow down the analysis unit into representative HEI firms in the two countries to observe detailed catching-up processes. While *Doosan*, including its

predecessor (KHIC), is selected in the case of the Korean HEI, MHI is selected among the three major HEI firms, including MHI, Toshiba, and Hitachi, in the case of Japanese HEI. *Doosan* and MHI developed PWRs under US firms' licences, whereas the other two Japanese HEI firms developed boiling water reactor (BWR) technology under GE's licence (Table 3.1 and 3.2). Given that PWRs have been developed in both countries while other reactors are either obsolete, such as CANDU reactors, or operate in a specific nation between two cases, such as BWRs in Japan, suppliers of PWRs are chosen as main subjects of analysis in the thesis.¹³

Furthermore, PWR is the dominant technology in the global nuclear market in terms of operating units and new construction projects whereas other reactors are limited in unit numbers and their construction orders have been virtually absent for the past decade or concentrated in a few countries. Among 416 operable nuclear reactors in the world as of 2018, PWR's share is about half with 204 units across sixteen countries. By comparison, its competitors are limited to historically accumulated political ties between supplier and host countries. BWRs are concentrated in the US and Japan with 75 units in total, pressurised heavy water reactors (PHWRs), commonly known as CANDU, are concentrated in Canada and India with 50 units in total, and Russian PWRs (VVERs) are concentrated in Russia and Eastern Europe with 53 units in total (Inside NRC Statistics Monthly, 2018).¹⁴

Among about 50 reactors under construction in the world as of 2018, 28 units are PWRs, originated from Westinghouse technology, 12 units are VVERs, and four units are PHWRs. Although two Advanced BWR(ABWR) units are recorded under construction status, namely Shimane-3 and Ohma in Japan, the prospect of the projects has hardly improved due to strengthened nuclear safety regulations and negative public acceptance

¹³ Although Korea has four CANDU reactors, Korean ESI and HEI abandoned the technology.

¹⁴ Most of remaining reactors are outmoded Former Soviet Union's graphite reactors (RBMKs) and British gas cooled reactors.

since the Fukushima nuclear accident in 2011. Although *Chugoku* Power, a Japanese electricity supply firm, applied for verification of compliance with the new regulatory requirements of *Shimane-3* in August 2018, there is no definite prospect that the reactor could start operation eventually (Schneider et al., 2018; *Chugoku* Electric Power Co., 2018).

Prospect of BWR needs more explanation in that it has been the main competitor of PWR in the US and Japanese markets. While BWRs are technically less complicated than PWRs given that the former directly use steam from reactor coolant water to drive turbines and do not need steam generators for heat exchange, the technical simplicity causes extensive radioactive contamination of the whole plants (Thomas, 2005). It leads to concerns on higher radiation exposure of labours. For instance, BWRs' average collective radiation dose per reactor has been 90% higher than that of PWRs in the US between 1974 and 2016. Although the average collective radiation dose of both reactors has decreased in absolute terms, the relative dose rate of BWRs to that of PWRs has hardly improved during the same period (US NRC, 2017). The concern has been the main reason why BWR has not been seriously considered by electricity power utilities in the global market (MacKerron et al., 2006) (Table 3.1 and 3.2).

Table 3.1 Selection of a Case Amongst Japanese Heavy Electrical Industry Firms

		Nuclear	
	Licensors	Westinghouse (PWR) 1960–'91	GE (BWR)
Gas Turbine	Westinghouse 1961–'87	<i>Mitsubishi (MHI)</i>	
	GE 1964–present 1982–present		Hitachi Toshiba

Table 3.2 Selection of a Case Amongst Korean Heavy Electrical Industry Firms

		Nuclear	
	Licensors	CE/Westinghouse (PWR)	AECL (CANDU)
Gas Turbine	GE (1990–2005) MHI (2005–present)	<i>KHIC (1980–'97)</i> <i>Doosan (1998–present)</i>	
	Westinghouse	<i>Hyundai Heavy Industry</i> (1977–'80, 1994–'97)	

Electricity Supply Industry and Demand Conditions

The ESI's main activities can be broadly defined as the construction and operation of power generation facilities, procurement of fuels for power generation, and sales of electricity to users with differentiated pricing schemes. The associated business activities are heavily influenced by the mode of ownership (whether private or state-owned) and overall regulations from energy ministries.

In turn, the ESI's business activities influence its major user sectors including electricity-intensive basic metal industries (BMI). At the same time, the BMI characterise demand conditions of the ESI in terms of bulk base-load electricity consumers, which shapes base-load power plant projects. The BMIs supply large volumes of primary metal products, such as aluminium and steels, based on cheap and abundant electricity, and are important industries to the ESI as major base-load customers (Table 3.3).

Table 3.3 Sectors from International Standard Industrial Classification

Division	Group	Class	Relevant Segments	
24. Basic Metals	241. Basic iron and steel	2410. Basic iron and steel	Re-melting of scrap ingots of iron or steels (EAF), Seamless tubes (specialty steels)	BMI
	242. Basic precious & other non-ferrous metals	2420. Basic precious & other non-ferrous metals	Production of Aluminium	
	243. Casting of metals	2432. Casting of Non-Ferrous Metals	Precious Metal Casting (Precision Casting)	
25. Fabricated Metal Products	251. Structural metal products, tanks, reservoirs & steam generators	2513. Steam Generators	Steam Generators, Nuclear Reactors	HEI
28. Machinery & Equipment	281. General Purpose Machinery	2811. Engines & Turbines	Turbines and Parts: Gas turbines	
35. Electricity, Gas, Steam & Air Conditioning	351. Electric power generation, transmission & distribution	3510. Electric power generation, transmission & distribution	Operation of Power Generation Facilities, Sale of Electricity to Users	ESI

Source: Adapted from UN ISIC Rev.4 2008

Note: The relevant industry segments are added by author on the right columns.

Institutions of the Electricity Supply Industry

The overall literature review draws attention to user sector institutions and their overall impact on the HEI catching-up performance through specific user-supplier relationships. Although there are conceptual overlaps between institutions, policies and regulations, the research considers all the three concepts as competing elements of institutional governance of the ESI, often established by different historical events or different government agencies in a national context. Some of the institutions could be intentionally set-up in relation to specific catching-up policies while others might be unintended and historical results beyond the authority of a specific government agency such as an energy ministry. Environmental regulations of ESI, for instance, do not belong

to the jurisdictions of energy ministries, but still heavily influence the ESI's technology and fuel choices. This assumption offers a dynamic perspective of catching-up efforts in a complex context consisting of incentives and constraints compared to static and narrowly defined catching-up policy perspective.

Also, the research assumes that sectoral institutions of the ESI shape 'quality of demand' for supplier's catching-up performance based on the broad version of NSI literature. This means a specific set of ESI institutions might incentivise catching-up performance of a specific technology while constraining that of another. Also, the research assumes the degree of the incentivising effects or constraining effects on a specific technology catching-up performance is proportional to the degree of demanding quality set by the ESI's institutions if other conditions are equal.

From the empirical literature review, most frequently depicted institutional elements of ESI are economic and environmental regulations. Although no generally accepted definition of regulation can be applied to the very different regulatory systems in OECD countries (OECD 1997a: 6), the OECD addresses regulation as the diverse set of instruments by which governments set requirements for enterprises and citizens for economic development, environmental protection and social cohesion (Table 3.4). From this classification, economic regulations and environmental regulations of ESI will be further elaborated in Section 3.3.2.

Table 3.4 OECD's Classification of Regulations

	Economic Regulations	Social Regulations	Administrative Regulations
Examples	Pricing, competition, market entry/exit	Health, safety, the environment, social cohesion	Paperwork, administrative formalities

Source: OECD 1997 a, Organisation for Economic Cooperation and Development (OECD) Report on Regulatory Reform Synthesis, Paris: OECD

Furthermore, the concept also complements the firm-capability approach. Although firm-capability approach captures catching-up firms' effort to overcome technology barriers through linking and leveraging with foreign firms, the approach does not capture a specific context in which the latecomers interact with foreign firms. The context regarding regulatory frameworks can be divided into three points. They include i) asymmetry of (economic) regulations between advanced economies and catching-up countries, ii) different effects of (environmental) regulations for foreign firms and local firms, and iii) overall effects of regulatory frameworks on domestic catching-up eco-systems including users, producers and upstream suppliers. The three points need some explanation.

First, the regulatory asymmetry between advanced and catching-up countries can open a window of technology transfer from foreign firms to latecomers. Specific economic regulations, which stifle a specific technology in advanced countries, may induce firms to turn to latecomer countries, which do not regulate them in the same way and increase the potential of technology transfer to the latecomers. Second, the environmental regulations in catching-up countries may have different effects between local firms and foreign firms. The former may consider the regulations as a strategic issue for long-term growth at the home market while the latter regard the regulations as a temporary or secondary issue compared to those of their own home market, as can be seen in the case of US firms' indifference to environmental regulations in foreign countries above. This perspective helps to capture a potentially active role of catching-up firms beyond a mere beneficiary of technology transfer from foreign firms. Finally, core regulations on ESI may shape overall catching-up eco-system of domestic users, suppliers and specialised suppliers and their interactions in response to the regulations may shape directions and degree of the catching-up performance.

3.3.2. Operational Definitions

The proposition of the sectoral institutions of the user and the effects on catching-up performances of HEI is articulated by operational variables in this Section. Among various institutions of ESI, institutions that affect the cost and environmental performances could be the key 'quality of demand' factors in inter-relationships with HEI. Thereby, business and environmental regulations are derived as key institutions. The two key institutional elements are narrowed down as below:

- Business Regulations of ESI: Among the business regulations, a specific electricity pricing scheme, such as Time-of-Use (TOU) pricings, for industry customers, and gas fuel procurement contract, which decides relative gas fuel cost of ESI, will be measured. Both regulations of the ESI business play a crucial role in allocating energy cost to different customer sectors, and at the same time influence operation and new construction performances of nuclear and gas turbine.
- Environmental Regulations of ESI: Regarding nuclear power, safety regulations and practices on steam generator tubes are selected. The steam generator issue is derived from American HEI's experience as depicted in Section 2.2.1. Also, environmental regulations on gas turbines are narrowed down to NO_x emission standards and regulatory practices. This issue is also derived from the experiences of the global gas turbine OEMs as depicted in Section 2.2.1.

Regarding the institutional effect on the HEI's catching-up performances of nuclear power and gas turbines, two types of operational variables, including quantitative and qualitative variables, are derived from the basic concepts as articulated in Section 3.3.1. Given the research defines catching-up of HEI as user-supplier interactions involved in construction, operation, technology transfer, and technology modifications, operational and construction performances are considered as the direct effects of the sectoral institutions of the user. In addition, further effects of the sectoral institutions of user can be 'learning by doing' through repeated construction projects and technology modifications efforts in order to overcome environmental and safety regulations of ESI. While the direct effects are observed in quantitative data, the indirect effects need to be analysed in a qualitative way (Table 3.5).

The institutional set of ESI and catching-up effects of HEI in explaining cross-nation and cross-technology dichotomy of catching-up performance will be compared to operationalised terms of the rival propositions in Section 7.3 in Chapter 7.

Table 3.5 Variables for Cross-Nation Comparison of ESI Institutions & Effects

Institutions of ESI		Direct Effects (Descriptive Statistics)	Indirect Effects (Qualitative Analysis)
Gas Turbine	Fuel Contracts	Gas fuel price (operation, construction)	Learning by doing (repeated construction)
	Emission regulations	Operation and construction of GT	Technology modification for emission control
Nuclear Power	Electricity pricing	Growth of base-load demand (new construction)	Learning by doing (repeated construction)
	Safety regulations	Operational performance of nuclear power	Technology modification for safety improvement

3.3.3. Operationalisation of Rival Concepts and Approaches

In order to verify the three rival concepts and approaches will be operationalised as below.

First, the firm capability approach might claim that different capabilities of HEI firms, including upstream suppliers, are the causes of the cross-technology and cross-nation contrast of catching-up performances. In this regard, the technology scope that each of HEI firms will be analysed in terms of indigenisation of nuclear steam supply system (NSSS) in the case of nuclear power, and the level of development and commercialisation performance of gas turbines in the case of gas turbines. In addition, the research will also analyse supporting specialized metal firms' capabilities in terms of their manufacturing capabilities in a few key component technologies, including steam generator tubes in the case of nuclear power, and turbine blades and vanes in the case of CCGT.

Second, the rival explanation of the SSI approach will argue that the two technologies are irrelevant to each other given that each of technology may have each one's sectoral system. In this regard, the rival explanation of the SSI approach is operationalised through pattern matching of institutional impact on catching-up performances of each technology in terms of operation, construction, technology transfer, technology modification, and export. If random patterns in the impact of ESI's business and environmental regulations on the performances are observed, the SSI's explanation could be verified as genuine. However, if consistent patterns are observed, it implies that the two technologies are bounded by the same sectoral institutions and the rival claim will be rejected.

Third, the practical rival explanation based on R&D efforts is operationalised in terms of size of major R&D expenditure, and duration and frequency of R&D programmes. The R&D expenditure and frequency will be compared to the catching-up performances of each technology. If consistent patterns between the R&D efforts concepts and catching-up performances are observed the rival claim will be verified as genuine. However, if the patterns are inconsistent, it will be rejected.

In addition to these specified rival explanations, there might be unspecified factors which have random effects. While statistical models can render such unspecified rival hypotheses implausible to a certain degree, qualitative case researches cannot control such potential of random effects in a complete manner. The only way to minimise such potential is to address the most plausible rival hypothesis to the main one. The primary hypothesis, namely causality of a broad version of NSI, assumes a specific combination of environmental and economic regulations of ESI induce a successful catching-up of particular technology over another. The hypothesis can be supported by the expected opposite combination of environmental and economic regulations in the reference case, which shows the different catching-up performances concerning the relative success of CCGT and unsatisfactory nuclear power.

Finally, it is necessary to address an implicit hypothesis of the thesis. It assumes that both nations have the intent of developing every variety of modern energy technology and export markets for them. The assumption is based on the conspicuous export-driven industrial policies of both countries in overcoming the deficiency of natural resources and limits in the domestic market size. Although it is a contestable premise, it is essential to evaluate the potential performance of the energy technology catching-up in both nations. This underlying axiomatic assumption is necessary to support the argument throughout the thesis and will be addressed later in Chapter 6.

3.3.4. Interview Protocol

Interviews on the Korean Case

Uniform formats of interview questions for interviews are difficult to define for such varied industry sectors, relevant actors and agencies as the firms of the HEI, ESI and BMI, environmental and business regulators, and government policymakers in this thesis. Equally, key informants who have comprehensive insights into both sectors, along with the relevant policies and institutions surrounding nuclear power and gas turbine technologies, are rare. Thus, the open interview format is inevitable for this study, with a particular concern with finding key informants per sector and institute.

Although the open-ended interviews do not have a uniform format exhibited by other methods, such as survey methods, the openness itself can help reveal how the interviewees construct reality (i.e. understand states of affairs) regarding the theme of the research, even beyond the researchers' specific questions (Yin, 2009). If the interviewees are key persons in the organisation or industry, the open-ended format can provide indispensable insights that researchers' initial questions do not capture.

Interviews with key persons in each sector were prioritised, such as a head engineer or general manager of firms and director-level government officials. More informants were sought for the ESI than for the others, given that the institutions of the

ESI heavily influence the other related sectors. Considering business regulations, including fuel pricing and electricity pricing practices, and environmental regulations, each relevant regulatory or government officials were interviewed.

To validate the interviews' credibility against interviewees' specific bias, all the interview results are triangulated with other information sources including other interviewees, documents, statistics and literature. Only validated interview results are presented in the case chapters. The interviewee list is added in Appendix C.

Interviews on the Japanese Case

The comparative case study considers the Japanese case as a reference rather than a 'full-blown' study case. Thereby, the study on the Japanese case depends mainly on secondary information sources, while conducting interviews with a few key informants in Japan. To supplement the limited empirical investigation in the Japanese case, the author asked Korean interviewees the same questions about their Japanese counterparts during the interviews as often as possible.

The interviews in Japan were conducted with a few key industry leaders and government officials in the nuclear catching-up case, as well as with the co-authors of a Japanese gas turbine catching-up report based on the 'Moonlight Project' (Kimura & Kajiki 2008) in the gas turbine case. The interviews with the author of the Japanese gas turbine catching-up report were conducted in three sessions, between 2010 and 2012, together with separate email discussions to gain insights into critical aspects beyond the contribution of the 'Moonlight Project' to the catching-up performances. The interviews and discussions with additional statistics led the Japanese case study to focus on the inter-sectoral impact of institutions. Although the number of interviews is quite limited, they led authors to key issues not captured in the initial research plan and led them to reinterpret the relevant literature, documents and statistics from a new perspective,

particularly regarding institutional issues. All the interview lists in the two countries are presented in Appendix A.

Choice of Interviewees

In-depth interviews were conducted to capture the effects of ESI's institutions on catching-up performance to answer the research questions and hypothetical assumptions. The rationale for choices of interviewee is described below.

- Interviews with director-level energy and industry ministry officials in charge of electricity demand and supply planning and those in charge of nuclear and gas turbine technology R&D projects were conducted to understand the policy-making background, which is not normally expressed in official documents. They, on the other hand, directly regulate ESI's businesses from gas fuel for power generation to electricity prices for industrial customers.
- Researchers from public R&D institutes were also interviewed since often the public R&D institutes have been hosts of nuclear power and gas turbine technology development projects. Interviews with senior researchers of the institutes were focused on examining main enablers and obstacles in explaining the successes and failures of the projects.
- As the main actor, the HEI firms design and manufacture nuclear power and gas turbine systems and subsystems. Senior engineers or management personnel could directly answer the research questions.
- As a user sector of HEI, the ESI covers managers and subsidiary R&D centre researchers, who were chosen to investigate their direct relationship with the nuclear power and gas turbine suppliers. In addition, pricing managers were also chosen to examine ESI's relationship with BMI customers (Table 3.11).

Table 3.6 Overall Feature of Interviewees

	Japan		Korea	
	Nuclear	Gas Turbine	Nuclear	Gas Turbine
Government (Policy-Maker & Business Regulator)	Vice chair of JAEC, Deputy director & officer (METI)		One retired & two current directors (MOTIE)	
Public R&D Institute	Retired senior researcher (CRIEPI)	Author of Japanese GT catch-up report (CRIEPI)	One retired & two senior researchers (KAERI)	Two senior researchers (KIMM)
Safety & Emission Regulator			Senior researcher, regulatory policy office (KINS)	Officer of air quality division (ME)
HEI Firm		Secondary information from Korean interviewees	Principal engineer of steam generator & senior engineer (<i>Doosan</i>) Former director of KEPCO Nuclear Fuel (KNF)	Head of gas turbine development, senior researcher & two senior engineers (<i>Doosan</i>) Material researcher (<i>Doosan Central R&D Institute</i>), Executive director of Research Centre (KLW), Former Senior Engineer (HHI)
ESI Firm	President of JAIF General manager of (FEPC)		Former quality control manager (KHNP) Manager of pricing office (KEPCO)	Three senior researchers (KEPRI) Marketing manager (Private IPP)
Export Consortium	Chief Officer (JINED)		General Manager of Power Plant Service (<i>Doosan</i>)	Senior Economic Analyst (KDB)
University			Energy economist (Korea Polytechnic) Electric power economist (<i>Konkuk Univ.</i>) Electricity network engineer (<i>Hongik Univ.</i>)	

Note: See Abbreviations in List of Acronyms

Chapter 4. Korean Case

4.1. Chapter Introduction

The Chapter shows how catching-up performances of nuclear power and gas turbine technologies progressed in contrasting ways, in conjunction with a specific set of ESI institutions. It shows selective match and mismatch between each of the technologies and the set of ESI institutions. In explaining the process of contrasting catching-up performances across the two technologies, it thus mobilises the co-evolving processes of the ESI and HEI sectors.

A virtuous circle between the nuclear power of HEI and the commodity BMI, and a vicious circle between gas turbines and the specialised BMI are explained through the set of institutions which governs the ESI. It highlights to what extent the historically established institutional set of business and environmental regulations of the ESI shaped the divergent pathways of the two technologies in Korea.

Section 4.2 analyses Korean ESI and its specific set of institutions based on a historical perspective. Section 4.3 describes the Korean HEI's contrasting catching-up performances across nuclear power and gas turbine for the past three decades. It also describes supporting industries' performances. Then, Section 4 analyses the effects of the ESI institutions on the interaction between the ESI and HEI, and contrasting catching-up performances between the two technologies.

4.2. Electricity Supply Industry Sector: KEPCO

4.2.1. Brief History of Korean ESI

From the establishment of *Hansung* Electricity Ltd. for lighting service in Seoul in 1898, early Korean electricity suppliers grew to 63 in 1934. As the Japanese military occupation increased its control over the electricity supply business, the number of suppliers reduced, and the structure was vertically integrated from the late 1930s. After the attack on Pearl Harbour in 1941, the Japanese occupiers merged private utilities, nationalising them into *Chosun Jounup*, ‘Chosun Electricity Business’ in Korean, for rapid mobilisation of cheap electricity supply to strategic heavy industries for warfare in 1943 (Kim, I., 1998; Oh, 2011).

Once WWII was over, the Korean electricity supply business was re-privatised by the American occupation regime in 1945. After the military coup of *Park Chung-Hee* in 1961, however, three private electric utilities were merged and nationalised as a monopoly utility, namely the Korea Electric Power Company (KEPCO). Although the military state justified the nationalisation as a necessary measure for rapid economic development, the nationalisation resembled the wartime measures applied by Japanese military occupiers during WWII.

Thanks to the country’s rapid economic growth, KEPCO’s power generation capacity increased from a mere 367 MW in 1961 to about 71 giga-watt (GW) in 2013. It owns six power generation subsidiaries (GENCOs), an architecture and engineering firm (KOPEC), a maintenance and repair firm (KPS), a nuclear fuel supplier (KNF), amongst others, as of 2013. Although there are three independent power producers (IPPs) based on gas turbine combined cycles, small-scale co-generation service providers, and miscellaneous renewable energy providers, their share is rather small, accounting for 13.2% in 2013 (KEPCO, 2014). On the demand side, industrial customers consume around 52%, whereas commercial ones consumed about 21% of total electricity in 2013. The large

share of industry customers in electricity demand is markedly different from other OECD counterparts, which mostly range from about 20% to 40% (IEA, 2013).

From Massive Reserve to Tight Supply in the 1980s and 1990s

Massive investment in nuclear reactors in the 1970s worsened both the HEI and ESI sectors' position to face the second oil shock in 1979, which caused a domestic and global recession. Thus, KEPCO had to implement a massive load-building programme to manage unbalanced electricity networks with depressed demand growth and the sudden input of large nuclear power capacity during the decade (Song, 1999). Accordingly, KEPCO arranged a special 40% discount to steelmakers in addition to a 60% discount on electric bills to the manufacturing industry sector, compared to a 40% discount on the commercial and residential sectors, on average, during the decade (Auty, 1995; Song, 1999).

As a result of massive load-building activity as well as the global economic recovery in the mid-1980s, KEPCO met a dramatic demand surge in the late 1980s and early 1990s (KEPCO, 1991). It could not respond to the demand surge with nuclear and coal in such a brief period, however. Instead, it inevitably had to import massive capacity of CCGT (around 11 GW), which has a short construction lead time and flexible characteristics, mostly from GE and Siemens. In effect, in a global market view, it was a natural trend to introduce massive CCGT to respond to the recovery of the global economy and subsequent electric demand hike. For example, electric utilities in Japan, Indonesia, Thailand, and India installed systems with capacities similar to that of CCGT to cope with the demand surge in the same period (Watson, 1997).

Nevertheless, the Korean government restricted natural gas for electricity generation by imposing a considerable share of the cost of the city gas business on the national ESI from the mid-1980s. Thus, KEPCO also had to restrict the operation of the

CCGT units only for peak-load purposes to save on the high cost of gas. Then, KEPCO had to pay additional costs for repair and replacement of crucial parts. In this way, a vicious circle between the institutionally high natural gas price, in addition to the 'Asian premium' of LNG price, and the peak-load mode operation of base-load-purpose CCGTs went on throughout the 1990s.

Stalled Restructuring and Continuity of the State-owned ESI in the 2000s

At the end of the 1990s, when the country experienced the financial crisis, the government's policy exercise through KEPCO was challenged by the International Monetary Fund (IMF). Following economic reform recommendations from the IMF, the Korean government launched a privatisation programme for KEPCO and KHIC at the end of 1990s. Thus, KEPCO's electric power generation sector was divided into six subsidiary generation companies (GENCOs), which consist of one nuclear GENCO, namely Korea Hydro and Nuclear Power (KHNP), and five fossil-fuel-based GENCOs in 2001.¹⁵ However, resistance from labour unions changed the government policy under the *Roh Moo-hyun* administration, and the privatisation plan was officially ceased in 2005. As a result, KEPCO's subsidiary GENCOs produce about 89% of electricity while a few private IPPs contribute the remaining 11% as of 2016 (KEPCO, 2017).

4.2.2. Demand Conditions of ESI: Basic Metal Industries

Aluminium Smelters in the 1970s and 1980s

The aluminium smelter industry started operation from 1969 in Korea when the country's aluminium demand started to grow. Korea Aluminium Company (KAC) constructed a smelting plant with a capacity of 15,000 tonnes in terms of annual production. The project was financed by a private loan from Japan as well as domestic credit. KAC's plant met nearly the entire domestic aluminium demand in 1970. The

¹⁵ KEPCO's privatisation programme was withdrawn due to political resistance in 2005, but the six GENCOs are still divided from their parent firm, KEPCO.

country's import of aluminium, however, began to rise rapidly as domestic demand increased further (Stern et al., 1995).

Due to the global energy crisis in the early 1970s and the big gap between product prices and imported ones, KAC went into bankruptcy in 1972. Then, Korea Development Bank, a major shareholder of domestic credit, and Pechiney from France jointly took over the bankrupt firm and changed the name to Aluminium of Korea Co. (AKC) in 1972.¹⁶ The joint firm expanded the production line by 2,500 tonnes to meet the growing domestic demand of aluminium in 1973. Nevertheless, Korea's dependence on imports rose from 21% to over 90% in the 1980s (*Maeil Business Newspaper*, 1973; Stern et al., 1995).

Although the Korean government devised several supporting institutions to protect the domestic aluminium industry, there were fundamental problems surrounding the industry. First, the electricity price, which accounts for nearly 40% of the total cost of the global aluminium-smelting industry, was too high to compete with foreign aluminium smelters from energy-rich countries. Second, the London Metal Exchange began to trade aluminium ingot in 1978, and it became an international commodity, freely available at international market prices from that point (Uriu, 1996). Third, the smelting technology that AKC used, the Soderberg smelting process, became obsolete a few years later with the introduction of a new process technology that saves vast amounts of energy (Stern et al., 1995).

Although KEPCO supplied electricity to the aluminium smelter at a subsidised electric rate, thanks to redundant nuclear capacity in Korea from the late 1970s to the 1980s, the joint owner of the company, namely Pechiney, withdrew the business from

¹⁶ It should be noted that Pechiney had built its own numerous hydroelectric power plants in France before the Second World War. Once all the power plants and electric price control were taken by EDF in 1946, controlling electricity prices became a priority for the French aluminium conglomerate. Then, it sought foreign interests in countries. For further reading, see Godelier and Roux (2005).

Korea, and the special electric rate was ceased in 1989. Even with electricity at half the price of the average industrial price, it was difficult for the smelter to compete with aluminium smelters from Canada or Nordic countries—where cheap hydroelectric power resources are abundant—in the global market. Indeed, the Korean electricity price for industry customers was three to four times that of those hydro-abundant, aluminium-producing countries throughout the 1980s (Table 4.1).

In effect, the co-owner, Pechiney, had already made a special electricity supply agreement with the Canadian government for a \$1.5 billion aluminium-smelting factory in Becancour, Quebec, in 1980. It was at a price of less than 0.8 cents/kWh, which was less than half of the average Canadian electric rate for industry of 2 cents/kWh at that time (Michal, 1984), or one-fifth of the price of the special electricity rate for aluminium smelters in Korea, which was around 4 cents/kWh in 1980. Thus, it was a result of a rather naïve expectation of the potential of cheap nuclear power amongst decision-makers, who were ignorant of international aluminium market conditions at that time.¹⁷

In this way, the temporary alliance between KEPCO and the aluminium smelter industry ended in the late 1980s. In effect, Korean ESI already started to suffer from massive increases in electricity demand as a result of repeated electricity rate discounts across all types of customer groups throughout the decade. Thus, it did not have any more room to further discount electricity rates for the aluminium industry in the late 1980s. Instead, it had another electricity-intensive metal industry, namely electric arc furnace (EAF) steel (Table 4.2); EAF became the most electric-intensive metal industry after the aluminium industry left Korea.

¹⁷ Open comments of Professor *Seungjin Kang* from Korea Polytechnic University during a conference meeting for the 2nd Energy Demand & Supply Basic Plan on 21 June 2013.

Table 4.1 Electricity Price for Industry in Aluminium-Smelting Countries

Unit		1978	1980	1985	1990
US cents per kWh	Norway	1.2	1.8	2.0	3.5
	Canada	1.5	2.0	2.6	3.6
	Sweden	2.9	4.0	2.8	5.0
	Korea	4.3	8.1	7.6	7.0

Source: International Energy Agency (IEA) 2001

Note: It shows average electricity prices for industry rather than specific prices for aluminium smelters based on special agreements between the smelters and power suppliers.

Table 4.2 Electric-Intensity of Korean Metal Industries in the 1980s (kWh/tonne)

	Aluminium	EAF Steel	Integrated Steel Mill
1986	15,734	456	51
1987	15,663	447	51

Source: Kim 1989

Note: Integrated steel mill consists of blast furnace (BF) and basic oxygen furnace (BOF).

Electric Arc Furnace Steel Industry from the 1980s to the 2000s

Once the aluminium industry left the Korean market in the 1980s, the iron and steel industry filled the gap in terms of KEPCO's base-load demand. Although POSCO is the well-known Korean commodity steelmaker based on the basic oxygen furnace (BOF), the country has another type of commodity steelmaker, which depends on EAF technology. It is another electric-intensive heavy industry that entirely depends on electricity for the smelting and refining of scrap steels. While BOF steelmakers produce carbon steels for diverse markets from automobile to shipbuilding, EAF steelmakers produce somewhat limited and low-end steel products for construction and civil engineerings, such as steel bars for concrete reinforcement material and structural beams. There are seven EAF steelmakers, and three of them—*Hyundai*, *Dongkuk*, and *Daehan*—dominate 80% of the EAF steel market in Korea as of 2010.

Korean EAF production capacity tripled and tied itself to that of BOF during the 1990s. Its share in Korean crude steel production increased from less than 30% in the 1980s to above 40% in the late 1990s and 2000s. Its share outpaced that of the world average throughout the past three decades (World Steel Association, 1983–2010). It is an impressive performance, given that the country depends on imported scrap steel for EAF steel and imported fuels for power generation. It can be explained by its special relationship with the ESI (see Section 4.2.4 for further detail).

In effect, Korea has been one of the biggest scrap steel importers in the world due to the rapid growth of its EAF steel production in the 1990s and 2000s. Its annual imports reached to more than five million tonnes, which took about one-third of total input scraps, in the mid-2000s (*Hyundai Steel*, 2009). While more than half of its domestic scrap steel consists of low-quality scraps that cannot be used for high-end steel products, it depends on imported scraps for high-quality scraps, including pig iron, mostly from Japan. Furthermore, the low-quality scraps consume more electricity per unit weight for purification.

On the contrary, most Japanese EAF steelmakers securely procure high-quality “home-grown” scrap steel, namely pig iron, from their *Keiretsu* member BOF steelmakers, and they export even more than seven million tonnes of surplus scrap steel to Korea and China. In effect, the voluntary control of EAF steel production capacity came from a combination of the BOF-steelmaker-led strategy for the overall Japanese steel industry and its arm’s length relationship with the ESI (Uriu 1996) (see Section 5.2.4).

The lack of strategic control over demand and supply of high-quality scrap steels and, subsequently, more electricity-intensive characteristics of Korean EAF made the industry desperately lobby the government to control the price of electricity. Although the cost of electricity accounted for around 5% of overall Korean EAF production costs in the past decade, it should not be underestimated, given that hiked prices of global scrap steels in the last half of the 2000s, thanks to the ‘Beijing Olympic Boom’, made the relative

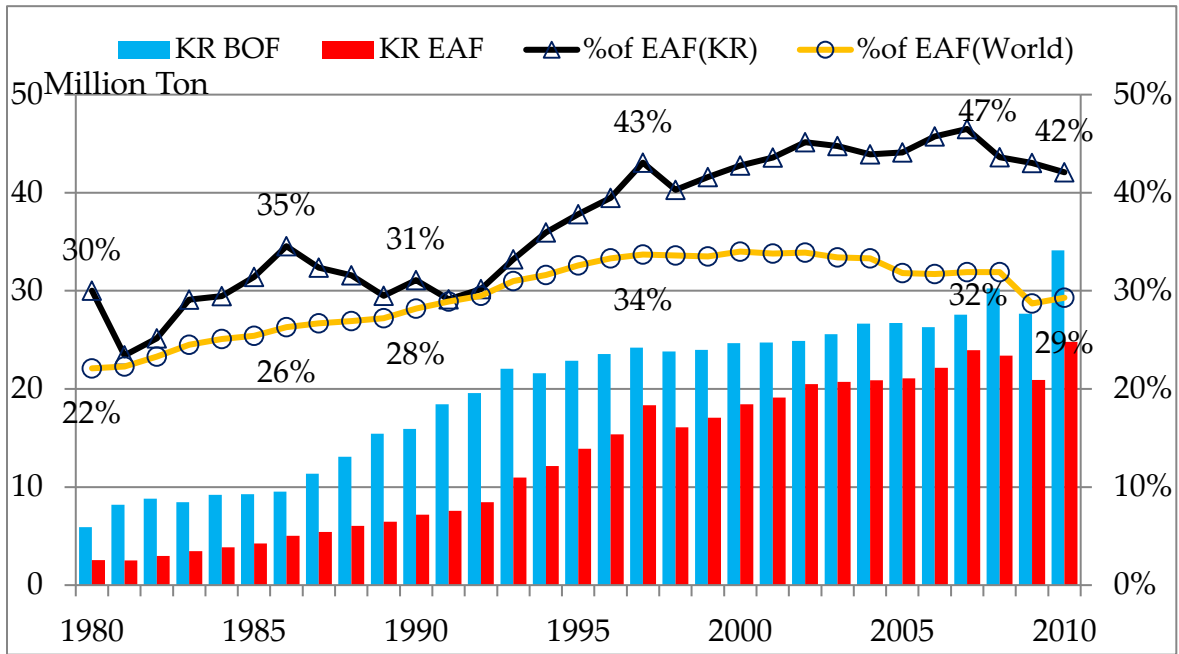
share of electricity costs in the industry look much smaller than they were (Minter 2004, McCurry 2007). *Kyungsik Kim* from *Hyundai Steel*, the biggest Korean EAF steelmaker, explains additional reasons why the industry focusses on electricity prices rather than scrap steel.

Although we try to save scrap steel input cost through every possible measure, including rationalisation of the domestic scrap steel market, there is an absolute limit in saving the cost since the scrap price is mainly decided by the international scrap steel market. Thus, electricity price is the only controllable input variable in improving the price competitiveness of our steels.¹⁸

The relative controllability of the domestic electricity price to the Korean EAF industry gives a clue as to why the industry increased its overall production capacity above the global average despite increasing scrap steel prices in such an energy-resource-poor country. Compared to BOF firms, EAF firms are much more sensitive to electricity prices due to much higher electricity intensity per tonne of steel production. It is reported that the share of electricity costs in the production costs ranges between 5% and 10% in the EAF steelmakers' case, whereas it only takes around 2–3% in the case of BOF firms in 2012 (Kim.YJ. 2012). In this sense, the Korean EAF industry successfully adapted to electricity demand and supply conditions throughout the past three decades (Figure 4.1 and Table 4.3).

¹⁸ Open speech by Kyungsik Kim, Director of External Cooperation Department, *Hyundai Steel*, during the conference meeting on the 2nd Energy Demand and Supply Basic Plan hosted by the Federation of Korean Industries on 2 October 2013.

Figure 4.1 Korean EAF Steel Production and Share of National Crude Steel



Source: Author's elaboration from *Steel Statistical Yearbook from 1983 to 2013*, World Steel Association

Table 4.3 Energy Consumption of Korean EAF and BOF Steels (1,000 TOE)

Year	EAF			BOF (including Blast Furnace)		
	Electricity (TWh)	Fuels	Coal Coke	Electricity (TWh)	Fuels	Coal Coke
2001	2,529 (29.4)	-	653	868 (10.1)	637	13,730
2002	2,630 (30.6)	-	671	787 (9.1)	632	14,186
2003	2,564 (29.8)	-	654	760 (8.8)	648	14,536

Source: Korea Institute for Industrial Economics and Trade (KIET) 2004.

Notes: 1. TOE stands for 'tonne of oil equivalent'.

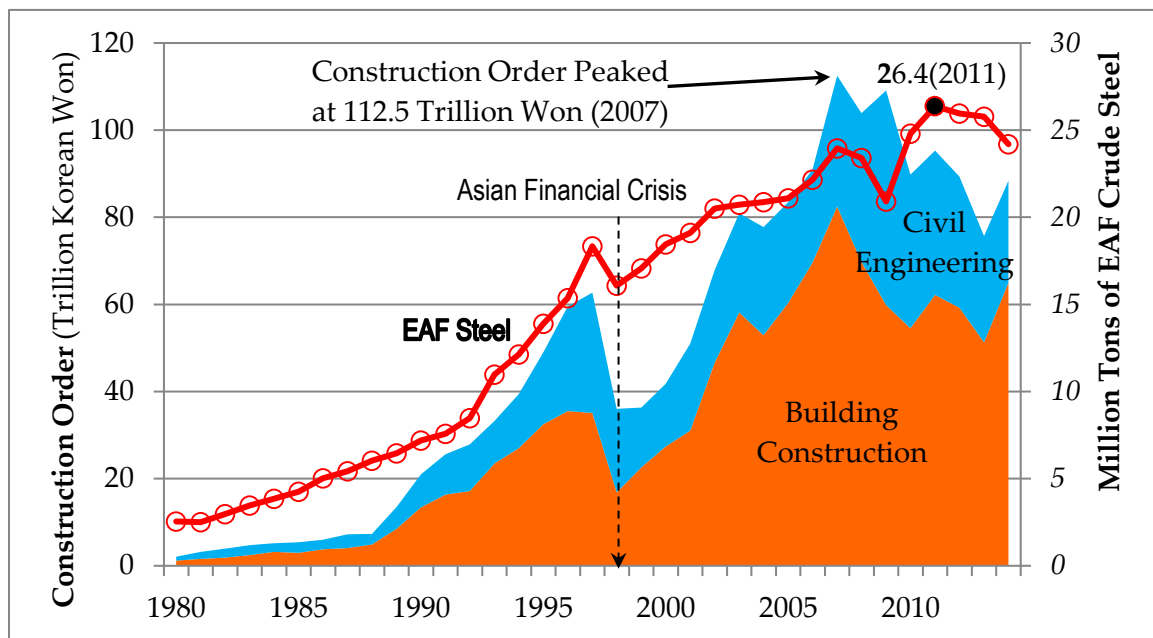
2. Self-power generation in BOF steel electricity is excluded in the Table.

Although Korean EAF steelmakers had enjoyed low electricity rates, a rolling blackout in 2011 changed such extreme pricing practices by KEPCO. After the incident, the government allowed KEPCO to continuously increase electricity rates for industry amongst various customers, resulting in intense public anger about KEPCO's unfair discounting practices for industries. Faced with increasing electricity rates and market

penetration of imported EAF steel products from China, the Korean EAF steel industry is in crisis (Kim YJ, 2012).

Furthermore, the construction market, which has induced crucial demand for construction steel beams and steel bars in the industry, has stagnated, too. In effect, the Korean EAF steel industry has been enjoying a continuous growth of construction orders over the past three decades. Construction orders peaked at 112.5 trillion won (about 102 billion US dollars) in 2007, however, and they never returned to that level despite increased government expenditures on large infrastructure projects to boost the construction industry. Following the construction market trend in four years intervals, the EAF steel production trend also peaked at 26.4 million tonnes in 2011 (Figure 4.2).

Figure 4.2 Construction Market and EAF Steel Production in Korea



Source: Author's elaboration from the Korea Iron and Steel Association 2014 and the Bank of Korea Economic Statistical System

4.2.3. Institutions of ESI: KEPCO as a Multi-policy Tool of State

With this historical background, KEPCO has been heavily regulated by the government since its establishment. The government imposed various energy policy agendas on KEPCO, including non-electricity energy issues. They vary from the incubation of the infant nuclear power industry, the indigenisation of reactor design and heavy electrical manufacturing technologies, to cross-subsidies to the household city gas sector and electricity-intensive heavy industries.

First, the utility had to absorb several nuclear power plant supplier segments for an aggressive nuclear technology indigenisation programme in the early 1980s. It undertook one-third of KHIC stock in 1980 when KHIC went into bankruptcy and absorbed Korea Power Plant Design and Engineering Services (the nuclear architecture and engineering company) and Korea Nuclear Fuel Supply (predecessor of KNF) as subsidiaries in 1982. KEPCO, as a parent company of those nuclear plant suppliers, delegated a monopolised supply right to each subsidiary firm for efficient indigenisation of advanced nuclear power technology (Sung & Hong 1999).

Second, the company has been forced to reduce natural gas prices for the household segment of the city gas sector through an obligatory natural gas purchase contract with Korea Gas, a state-owned wholesale natural gas supplier, since 1985. Third, it also has subsidised electricity prices for industry. A few electricity-intensive industries have been the main beneficiaries. Given that the cross-subsidies to electricity-intensive industries and the city gas sector are highly related to the catching-up performances of nuclear and gas turbines, they are analysed separately in the next Section.

4.2.4. Tight Business Regulations

The Electricity Business Act makes the Ministry of Trade, Industry, and Energy (MOTIE) primarily responsible for the economic regulation of the electricity sector,

including supervision of final electricity rate changes. Furthermore, the Korea Electric Power Corporation Act states that the Minister of MOTIE ‘shall instruct and supervise the business of the corporation’, in effect giving the minister control over KEPCO’s budget and operating decisions. Based on these acts, in effect, the Korean government can exercise its authority over virtually all kinds of business activities of KEPCO (OECD, 2000a). Amongst them, cross-subsidies through fuel contracts and pricing practices of Korean ESI are more tightly controlled by the government for societal and industrial policy goals.

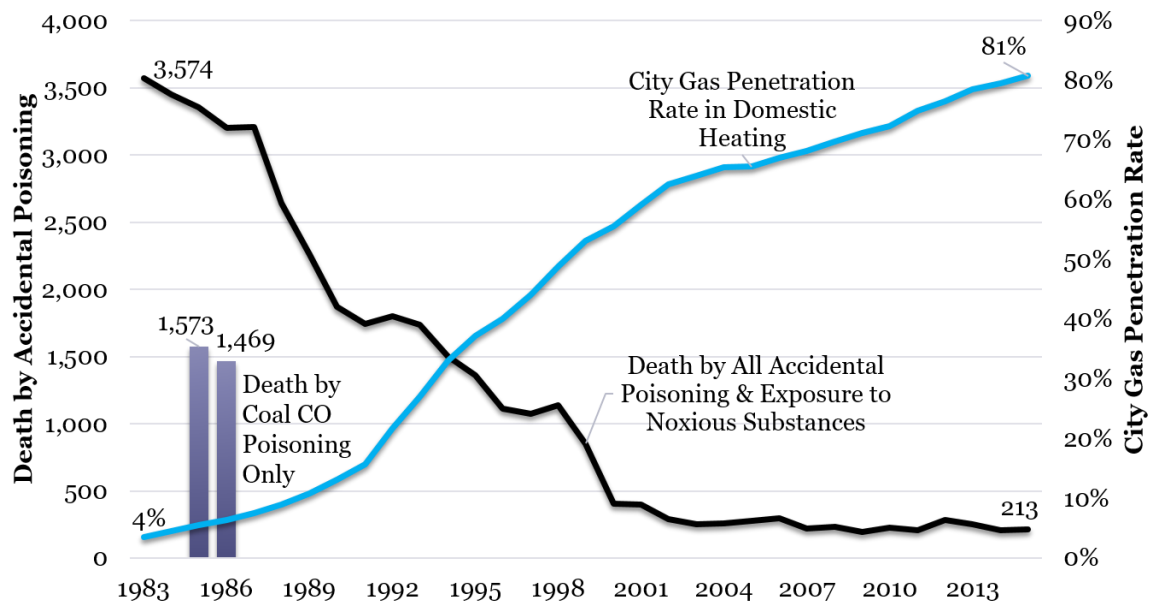
Carbon Monoxide Poisoning Issues and Cross-subsidy to City Gas

Coal briquettes were widely used as the main fuels for domestic heating from the 1950s to early 80s in Korea due to their cheap price compared to other available fuels, such as oil. The coal consumption in households generated massive carbon monoxide (CO) poisoning incidents, however, and the death toll had risen to more than 1,000 every year. About 60,000 nationwide CO poisoning deaths due to the coal briquette use between 1954 and 1982 were reported by the Department of Preventive Medicine of Seoul National University (Kang 1983). Occasional announcements by the Korean government show that there were around 1,500 deaths annually due to the coal CO poisoning until the mid-1980s (*Maeil Business News Editorial* 1986, Figure 4.3). The black line graph in Figure 4.3 shows periodical statistics for the overall death rate reported by the Korean government—‘All Accidental Poisoning and Exposure to Noxious Substances’—and about half of the death rate comes from coal CO poisoning.

Amidst growing public discontent about the CO poisoning issue, thanks to Japanese ESI’s development of Indonesian gas fields in the 1970s (see Section 5.3.3), KEPCO also made a natural gas import contract with the Indonesian government for power generation in 1983. The government set up a state-owned wholesale gas supplier, namely KOGAS, and transferred ownership of the gas import contract from KEPCO to KOGAS for rapid gasification of Korean household heating sector in the early 1980s. As

the market penetration of city gas rapidly increased, the CO poisoning death rate dramatically reduced after the mid-1980s. When the share of households that have access to the natural gas network reached about 65% in the early 2000s, the annual CO poisoning death cases dropped to less than ten. Most of the causes were liquefied petroleum gas or natural gas rather than coal briquettes (Lee & Lee 2006).

Figure 4.3 Death by Carbon Monoxide Poisoning from Domestic Heating Coal



Source: Author's elaboration from Statistics Korea, "Deaths and Death Rates by Cause (Annual 1983~2014)" and Annual Statistics of Korean City Gas Association, 2017

However, this achievement did not come without cost. For a rapid transition of the country's domestic heating fuels from coal to expensive natural gas, the government imposed the cost burden of city gas business upon KEPCO through a compulsory LNG procurement contract with KOGAS at peak prices. In terms of supply cost, there is a big gap between the two sectors due to, for instance, differentials in pipeline pressure, seasonal demand fluctuations causing expensive gas tank storage costs, designated terminals, and additional distribution service. For instance, wholesale LNG supply costs for power generation were 53.7 won/m³, whereas the costs in the household sector amounted to 107.8 won/m³ in 2000 (APEREC, 2001).

However, the government arrangement made the prices of the two sectors almost even. It heavily increased the cost of natural gas for electricity generation and made KEPCO avoid construction and operation of gas turbines unless there is an urgent supply crisis. The additional cost that KEPCO should pay due to the cross-subsidy arrangement is estimated to be around 10% of its total natural gas bills in 1997 (OECD, 2000b; Son & Roh, 2002). The additional cost burden, however, can increase further whenever government officials have a reason to do so. Thanks to this cross-subsidy, the gas turbine technology have been considered the most expensive power generation option for KEPCO, whereas household city gas customers enjoyed even cheaper gas prices than those of countries with indigenous natural gas reserves, such as the UK and the Netherlands (IEA, 2015) (Figure 4.4 and 4.6).

If we look at the price change by each group of natural gas customers in Korea for the past quarter-century, the average price difference between power utilities and household customers is merely 5%. Even further, sometimes LNG prices for power generation increase above those for household city gas due to government intervention in the pricing of natural gas in Korea (Figure 4.4). *Heebong Chae*, Director General of the MOTIE explains the reason.

When the natural gas import price skyrocketed in 2007 and 2008, our main concern was that household city gas customers would face a more acute economic burden than power generation companies would. That was the main reason we decided to pass more of the cost burden of total natural gas import to the power generation sector in 2008.¹⁹

¹⁹ Public comments of *Heebong Chae*, Director General for Energy Saving and Efficiency and former Deputy Director of Gas Industry of Ministry of Trade, Industry, and Energy: Participatory observation during a conference meeting for the 2nd National Energy Basic Plan on 14 June 2013.

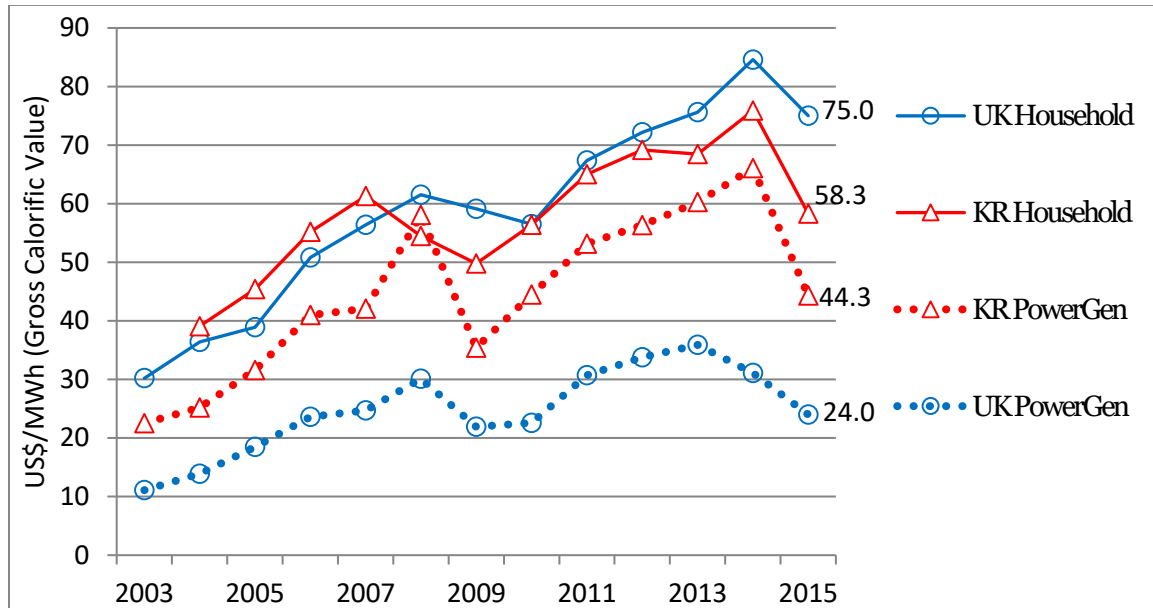
Heebong Chae's address sounds quite impressive in terms of the degree of government intervention in energy pricing practices as well as the sympathy for household customers. In terms of welfare policy, however, the Korean cross-subsidy to city gas households has been quite regressive for the past three decades. The household gas customers mostly locate in urban areas and belong to a middle-income group while 'off-gas' households in rural areas, who should depend on kerosene for space heating, mostly belong to a low-income group but pay twice as much as the city gas households do to get the same amount of calorific value in Korea (IEA, 2016). The initial background of the cross-subsidy policy was a rapid fuel-switching of households heating energy from coal(briquette) to natural gas, but the cross-subsidy became a 'norm' even after the household gasification rate of Korea reached the world highest level.

The cross-subsidy issue has been well addressed by international communities in terms of allocation efficiency and energy efficiency. Experiences of the energy subsidy policies in the OECD countries show that much of the subsidy goes to high-income households while it drains financial resources for the households in actual energy poverty. International agencies such as OECD, IEA and World Bank recommend energy price reform to those countries that subsidise energy prices and urge to reflect market price in the final customer price while supporting the households in energy poverty with direct subsidies, either monetary or energy voucher.

In that it is still difficult to estimate the extent of cross-subsidy from the comparison between the power generation and city gas sectors in Korea, Figure 4.4 is juxtaposed to that of the UK, where private utilities supply electricity and gas markets without such cross-subsidies between customer groups. It shows that there is a big gap in relative prices between the two countries. While there is only a 27% difference between the two sectors in Korea, the UK shows a 131% difference during the 2000s. It clearly shows that Korean CCGTs need to take a huge cost burden for the cross-subsidy to domestic city gas (Figure 4.4). Furthermore, the nominal prices of Korean and UK

household city gas customers start to converge from the year 2008, and sometimes the Korean household group even pay less than their UK counterparts. It should be noted that the UK has its own natural gas fields and often exports natural gas.

Figure 4.4 Natural Gas Price by Sectors in the UK and Korea



Source: Author's elaboration from IEA *Energy Prices & Taxes* 2016 4Q

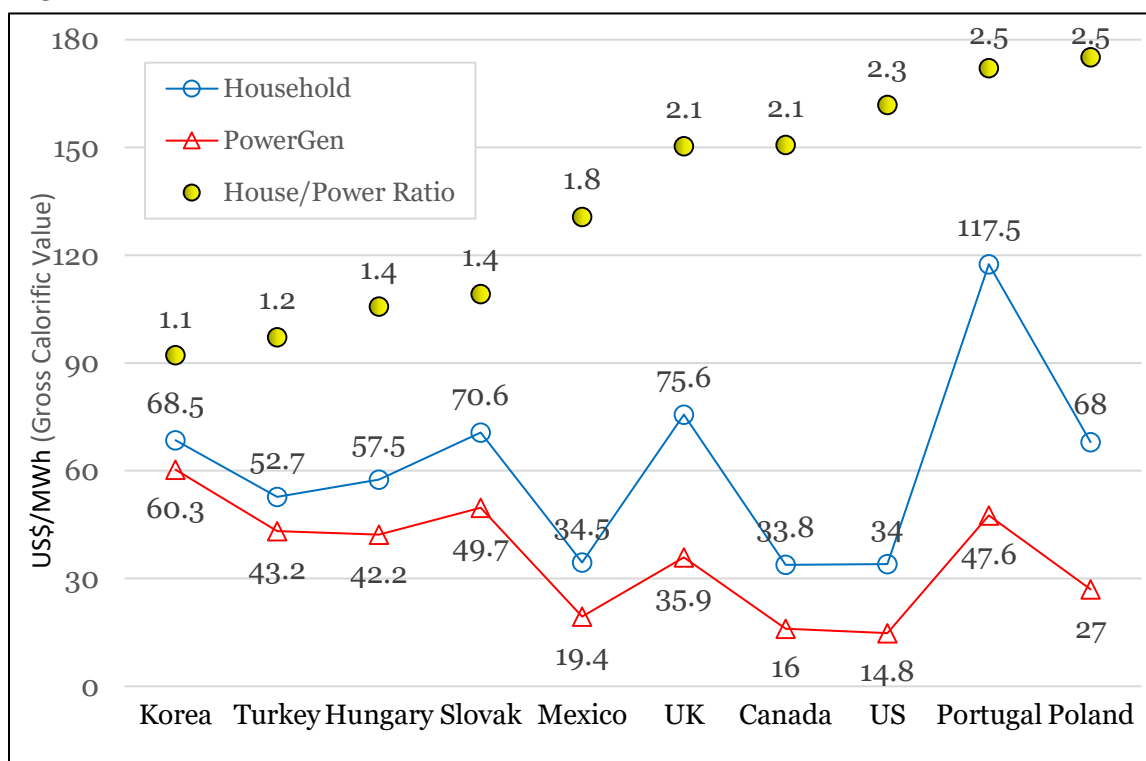
In effect, the cross-subsidy of gas prices from the power generation sector to the household city gas in Hungary, Slovakia and Turkey has been one of the major issues in international agencies, including International Energy Agency (IEA) and World Bank. The cross-subsidy not only distorts competition in the electricity markets but also weakens the incentives for the energy efficiency of buildings in the three countries. In terms of welfare policy, the cross-subsidies are regressive as the major portion of the subsidy goes to a high-income group while the subsidies exhaust public resources for the actual energy poverty group.²⁰ The three countries are suggested to establish cost-reflecting pricing

²⁰ Although the cross-subsidies may accelerate gasification of households initially, they do not support off-gas grid households that mostly belong to a low income and rural area residential group. Unintentionally, the subsidy scheme concentrates resources of public energy suppliers to those who already have access to gas networks and discriminate the energy poor group.

mechanisms, to remove the cross-subsidies to facilitate competition in both gas and electricity markets. Regarding the energy poverty issue, they are recommended establishment of social safety through a direct subsidy mechanism rather than tariff to the households (IEA, 2007, 2012, 2016, 2017; Dilli & Nyman, 2015) (Figure 4.5 and Table 4.4).

Considering the cross-subsidy was introduced for rapid penetration of natural gas for household heating, the policy goal has been achieved in terms of a penetration rate of city gas. The share of Korean retail customers connected to the city gas network reached 83 per cent in 2017, which is the third-highest level in the world. Compared to the share of large OECD economies, including the US, Germany and Japan, which show around 50 to 60 per cent, the result is more surprising. Although natural gas was introduced in Korea in 1983, quite late compared to other OECD countries, the penetration rate of retail city gas dramatically increased thanks to the substantial cross-subsidy from the ESI to the household sector for the past three decades (Figure 4.5 and 4.6, and Table 4.4 and 4.5).

Figure 4.5 Natural Gas Prices for Household and Power Generation (2013)



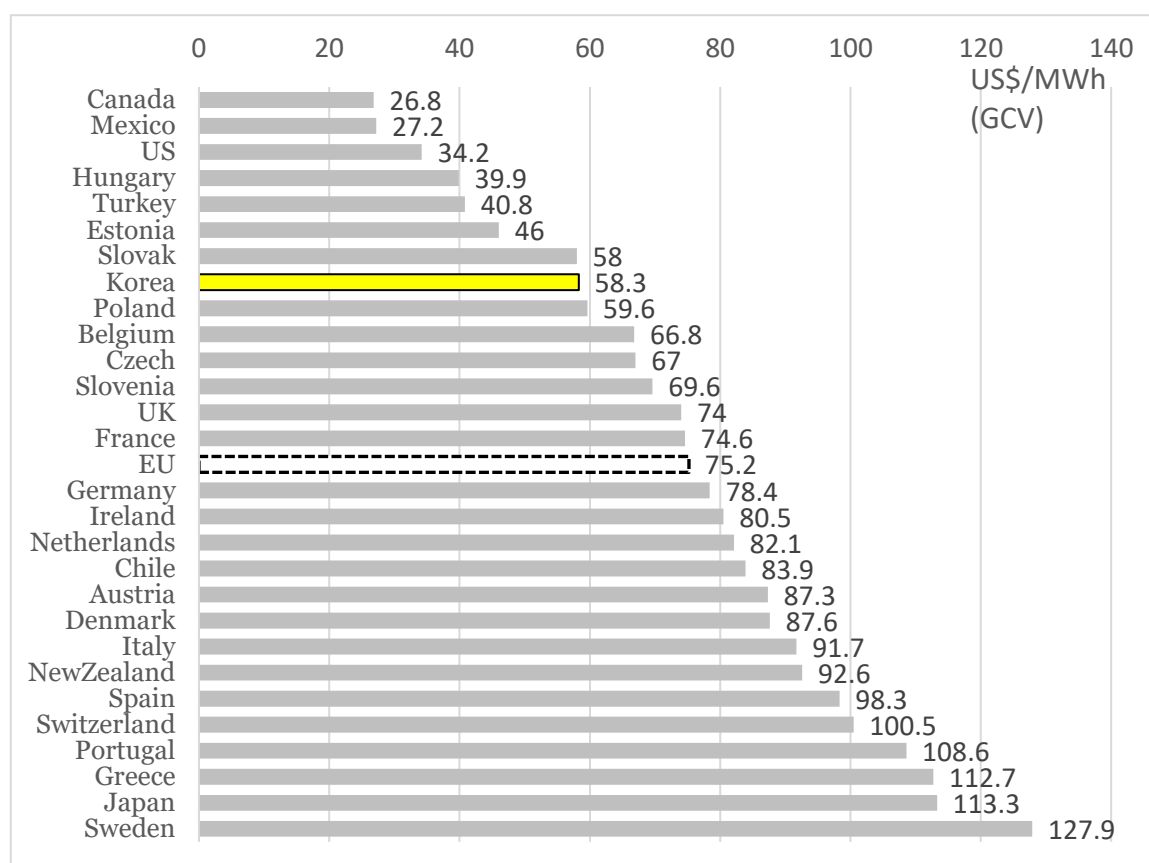
Source: Author's elaboration from International Energy Agency, *Natural Gas Information 2016 4Q*

Table 4.4 Ratio of Household Gas Price to Power Sector Gas Price in OECD

	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average
Portugal	3.0	2.2	2.7	2.4	2.3	2.2	2.5	2.8	3.5	2.62
Poland	2.2	2.5	2.9	2.6	2.6	2.5	2.5	2.8	2.7	2.59
UK	2.3	2.0	2.7	2.5	2.2	2.1	2.1	2.7	3.1	2.42
US	1.8	1.5	2.5	2.1	2.3	3.0	2.3	2.1	3.6	2.35
Canada	1.9	1.9	2.0	2.1	2.3	2.6	2.1	-	-	2.15
Mexico	2.0	1.1	2.2	2.0	1.9	2.1	1.8	1.7	2.0	1.86
Slovakia	1.6	1.1	1.2	1.8	1.6	1.3	1.4	1.4	1.3	1.39
Hungary	1.2	1.2	1.4	1.7	1.5	1.4	1.4	1.1	1.3	1.35
Turkey	1.2	1.2	1.2	1.3	1.3	1.2	1.2	1.2	1.2	1.23
Korea	1.5	0.9	1.3	1.3	1.2	1.2	1.1	1.1	1.3	1.23

Source: Author's elaboration from International Energy Agency 2016, *Natural Gas Information 2016 4Q*

Figure 4.6 Natural Gas Prices for Households



Source: Author's elaboration from International Energy Agency, Natural Gas Information 2016, 4Q

Table 4.5 Share of Gas Retail Customers of Major OECD Countries

	Market Entry ^a	% of Retail Customers Connected to City Gas		No. of Retail City Gas Customers (1,000s)
		1998	2017	2017
Netherlands	1960s	97.0% ^a	98% ^b	7,152 ^f
UK	1960s	81.9% ^a	86% ^c	23,714 ^c
Korea	1983 ^d	49.0% ^d	83% ^d	17,177 ^d
Italy	1960s	69.6% ^a	82% ^e	23,203 ^f
Belgium	1960s	55.1% ^a	69% ^{f, i}	3,268 ^f
US	n/a	61% ^g	58% ^g	68,600 ^g
Japan	1969 ^h	n/a	56% ^h	30,246 ^h
Germany	1960s	42.0% ^a	52% ^{f, i}	20,979 ^f
France	1960s	41.0% ^a	39% ^{f, i}	11,268 ^f

Source: Griffin 2000 ^a, Honoré 2017 ^b, BEIS (UK) 2017 ^c, Korea City Gas Association 2017 ^d, Baratto 2017 ^e, Capgemini 2018 ^f, US EIA RECS Data ^g, The Japan Gas Association 2018 ^h, Eurostat 2018 ⁱ

Additional Cost Burden of CCGTs due to Seasonal Demand Shift of City Gas

The household demand for natural gas in Korea plummets in the summer and skyrockets in the winter, and the seasonal differential reaches up to 15–20 times, whereas KOGAS should take contracted volumes of gas regularly from export countries, regardless of season, based on the “take-or-pay” principle.²¹ This extreme seasonal difference of demand in the city gas sector causes an enormous amount of additional management costs, such as expensive LNG tank storage. In this sense, the government designated KEPCO as a main consumer of natural gas in the summer season.

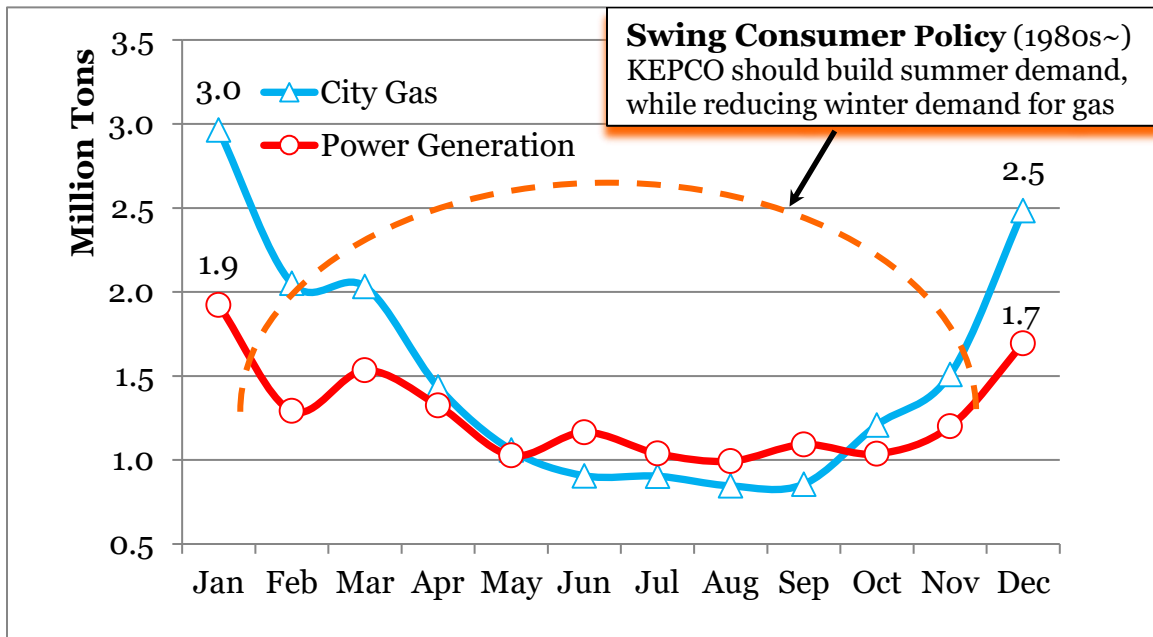
In managing the cost burden of the asymmetry between domestic seasonal fluctuation and gas import contracts, the Korean government arranged for KEPCO to play as a so-called seasonal ‘swing consumer’ of the country’s national natural gas supplier, KOGAS, since the mid-1980s when the country introduced the city gas business. The idea of a ‘swing consumer’ came as a solution to the unbalance between the considerable seasonal fluctuations of household natural gas demand—‘turndown ratio’, in other words—and rigidity of long-term liquefied natural gas (LNG) import contracts, namely “take-or-pay” contract (Kim & Do, 2004; OECD, 2000b, 2004).

Although KEPCO had to install a massive capacity of CCGTs in the early 1990s when a supply shortage occurred, KEPCO kept CCGTs only for peak-load purposes due to the ‘institutionally’ high natural gas prices in addition to the ‘Asian premium’. In effect, KEPCO had a better option than CCGTs to manage electricity demand during the summer peak days, namely the EAF steel industry. For instance, major electricity-intensive industries, such as EAF steel and cement makers, shift their major production schedules from daytime to night-time to ‘cream-skim’ cheap off-peak electricity. As a result of the

²¹ A ‘take-or-pay’ contract between a natural gas field owner and buyer is a universal contract custom due to technical difficulties in controlling the output of natural gas fields.

mismatched policies and institutions across sectors, KEPCO's subsidiary GENCOs operate CCGTs more in the winter than in the summer season. In this kind of price distortion, thereby, the 'swing consumer policy' was never realised (Figure 4.7).

Figure 4.7 The "Swing Consumer Role" of KEPCO & Actual Gas Demand (2011)



Source: Author's elaboration from KOGAS Management Statistics 2012.

Note: The figure for city gas includes households and industrial customers to show the total volume of city gas demand compared to that of CCGTs. Households' seasonal differentials of demand are much larger than the figure shows, around 15–20 times, for instance.

Overall Electricity Price Control for Industry Support

KEPCO also had to keep subsidising industrial electricity customers through low electricity rates from the 1970s when the *Park Chung-Hee* administration launched a heavy industry policy. Its 50% discount off of electricity rates as a special contract with the Korean Aluminium Co. from 1976 to 1989, in addition to a discount to the overall manufacturing industry, shows a dramatic aspect of its support for energy-intensive

heavy industries in Korea (Auty 1991)²². Although the initial policy of heavy and chemical industries (HCIs) promoting was officially withdrawn in 1979, the Korean government's extensive export-oriented economic growth policies with a focus on the HCIs led its energy policies to continue tight electricity price regulation even after the 1970s.

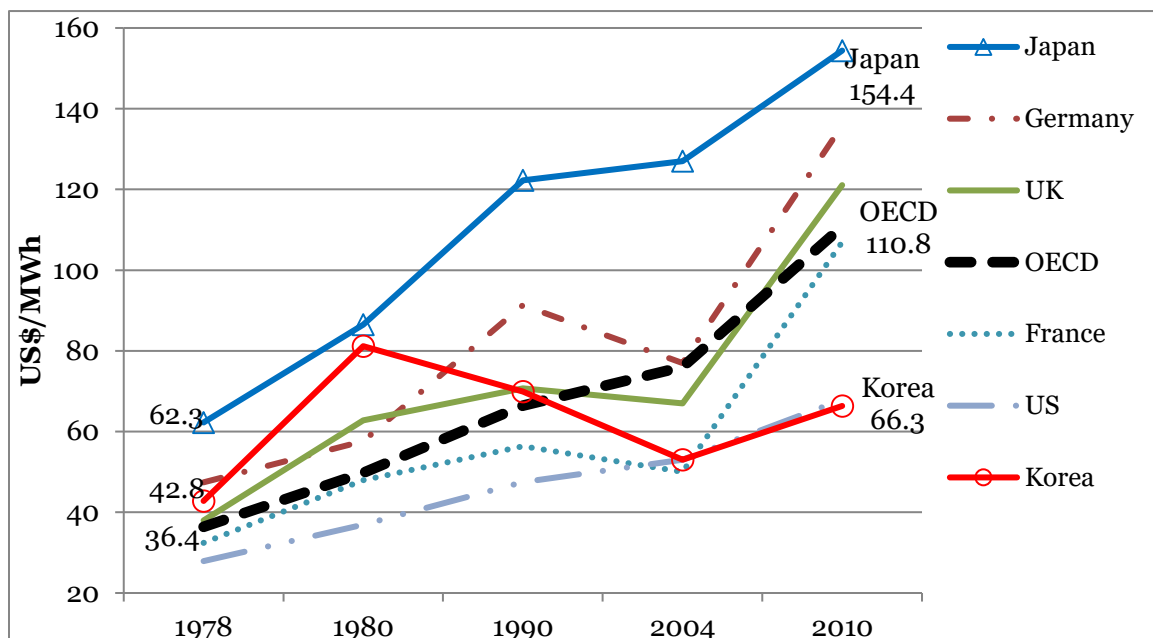
One main objective of the Korean government's energy policy was to ensure that the energy sector would provide low-cost energy supplies to encourage economic development. Keeping energy prices low was viewed as being essential to ensuring electricity-intensive HCIs' competitiveness and to supporting social welfare so that all customers could have access to reasonably priced energy, regardless of the cost of supply. This policy, while apparently successful, as shown by unprecedented economic growth and improvement in social welfare, has also brought about undesirable effects. Facing strict price regulation, public firms in the energy sector were unable to generate sufficient funds to meet their future investment needs. Serious distortions in relative prices amongst various energy sources resulted in an inefficient allocation of resources. Low energy prices discouraged investment in technologies of energy conservation, thus hindering the government's own efforts to improve energy efficiency (Chang Hyun-Joon, 2003).

Based on the massive supply reserve margin of electric power generators in the 1980s, KEPCO repeated price reductions throughout the decade. As a result, all types of Korean customers enjoyed cheaper electricity prices than did their OECD counterparts from the 1990s. Price discounts for industrial customers were pronounced amongst all the subgroups from the 1980s to the 2000s. From around 2000, electricity prices for industrial customers in Korea reached the cheapest level amongst OECD countries. Although the electricity price for the industry was once similar to that of Japan in 1980, it continuously decreased until it reached that of Canada, which has abundant and nearly 'zero-cost' hydropower resources in the early 2000s (Figure 4.8).

²² Open comments of Professor Seungjin Kang from Korea Polytechnic University during a conference meeting for the 2nd Energy Demand & Supply Basic Plan on 21 June 2013.

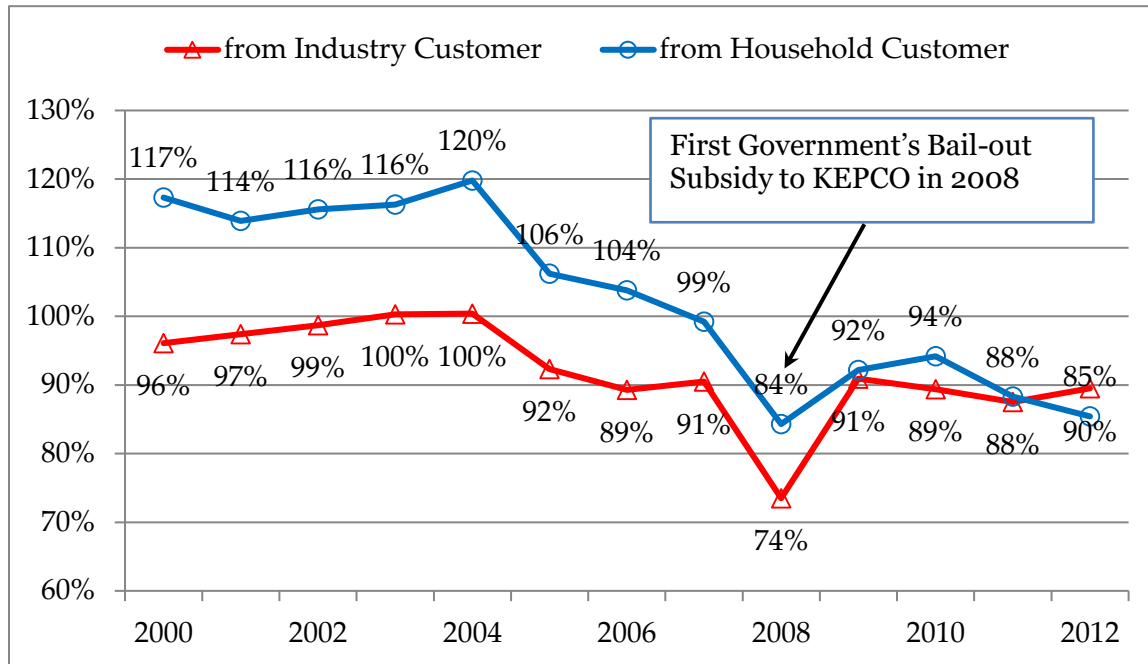
The government's tight regulation of the electricity pricing practices of KEPCO dramatically manifested itself from the mid-2000s when global oil prices, together with other fossil-fuel prices, hiked to a record level. Although it would be rational for electric utilities to reflect fuel price changes in electricity rates even if they are under regional or national public regulation, the Korean regulatory system did not allow such pricing practices, and the utility had to bare its huge deficit by itself. Even after it was bailed out by the government's special subsidy for the first time in its history in 2008, it was forced to continue such price practices, irrelevant to fossil-fuel price changes (Figure 4.8 and 4.9).

Figure 4.8 Electricity Prices for Industry Customers by Country



Source: International Energy Agency 2006, 2013.

Figure 4.9 Deteriorating Cost-Recovery Rate of KEPCO's Tariffs in the 2000s



Source: Author's elaboration from KEPCO 2013: 214.

Meanwhile, industrial electricity customers did get incorrect price signals. In effect, the country's five major steelmakers started to massively invest in new production lines from the year when KEPCO was bailed out. Their total investment in new iron and steel production facilities between 2008 and 2012 was about 36 trillion won, equivalent to 32 billion US dollars (Song, 2013). As a result, the country had to face its first rolling blackout²³ since the late 1970s on September 15, 2011. Public discontent made the government replace the minister of energy ministry and related officials. Although KEPCO was to increase the electricity rate, somehow, after the rolling blackout, the government's regulation still did not allow KEPCO to pass fuel cost fluctuations on to its customers.

²³ The local outages affected around 2.5 million customers.

In effect, thanks to the ‘Beijing Olympics construction boom’ in China, many Korean steel industries enjoyed an increased export performance until 2008. KEPCO had to face a huge deficit due to its continued low prices for industry and the outperforming capacity factor of steel industries; it also had to get a special subsidy from the government to offset part of the deficit in 2008.²⁴ The average level of electricity prices for industry customers does not show the unique characteristics of the relationship between KEPCO and electricity-intensive industries in Korea, however. Thus, it needs to go deeper to see the pricing mechanism.

Intense Practice of “Time-of-Use” Pricing Scheme

KEPCO’s price scheme had been entirely based on the quantity of electricity consumed, regardless of the time of use in a day and season until 1976 (World Bank, 1985). Once nuclear power was introduced, however, KEPCO set up a “Time-of-use (TOU)” pricing scheme for large industrial customers. The TOU pricing mechanism itself is well known and has been widely practised by electricity utilities in numerous countries to reduce peak demand in the daytime and to increase the operation of cheap base-load power during night times. The basic principle of TOU pricing is to charge a higher rate during peak hours and discounted rates during off-peak hours, typically at night, encouraging customers to shift to off-peak hours with discounted prices. In effect, KEPCO has been offering unparalleled, disproportionate TOU prices since 1978 when its first commercial nuclear reactor, *Kori-1*, started commercial operation.

Although KEPCO’s TOU pricing scheme is often praised as efficient (Hill, 1992), the extreme level of pricing has been questioned by economists and research communities regarding its extreme discount during night times from the 2000s (Lee et al., 2009). The criticisms are focused on the fact that the off-peak prices at night hours, typically from 11

²⁴ Open comments of Professor *Seungjin Kang*, Korea Polytechnic University during a conference meeting for the 2nd Energy Demand and Supply Basic Plan on 21 June 2013.

p.m. to 9 a.m., do not reflect actual production costs and cause equity issues between customer groups.

In 2012, for instance, KEPCO bought electricity from power generation companies (GENCOs and IPPs) at around 82 Korean won(KRW)/kWh during off-peak hours, but the company sold electricity to large industry customers at about 62 KRW/kWh during the same hours. This brought a massive revenue loss (2.2 trillion Korean won, equivalent to about US\$ 2 billion) to KEPCO in the same year (KEPCO, 2013; National Assembly Budget Office, 2013) (Table 4.6). Although most of the loss was apparently recovered by peak-load prices charged to industry customers during the daytime, it causes a serious equity issue between cream skimmers of the pricing scheme, such as EAF steel and cement firms, and other industries that do not operate factories at night hours or that have to operate factories 24/7.

Table 4.6 KEPCO's TOU Pricing for Large Industry Customers and Results (2012)

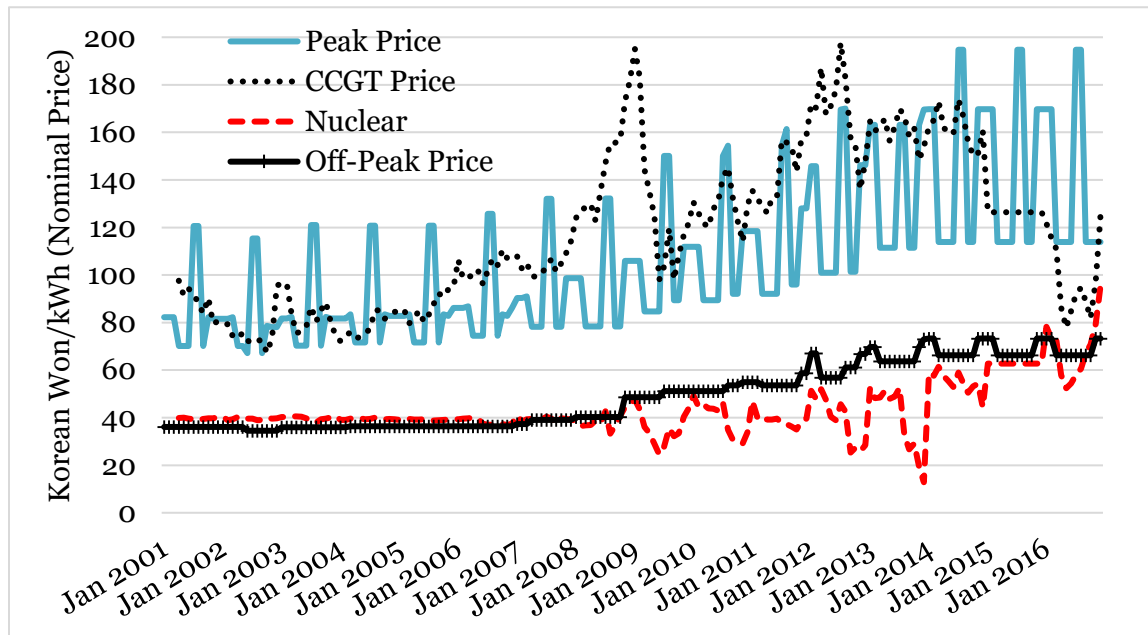
		Off-Peak Hours	Partial-Peak Hours	Peak Hours
Average Cost	(KRW/kWh)	81.8	103.2	108.4
Average Price		61.8	103.7	154.8
Price Gap		-20	0.5	46.4
Sold Electricity (GWh)		111,374	72,890	42,117
Profit (Billion KRW)		-2,233	35.3	1,954
(Million US\$ in 2012 price)		-1,983	31	1,736

Source: National Assembly Budget Office, 2013: 47.

The problem of TOU pricing practice does not end here. The off-peak electricity price has been even lower than the nuclear power generation price in the 2000s. It shows the off-peak price was kept below the nuclear power price, which KEPCO pays to KHNP, from the early 2000s to late in the decade. Although relatively lower off-peak prices can

be justified to increase loads during off-peak hours and flatten overall daily load, a price level lower than the cheapest base-load power generation price cannot be easily justified (Figure 4.10).

Figure 4.10 KEPCO's Time-of-Use Pricing for Large Industry Customers ²⁵



Source: Author's Elaboration from Korea Power Exchange's Historical Monthly Power Generation Price (2001–2014) and KEPCO's TOU Pricing Scheme Archives.

Note: The figure shows the price scheme for the largest industry customer group, which consists of about 350 customers and consumes about 45% of industrial electricity and about a quarter of total national electricity consumption. This pricing category is merged with that of a smaller industry customer group in 2012.

Professor *Jongbae Park* from *Konkuk University*, Seoul, explains the rare pricing practice and its potential impact on electricity supply planning:

²⁵ The reason why nuclear power generation price started to fluctuate from 2009 mainly comes from application of a 'modification factor' on electricity transaction between KEPCO and GENCOs, including KHNP, in order to decrease electricity prices in the face of global energy price increases from 2008 (Lee et al., 2013). Thus, the nuclear power generation price does not reflect real cost of nuclear power from 2009.

It would be difficult to find a similar case of such an extreme pricing scheme in other countries. The level of off-peak price lower than nuclear power generation price can be justified only in exceptional cases. For instance, it would be justifiable when nuclear power units operate in a ‘daily start and stop (DSS)’ mode due to low base-load demand during night hours given that nuclear power operation in a DSS mode would be extremely expensive.

However, such a DSS mode operation of nuclear power never happened during the past three decades in Korea. I assume that the extreme pricing was the background of the chronic shortage of base-load power capacity in the Korean electricity market for the past 15 years. I participated in the planning processes of the Basic Plan for Long-term Electricity Supply and Demand as an expert panel member from its first to the fifth plan, consecutively. Each time, I repeatedly heard that ‘we are suffering a dire shortage of base-load power capacity’ from the Korea Power Exchange.^{26,27,28}

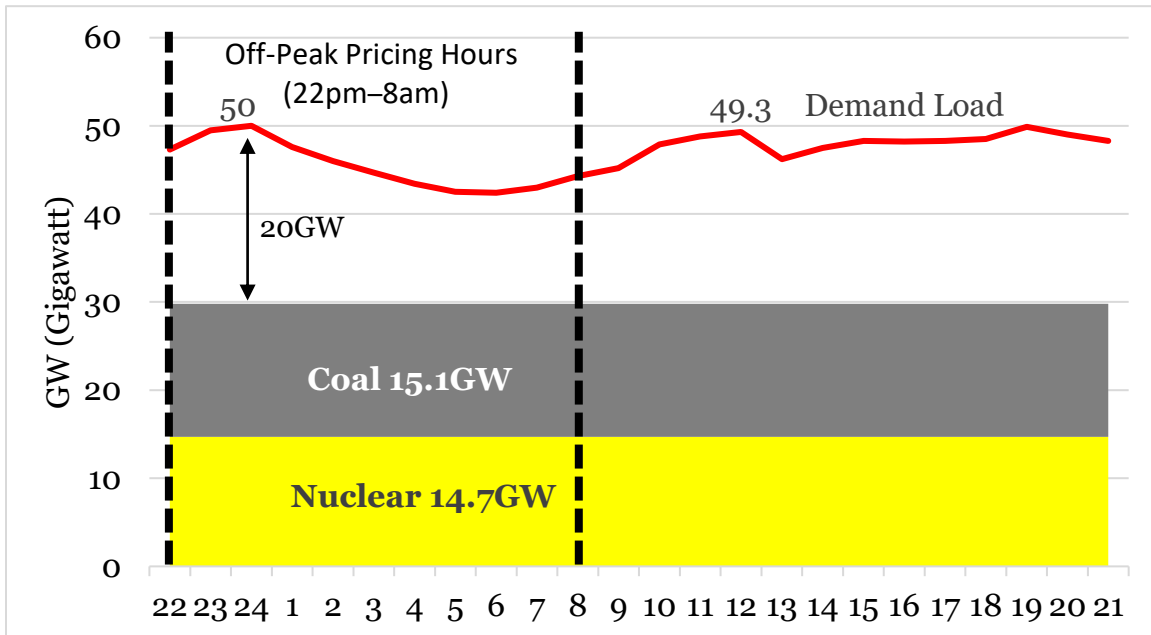
Figure 4.11 and 4.12 show what the phrase ‘we are suffering a dire shortage of base-load power capacity’ means. The former shows a so-called ‘shifting peak’, meaning peak load simply shifted from daytime to night-time hours, thanks to the aggressive TOU pricing scheme. The night peak on 1 February was the annual peak of the Korean electrical system in the year 2005. It makes a 20 GW gap between the night peak and the total base-load power capacity in operation. In this circumstance, electricity utilities need to either modify the pricing scheme to reduce the night peak or construct a large capacity of base-load power plants. KEPCO hardly changed the pricing scheme until the early 2010s, and the gap continued to increase.

²⁶ Electricity Market and Power System Operator

²⁷ Telephone interview with Professor *Jongbae Park* of the Department of Electricity and Electronics, *Konkuk University*, Seoul, on 14 May 2015.

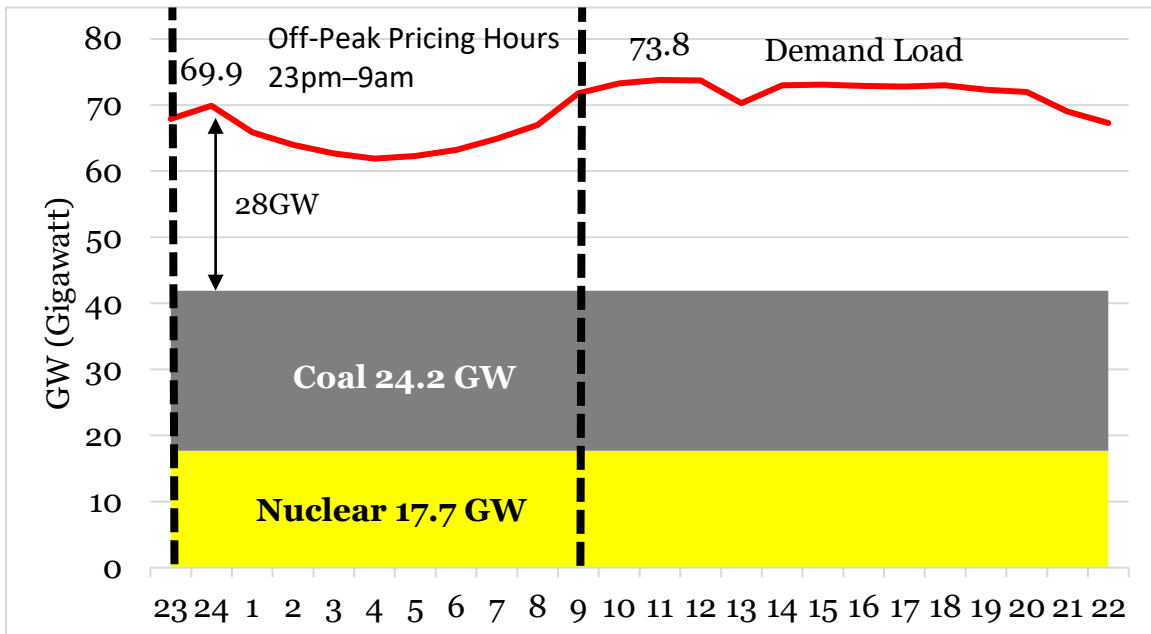
²⁸ ‘The Basic Plan for Long-term Electricity Supply and Demand’ or its previous version, ‘The Long-Term Electricity Demand & Supply Plan’, has been made every other year.

Figure 4.11 Impact of Aggressive TOU Pricing (1 Feb. 2005)



Source: Author's Elaboration from the Korea Power Exchange's Monthly Statistics of the Electricity Market.

Figure 4.12 Continued Aggressive TOU Pricing and Increasing Gap (2 Feb. 2012)



Source: Author's Elaboration from Korea Power Exchange's Monthly Statistics of Electricity Market.

Instead, the new large units of nuclear and coal power were authorised during the electricity supply planning processes throughout the 2000s. There is no direct evidence that the Korean government and KEPCO intentionally kept the extreme pricing practices to justify new nuclear and coal power construction projects. Nevertheless, there are numerous pieces of evidence showing a correlation between utilities' pricing schemes and nuclear power programmes in European countries in the past. Specific pricing schemes to encourage electricity demand at night hours and their implications for the nuclear power programme in the UK in the 1960s are shown as below:

Such electrical storage heating was particularly successful in the UK as a complement to the nuclear power programme from the 1960s. The requirement for nuclear generators to operate continuously caused the then state-owned system operator to incentivise load shifting to provide a higher and stable night-time base-load. (Torriti et al., 2010: 11–12)

Professor *Younghwan Chun* from *Hongik University* explained more specific implications of such pricing schemes to nuclear power rather than other base-load power technologies.

Sustaining electrical demand at night hours is a critical issue to nuclear power. If you have low demand load at night, you may have to shut down nuclear reactors, rather than reducing their unit output, to keep the balance of the entire electrical system. Nuclear power cannot be operated in a load-following mode for a safety reason. Although France exceptionally boasts a 'load-following' operation of nuclear plants, I doubt whether they actually can do it. When I requested EDF for details of such an operation several years ago, they refused to answer my inquiry.

By comparison, almost all modern fossil power plants, including coal power, are equipped with the 'governor' system, which enables turbines to automatically respond to frequency changes of the electrical system and

restore a standard system frequency.²⁹ For instance, most coal power plants in Korea have the ability to change their output by about 5% within a minute following frequency changes. Although it is slower than a gas turbine in responding to load changes, its governor system makes a big difference from nuclear.”³⁰

Indeed, the big gap between night peaks and base-load power capacity easily justified new nuclear and coal power projects against the other technology options in the energy planning processes. It should be noted that the construction plan of Shin-Kori 3 and 4, the first APR1400 and the reference reactors of the Barakah nuclear project in the UAE, was also authorised in 2000 (MOTIE, 2000a).

While optional price differential is not over two times greater between base-load and peak-load hours in most OECD countries, it is 3.4 times in the summer season in Korea as of 2013. As compared in Table 4.7, Public Gas and Electricity (PG&E), the biggest utility of California, practices the optional price programme with 1.9 times differential at most. Although the bigger differential would result in larger customer response and peak-load reduction, KEPCO’s extreme pricing scheme causes not only equity issues between industrial customers but ‘wrong price signals’ and ‘shifting peak’ problems. Customers who do not operate their factories at night times and who should operate factories 24/7 would pay KEPCO’s loss from the intensely discounted off-peak prices. In this way, the two types of industry customers cross-subsidise those who can cream-skim the cheap off-peak prices, such as EAF steelmakers (Jung & Park, 2010).

For instance, EAF steelmakers or the cement industry can flexibly change their production activities from ‘load-shedding’ to complete shutdowns during peak-load

²⁹ The frequency change means an unbalance between electricity supply and demand caused by demand changes or sudden outages of power plants.

³⁰ Interview with Professor *Younghwan Chun*, Electrical Engineering Department of *Hongik University*, Seoul, on 12 July 2017.

hours while operating their production facilities at full capacity during night hours. Most manufacturing industries, including BOF steelmakers, however, cannot follow the same path, in that they do not have such flexible characteristics in their production process. Instead, Korean BOF steelmakers, such as POSCO, operate their own self-power generation plants using by-product gas from their blast furnaces during peak hours.

Table 4.7 International Comparison of TOU Electricity Prices (2013)

	Peak & Off-Peak Hours		Differential (Peak/Off-Peak)	Load Factor (Average/Peak)
	Off-Peak Hours	Peak Hours		
Korea (KEPCO)	11 p.m.–9 a.m.	11 a.m.–noon, 1–5 p.m.	3.4 times	77.1%
US (PG&E)	9:30 p.m. –8:30 a.m.	12 p.m.–6 p.m.	1.9 times	57.5%

Source: Korea Electric Power 2013; California Public Utility Commission 2017

Note: The presented TOU prices of both countries are applied during the summer season.

Nevertheless, KEPCO kept the pricing practice with the justification of demand management of electricity under the supervision of the government, namely the MOTIE. The general manager of KEPCO's pricing office explained this:

The level of off-peak price for large industry customers is about 80% of average power generation cost during the off-peak hours. Although it does not accord with the cost-based pricing principle and there are numerous complaints from industry customers who operate production facilities 24 hours a day, the pricing scheme serves as a policy tool such as demand-side management. Also, the economic loss due to the off-peak price could be recovered by peak pricing.

The pricing scheme is a result of consultation between KEPCO and government rather than KEPCO's own decision. The government seems to

consider that the economic loss due to the pricing scheme is somehow reasonable compared to the effect of demand-side management.³¹

Furthermore, the extreme pricing, which is even lower than the nuclear power generation price, sent an incorrect signal to numerous Korean electricity-intensive industries, mostly EAF steelmakers, to massively invest in new production facilities from the late 2000s. Often, they face overcapacity and end up with abrupt results, such as the bankruptcy of 'Hanbo Steel' in the late 1990s and the restructuring of eight EAF steelmakers in 2015. Regardless of the eventual economic results, the pricing scheme played as a 'matchmaker' between base-load power, namely nuclear and coal, and commodity metal industries for the past three decades in Korea. The rapid growth of the steel industry induced by the excessive TOU pricing, in return, gave rise to the persistent growth of base-load electric demand, which is a prerequisite for new nuclear power construction projects.

EAF-centred Load Management Rebate Programmes

In addition to the aggressive TOU pricing scheme, KEPCO has been practising special load control programmes that offer rebates to industrial customers who reduce usage during summer peak days. Even in this case, the main beneficiaries of the programme are from the same commodity BMI, namely EAF steelmakers. Whether the programme was intended to do so or not, EAF steels have been the biggest beneficiaries of the programme.

When KEPCO offered a peak cut rebate programme in 1994, for instance, the biggest beneficiaries of the programme were three EAF firms and Pohang Steel (POSCO), the only BOF steel firm until the 2000s in Korea. The three EAF firms, whose crude steel

³¹ Telephone interview with a general manager of the pricing office, Korea Electric Power Co., *Naju*, on 19 May 2015. The interviewee's name is not presented here due to the interviewee's request.

production capacities were much smaller than those of Pohang Steel, exploited the rebate programme much more than Pohang Steel did. In terms of contracted capacity, all three EAF firms performed load control of more than 50%, whereas Pohang Steel could reduce its demand load lower than 30% (Table 4.8).

The programme and the EAF steel sector's active involvement have increased further since then. For example, six of the ten largest participants in the load reduction rebate programme during the summer peak days in 2012 were also EAF steel firms. Only 13 EAF steel firms amongst 3,111 participant firms of the programme took nearly half the amount (49%) of the total rebate, which was 287 billion won, equivalent to US\$ 254 million dollars (KEPCO, 2013).³² It indicates both the scale of the Korean EAF steel industry in terms of electric consumption and its complementarity with the Korean electric supply industry (Tables 4.8 and 4.9).

Table 4.8 Major Participants of Electric Load Control Rebate Programme in 1994

Participants	Industry	Contracted Capacity	Load Reduction	Reduction /Contract Ratio (%)	Rebate (Million Won)
		MW			
Kangwon	EAF Steel	295.0	148.7	50%	471.8
Pohang Steel (POSCO)	BOF Steel	290.0	85.1	29%	268.0
Dongkuk Steel	EAF Steel	143.6	143.6	50%	168.0
Hankuk Steel	EAF Steel	72.0	41.4	58%	227.9

Source: Ministry of Energy and Resources 1995

Note: The figure is the result of a programme practised for 10 days in August 1994, and the rebate is converted into 2013 prices.

³² It should be noted that the size of rebate programme in 2012 was the biggest case ever in terms of rebate size and the number of participant firms due to the tight electricity supply–demand situation in the year. Nevertheless, it highlights the close relationship between EAF steelmakers and KEPCO.

Table 4.9 Top 10 Participants of Electric Load Control Rebate Programme in 2012

	Participants	Industry	Load Reduction (MW)	Rebate (Million Won)
1	Hyundai Steel	EAF + BOF	95,489	43,537
2	Daehan Steel	EAF Steel	42,153	18,778
3	Koryo Zinc	Zinc Smelter	38,703	17,148
4	POSCO	BOF Steel	29,993	13,163
5	Hankuk Iron & Steel	EAF Steel	25,793	11,829
6	Dongkuk Steel	EAF Steel	27,048	11,556
7	Hankuk Beam Steel	EAF Steel	23,605	10,908
8	Youngpoong Smelting	Zinc Smelter	24,625	10,336
9	Ssangyong Cement	Cement	20,515	8,957
10	Hankuk Steel	EAF Steel	19,686	8,824

Source: KEPCO 2013, Report to Committee of Industry, Trade, and Resources, National Assembly of Korea during the 320th National Audit (25 October), Vol. II: 418.

Note: The amount of load reduction by each firm is counted in accumulated terms during 45 days of the programme in the summer season.

4.2.5. Lax Environmental Regulations

Lax Emission Control Practices on Fossil Power Plants

Although emission control regulations on the electricity market were established in 1978 under the Environmental Preservation Act, its emission standards and practices have been loose. First, its national standard of NO_x on coal power plants was set at 500 ppm and continued until 1987, looser than even the pre-1973 standard of Japan. Even after amendment in 1987, the standard remained 350 ppm, which is still weaker than Japan's 1973 standard, until 2004. It is only from 2005 that the country's emission standards were strengthened to OECD members' average standards (see Section 5.2.5) (Table 4.10).

Table 4.10 Korean NO_x Emission Standards on New Power Plants³³

Fuels	National Standards (ppm, % of O ₂)			
	1978–'86	1987–'04	2005–'09	2010–'14
Gas	-	400	50 (13)	20 (15)
Oil	250 (4)	250 (4)	250 (4)	50 (4)
Coal	500 (6)	350 (6)	150 (6)	50 (6)

Source: Author's elaboration from the Enforcement Decree of Environmental Preservation Act (enacted in 1978) and the Enforcement Decree of the Clean Air Conservation Act (enacted in 1991)

Second, although the Korean emission control acts prohibit electricity suppliers from using coal fuels in its metropolitan areas, such as Seoul and Incheon, according to the regulation³⁴, the electric utility has been repeatedly exempted from the regulation (Table 4.11). For instance, KEPCO and its subsidiaries have built six large coal power plants in Incheon since the late-1990s. Although the Clean Air Conservation Act also allows a few local governments the authority to negotiate with the utility, their opposition was not recognised in practice. The official from the Ministry of Environment explained the legal background of the repeated exemptions.

If the Ministry of Trade, Industry, and Energy (MOTIE) requests permission of coal power plant construction project in the designated areas, the Ministry of Environment should settle with the MOTIE. Initially, it was agreed to permit four coal power plants in Incheon in the 1990s. However, the MOTIE requested another exemption for additional coal power plants again in the early 2000s. That is why we have six coal power plants in the area now.³⁵

³³ The standards in the Table only apply to new power plants.

³⁴ Article 42. Enforcement Decree of the Clean Air Conservation Act (enacted in 1991). The regulation was elaborated to control the total volume of emissions beyond concentration level.

³⁵ Telephone interview with an officer of Climate and Air Quality Policy Division, Ministry of Environment, *Sejong*, on 8 June 2015. The name of the interviewee is not presented here due to a request of anonymity.

Table 4.11 Designated Areas under Mandatory Use of Clean Fuel

Designated Areas		Target Facilities
1988	Seoul City	Power Plants, Boilers
1991	Incheon City and 13 Cities of Gyunggi Province	Power Plants, Boilers, and Apartment Complexes
1993	Busan City and Daegu City	
1998	12 Cities, including Ulsan, Gwangju, Daejeon	
1999	6 Cities including Pohang, Gimhae, Gumi	

Source: Ministry of Environment 2004

The loose emission standards and practices imply important ramifications for KEPCO and its subsidiaries. The Korean power producers have not been under pressure to replace their high sulphur and/or nitrogen content fuels with alternative ones, such as natural gas, under such loose standards and practices. The share of coal power has been always above 30%, and often even above 40%, in the Korean electricity market for the past three decades. By comparison, gas turbines could not exploit their environmental competitiveness under such loose regulation and practice, and the share has been less than 20% during the same period.³⁶

Lax Nuclear Safety Regulations and Practices

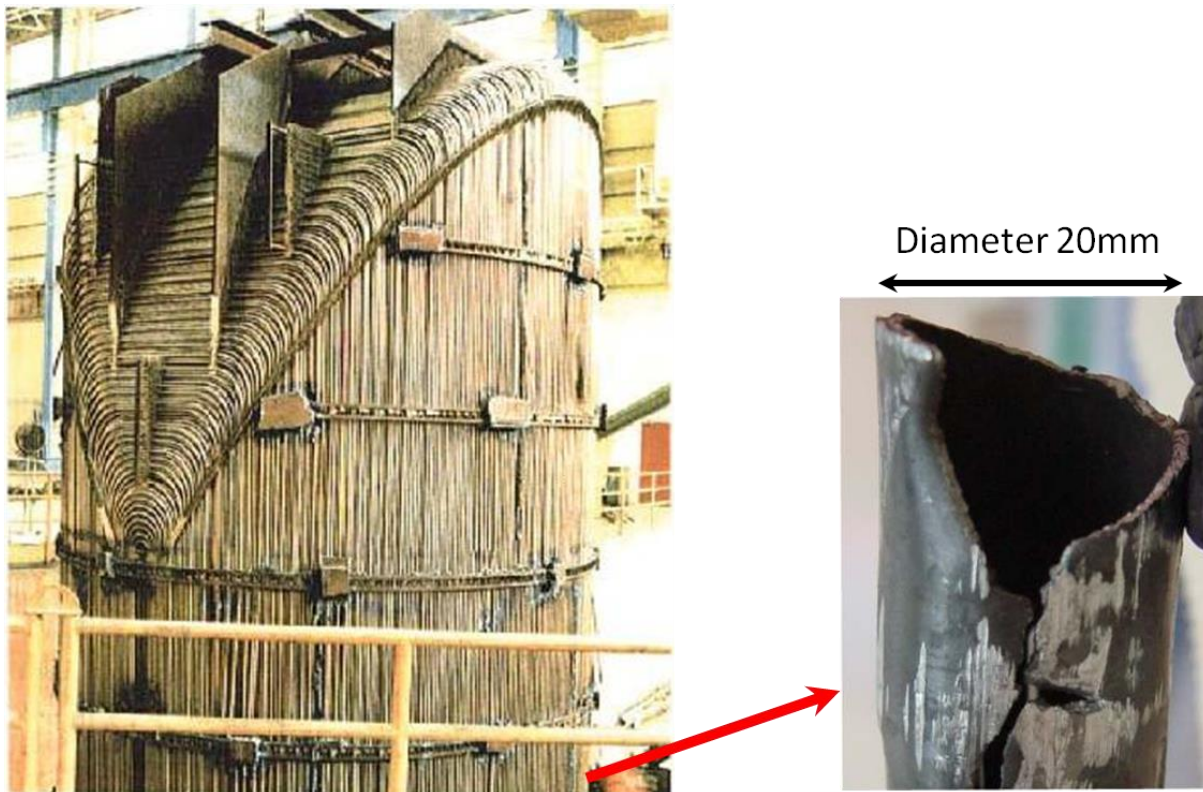
Although codified Korean nuclear safety regulations seem to benchmark those of the US, namely the U.S. Nuclear Regulatory Commission and its regulatory guidelines, the regulatory practice has been loose in operation and in new reactor construction projects. The industry-friendly regulations of the Korean nuclear safety regulators allowed a higher capacity factor (CF) of nuclear fleets and the rapid construction of new nuclear power plants in Korea. This Section discusses this issue in detail, particularly focusing on the issue of steam generator tubes' safety.

³⁶ The share of gas power temporarily increased to around 20% in 2013 due to a surge in electricity demand and an abrupt shutdown of several nuclear reactors.

One of loose safety regulatory practices regarding nuclear reactors in operation was the case of a steam generator tube rupture (SGTR) accident at *Ulchin* unit 4 in 2002 and the following actions by Korean regulators (Figure 4.13). The SGTR accident was a rare and serious event in the global nuclear power history. However, the regulator allowed the operator to restart the reactor after only two months of repair work even without identification of the root cause of the event. The regulatory action was criticised as a “hasty and industry-friendly action” by foreign experts as well as by civil society and media in Korea. There was international criticism by industry journals, such as *Nucleonics Week*, on the regulatory decision, as shown below.

Experts outside Korea questioned how Korean regulators have allowed *Ulchin-4* to restart only 7.5 weeks after a ruptured tube had been detected. The unit was shut from April 5 to May 27, according to KHNP. In Japan, for example, a steam generator tube rupture at Mihama-2 in 1991 led to a long forced-outage during which a comprehensive examination of tubes was carried out and which did not end until the steam generators were replaced a year later. In that case as well, the results of investigations by Japan’s Nuclear Safety Commission were made publicly available (Hibbs, 2002: 1).

Figure 4.13 CE-type Steam Generator and the Ruptured Tube at *Ulchin 4*



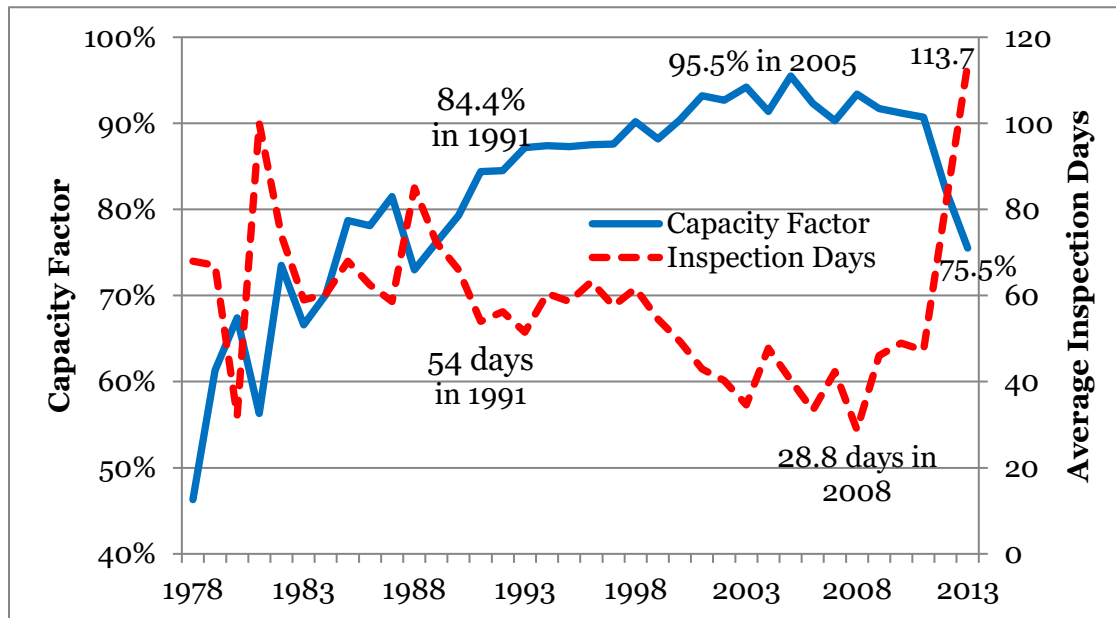
Source: U.S. Nuclear Regulatory Commission Photo Gallery on the left and Lee 2008 on the right.

In addition, the material issue of steam generators, namely Alloy 600, was not seriously considered when the Korean nuclear industry, including the utility and manufacturer, imported nuclear power plants and built up the technological capability in the 1980s. Even in the 1990s, when the global nuclear industry shared the vulnerability of Alloy 600 to stress corrosion cracking (SCC) with all the PWR operators all over the world, KEPCO constructed six reactors of Korean standardised PWRs, namely OPR1000, with Alloy 600-based steam generators.

Thanks to the rather loose inspection requirements and rapid periodic inspection practices, the Korean nuclear industry performed at the world's highest capacity factor over the past quarter-century. Once the country's nuclear fleet performed above 80% of the capacity factor in 1991, it never went down below 80% until 2012. Even then, it maintained above 90% on average throughout the 2000s. Its performance surpassed all

the countries with large nuclear reactor capacities, including Canada, France, Germany, the US, and Japan, between 1989 and 2010. Only that of the US has been close to the Korean capacity factor in the 2000s (Figure 4.14).

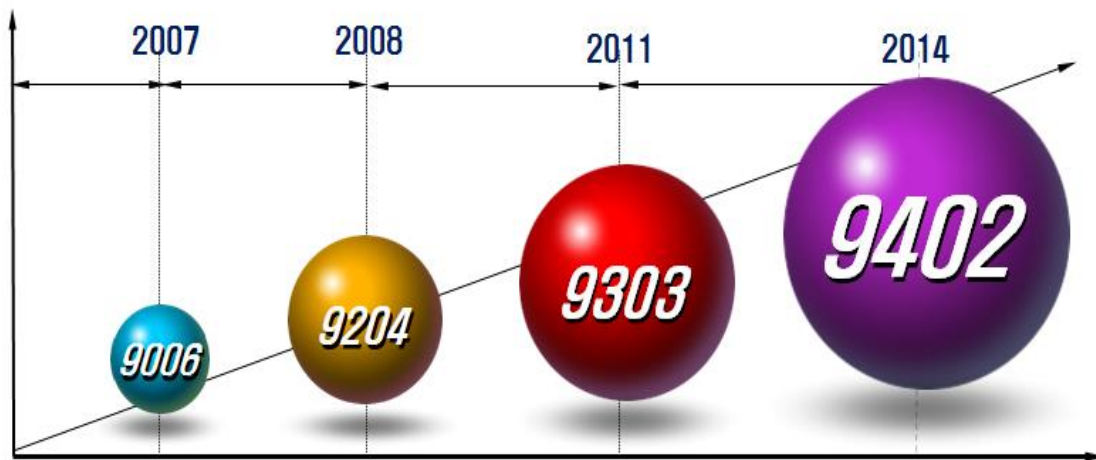
Figure 4.14 Average Inspection Days and Capacity Factor of Korean Nuclear Fleets



Source: Author's elaboration from Korea Hydro & Nuclear Power, *White Paper of Nuclear Power*, each year from 1990 to 2013.

Even further, KHNP, a nuclear subsidiary of KEPCO, launched a high capacity factor campaign, such as 'One Cycle Trouble Free', in 2009. At the same time, it also planned to launch the so-called '9402' Campaign, which implies a 94% capacity factor and 0.2 times of unplanned shutdown per reactor unit by 2014 (KHNP, 2009:16). The first two-digit number indicates the capacity factor, and the second one represents the average shutdown frequency per reactor unit (Figure 4.15).

Figure 4.15 KHNP's Ambitious Capacity Factor Maximisation Plan in 2009



Source: KHNP 2009, Report to Standing Committee of Knowledge-Based Economy for the 284th Parliamentary Inspection of Government Administration, 13 October 2009: 16.

However, the plan was not realised due to a manifestation of a massive steam generator tube cracking at *Ulchin* 3 and 4, the first Korean standard reactors, in 2011 and several years maintenance and steam generator replacement thereafter. The special task force team of Korea's Nuclear Safety and Security Commission, a newly established independent regulator in the aftermath of the Fukushima accident, found that the cracked tubes accounted for more than 50% of the total tubes, pointing out that the previous inspections overlooked the accumulating cracks (NSSC, 2011).

Subsequently, the regulator disapproved the restart of the *Ulchin* 4 reactor. Following the regulatory guidelines, KHNP shut down the reactor for 2 years until new steam generators could be prepared. Eventually, it scheduled to replace the steam generators with new steam generators made of more corrosion-resistant material, namely Alloy 690, in August 2013. The earlier loose regulatory practices of nuclear power in the 2000s made Korean ESI pay the cost, eventually.

In addition, the steam generator tube scandal was followed by a series of certificate forgery scandals in 2012 and 2013. Two operating reactors were forced to shut down when

it was revealed that thousands of substandard parts had been supplied with fake warranties in 2012. Another revelation about fabricated certificates of control cables in 2013 forced another two operating reactors to shut down and delayed the operation of the newly constructed Shin-Kori 3 and 4—reference reactors of the *Barakah* nuclear project in the UAE—until December 2016 (Choi, 2013; Park, J., 2013).

Subsequently, the nuclear operator experienced a lower capacity factor than 80% for the first time since 1990. All the events in the early 2010s revealed that the previous practices of Korean safety regulators had been far looser than international standards. The strengthened regulatory overview in the aftermath of the Fukushima accident and the massive manifestation of the steam generator tube cracking indicates that the world-record operational performance of the Korean nuclear fleets in the 2000s was related to the lax regulatory practices.

The series of scandals not only shattered KHNP's ambitious capacity factor maximisation plan but also delayed the operating licences of the first reactors, Barakah 1 and 2, in the UAE. According to the nuclear export contract between Korea and the UAE, Shin-Kori 3 and 4 reactors should perform safe operations for several years from the end of 2013, given that the APR1400 reactors did not have any operational track record. Furthermore, candidate operators of Barakah reactors were supposed to train with Shin-Kori 3 and 4 under KHNP's supervision for the same period to get the operating licence. The safety regulator of the UAE, thereby, refused issuance of the operating licence in May 2017, and the start-up of the first reactor has reportedly been delayed by a year without a specification of a date (Carvalho & Clercq 2017; World Nuclear News 2017).

The delay of operations not only caused penalties (US\$ 600,000 per day according to the contract's 'Liquidated Damages Clause'), but also increased KEPCO's labour cost. The total labour at the Barakah construction site is reportedly about 21,000 (Choi 2017; Clercq 2017). A year-long delay of operations alone can cause more than \$1 billion of cost overruns, aside from capital costs. KEPCO hardly experienced this kind of delay in

construction and operation schedules in the loose domestic regulatory environment before the Fukushima accident. The uncertainties under enhanced domestic safety regulations and foreign safety regulations will decide the fate of the UAE nuclear project.

4.3. Heavy Electrical Industry

4.3.1. A Brief History of Korean Heavy Electrical Industry Policy

Changwon Complex and Machinery Policy in the 1970s

As we have seen from the Literature Review Chapter, the Korean HEI experienced daunting circumstances decades before its surprising nuclear export case in 2009. The sector's experience has followed quite a different path from other comparable Korean machinery sectors, such as shipbuilding, where a typical Korean '*Chaebol*-governance' style worked well. It went through such a difficult time not because the Korean government and *Chaebols* were indifferent, but ironically, because both sides were so enthusiastic about the sector.

The Korean HEI started with a massive but hasty investment decision-making process on the HEI complex with the world largest heavy forging and casting machines under the military *Park Chung-Hee* state in the 1970s. As a part of the famous heavy and chemical industry policy, the so-called 'HCI Push', the Park government made an ambitious plan to construct a heavy machinery complex, including heavy electrical equipment production infrastructure, imitating Japanese Hitachi machinery complexes, in Changwon, a southeast region of Korea in the early 1970s (O, 2006).

However, experienced *Chaebol* firms, including *Hyundai*, *Samsung*, and *Daewoo*, did not consider the ambitious plan feasible and were reluctant to join in the complex project (Rhee, 1994). Instead, a novice *Chaebol* firm in overall heavy machinery sectors,

namely *Hyundai International Inco*,³⁷ joined in the ambitious plan as a main construction contractor as a reward for its compliance with the *Park* state.

The heavy forging and casting facilities were initially designed by GE, *Hyundai International Inc.*'s (HII's) OEM at that time, based on over-forecasting of future demand in the Asian power plant market. The scale was further increased by *Park*'s military ambition to compete with the massively mechanised North Korea. *Hyundai International Inc.* constructed an immense heavy forging-and-casting complex following the *Park* state's guideline. The world largest complex was financially facilitated by a large but conditional loan offer from the World Bank, which guaranteed monopolisation of the Korean HEI.

When they were planned in the mid-1970s, the heavy forging and casting machines were supposed to produce heavy equipment such as large steam turbine rotors, casings, reactor pressure vessels and steam generator shells. However, global and domestic electricity markets plummeted in the late 1970s and 80s due to the global energy crisis, and the facilities idled most of the time. Unsurprisingly, HII went into bankruptcy at the end of the 1970s.

In parallel, the Korean government set up the Machinery Indigenisation Policy in 1976 with intention to increase the local contents of plants and equipment and to reduce the portion of turn-key plants constructed by foreign firms. Following the policy, the state-owned KEPCO and Bechtel made a technology transfer contract in the fourth and fifth nuclear construction projects. The contract included the transfer of architecture engineering from Bechtel and subsequent training of Korea Power Engineering Company (KOPEC) engineers to build architecture design capabilities. Following the Machinery

³⁷ Although *Hyundai International Inco*. (HII) was established by a younger brother, *Chung Inyung*, of the *Hyundai Chaebol* CEO, *Chung Juyung*, their business management were not at all shared and even hostile to each other. *Chung Juyung* did not recognize his younger brother's management capacity in heavy machinery industries including the Changwon Complex project and HEI business (Rhee, 1994).

Indigenisation Policy, KEPCO increased the local content of equipment from the fourth and fifth nuclear project through procuring the components from local manufacturers, mainly from *Hyundai Heavy Industries*, a subsidiary of *Hyundai Group*, rather than HII (MER, 1988).

Continued 'Curse' of Changwon Complex in the 1980s

Right after the bankruptcy, the other three *Chaebols*, namely *Hyundai*, Daewoo and *Samsung*, competed fiercely to get access to the HEI market. Although the immediate disputes around the HEI were resolved by nationalisation of the bankrupted HII into KHIC in 1980, the initial massive investment on heavy forging and casting machines continued to frustrate the nationalised HEI firm and its major customer, KEPCO, for the next two decades (Rhee, 1994).³⁸

The Korean government had to arrange the Korean Development Bank (KDB) to take 42.3% of the KHIC stock, with KEPCO taking 38.2% and the Korea Exchange Bank taking 19.5%, to bail out the firm from bankruptcy in 1980. Additionally, the government aided the aggressive recovery of KHIC from chronic financial deficiency and management problems by appointing *Nak-Jung Sung*, a former president of KEPCO, as the president of KHIC in 1983. Thanks to this aggressive recovery programme, the KHIC sustained its autonomy from KEPCO in its overall management, while it still could take advantage of guaranteed monopoly status in its domestic market (KHIC, 1995).

Nevertheless, the KHIC suffered chronic financial deficit throughout the 1980s due to the continuously shrinking domestic power plant market and an inability to export the global power plant market. Even after the merger, KHIC's overall production capacity factor remained at only 30% in 1980, 35% in 1981 and even less than 10% in the mid-1980s (Auty, 1995: 210). It is not a surprising result in that the KHIC's major asset, namely the

³⁸ For more detailed analysis on the saga of the Korean military state, the four *Chaebols*, and the World Bank in the late 1970s and the early 80s, see Rhee, 1994.

heavy forging and casting facilities, which took 40% of total capital assets, was needed for only a few weeks per production of equipment, such as reactor vessels, steam turbine rotors, and generator rotors, and used to be idle for most of weeks a year. *Unghan Lee*, a former quality control manager of Korean nuclear power plants, explains the technological difficulties that KHIC had to face in the 1980s.

The curse of KHIC came from its gigantic size heavy forging and casting facilities. Initially, it was intended to supply GE complementary products of its local turbine business in Asia, such as heavy forging, but GE's turbine business did not go well due to low demand for growth in the 1980s. Furthermore, the final size of the heavy forging facility was enlarged again by *Park Chung-Hee* government's military ambition considering the competition with mechanised North Korea at that time. The 10,000 tonnes' heavy press machine was the world largest class at that time. In fact, power plants consist of much more precision equipment and parts rather than a piece of a few heavy forging equipment. Unfortunately, KHIC did not have such a capacity to produce precision products.³⁹

The enormity of the 10,000 tonnes' press together with a decade's low demand for growth had KHIC facing financial crisis again and again. Although over-forecasting of electricity demand in the 1970s, followed by overcapacity of power generation in the 1980s, can be observed in many industrialised countries (MacKerron 1992), the KHIC suffered more intense overcapacity problems. As Lee points in the interview, it was virtually impossible for KHIC to diversify its technology from heavy forging products to more sophisticated ones, such as gas turbines, due to state ownership and tight financial conditions. It was unimaginable for the state-owned firm to put its financial efforts into technology R&D, unlike the resilient *Chaebols*, such as *Hyundai Heavy Industries*, which

³⁹ Email Interview with *Unghan Lee*, a former deputy director of the Quality Control division at *Yonggwang Nuclear Power unit 5 & 6*, on 14 July 2012

were free to mobilise their cash in hiring foreign experts and training their employees on new technologies (Amsden & Kim 1986).

Amidst its repeated financial crisis, including KHIC's huge revenue loss from its desalination plant project in the UAE in the late 1980s, the Korean government decided to privatise KHIC in 1988. The only viable firms who could afford the offer and expressed intentions to buy KHIC were *Hyundai* and *Samsung* at that time. However, the privatisation process, based on a competitive bidding scheme, was miscarried by intentional abstention by *Samsung* on the day of bidding.⁴⁰ Then, the KHIC was bailed out again by KEPCO and the Korea Development Bank, and its monopoly status was extended to the mid-1990s. A nationalistic view of politicians that such a strategic industry should be held by the public ownership also supported the monopoly status of KHIC (Korea National Assembly, 1996).

Despite the miscarriage, Korean *Chaebol* firms prepared for entrance into the market again given that the temporal monopoly status of KHIC was supposed to end in 1995. Also, the Agreement on Government Procurement in the Uruguay Round of GATT, the predecessor of WTO, pushed the Korean government to open its power plant manufacturing market by 1997. Four *Chaebol* firms and KHIC actively sought to arrange technology licensing relationships with advanced foreign firms. For instance, the HHI made a gas turbine licence contract with ABB in 1991,⁴¹ and *Samsung Aerospace* did so with GE and SDC Turbine, a small Russian engineering group, in 1992 and 1993, respectively. In addition, KHIC made a licence contract with GE in 1991 (Lee, 1994).

⁴⁰ *Samsung* allegedly perceived that it would not be able to win *Hyundai* in the competition bid due to a capability gap in the HEI sector and decided not to bid to call off the entire privatisation program.

⁴¹ HHI maintained dual license relationships with foreign HEI firms. For instance, its license with Westinghouse was for steam turbine and nuclear power, and the other license with ABB was for gas turbine in the 1990s.

However, the Korean HEI sector was monopolised again, as the Asian Financial Crisis arrived in Korea in 1997. As the IMF got involved in the industrial restructuring of Korea for an economic recovery from the financial crisis, the Korean government had to go through restructuring of the HEI sector, including an amalgamation of all the private production capacity into KHIC and the privatisation of KHIC with a 10-year guarantee of monopoly status in 1998. In this way, the *Chaebol* firms were locked out from the HEI market again (KHIC, 2000). All the networks between foreign licensors and the *Chaebol* firms vanished and the mobilised human resources were reallocated to different divisions (Table 4.12).

Table 4.12 Result of Korean HEI Restructuring in 1998 (MW/year)

	Before Restructuring				After Restructuring
	KHIC	HHI	SHI	Total	KHIC
Production Capacity	5,800	3,450	1,000	9,250	5,800
Employees	3,628	596	633	4,857	4,033
Domestic Demand	2,500 MW/year				

Source: KHIC 2000

Ironically, KHIC was sold to a complete novice firm, namely the *Doosan* Group, a resort development and liquor manufacturing firm at that time, in 2000. The 10-year monopoly status of the newly privatised HEI firm was guaranteed by the government. It locked out other *Chaebols*, such as *Hyundai Heavy Industries*, and let them completely give up the HEI business. Although the *Park* state and the resourceful Korean *Chaebols* were enthusiastic about the industry, they had never experienced the famous ‘Korean government-*Chaebol* dynamics’ in the HEI sector over the previous three decades.⁴²

⁴² Although *Doosan* is also recognized as a “*Chaebol*” firm, its fields were too narrow and irrelevant to heavy electrical industry such as resort development and liquor manufacturing, unlike typical *Chaebols* which are diversified in various manufacturing industries and have accumulated experiences over decades.

Instead, the private successor, *Doosan Heavy Industries & Construction (Doosan)*, specialised its heavy forging equipment technologies through repetitive orders of nuclear power equipment from KEPCO and its subsidiary KHNP, beginning in the 2000s. In addition, *Doosan* could put its efforts towards technological diversification into the advanced steam turbine and gas turbines with much better financial conditions. It invested, for instance in the small gas turbine (5 MW) development programme with government sponsorship for technological capacity-building in the mid-2000s, following MHI's MF111 (11 MW) development case in the 1980s.

4.3.2. Nuclear Power Catching-Up Experiences

Development of the First Korean Standard Reactor

While Korean equipment and engineering suppliers increased their share of nuclear power construction projects in the early 1980s, they witnessed a collapse of the US nuclear market due to the effects of the Three Mile Island accident (1979) and stagnation in demand for electricity growth. Korea Electric Power Co. (KEPCO) and its subsidiaries requested that the Korean government set up nuclear reactor technology indigenisation programmes. Subsequently, the Ministry of Energy and Resources (MER) outlined guidelines for the indigenisation programme and requested the nuclear-related firms and institutes to submit each one's implementation plan by the end of 1984. KEPCO organised a consortium for the programme, namely the Electric Power Group Cooperation Council, which included the Korea Atomic Energy Research Institute (KAERI), KOPEC, KHIC, the Korea Nuclear Fuel Supply, and *Hyundai Construction* in the year (MER, 1988).

Furthermore, the Korean consortium exploited aggressively its bargaining power in order to achieve its ambitious nuclear technology indigenisation plan. It demanded its foreign partners virtually full-scale technology transfer options even at the expense of a

longterm relationship. One of the leading engineers of the consortium at that time recalls the aggressive catching-up process:

The Master Plan for the Technological Indigenisation of Nuclear Power Plants was set up in 1985. It enforced domestic firms as a prime contractor in nuclear power construction projects and defined the technology transfer list and technology indigenisation schedule, which targeted domestic firms' contribution of up to 95% of overall nuclear power technologies by 1995. Korea's government requested foreign licensors through KEPCO to transfer the whole technology package of the nuclear steam supply system (NSSS) design and equipment in 1985 and the council set up a schedule for the indigenisation programme, which planned an increase of local content ratio from mere assembly to 95% in the 11th nuclear plant, namely *Yonggwang* unit 3, by 1995.

We initially requested a package deal combining the *Yonggwang* reactor 3&4 construction project with a reactor technology transfer option from our licensor, Westinghouse. They answered with a rather cheap construction price without a technology transfer option. Then, we contacted CE and got an answer with a more expensive reactor construction price than the Westinghouse proposal, with a technology transfer option. We chose CE as a new licensor, and Westinghouse seemed quite surprised at the sudden change of the licence relationship.⁴³

Indigenisation of 95% means that the Korean HEI firm lacks the technology of the reactor coolant pump (RCP), man-machine interface system (MMIS), and reactor core

⁴³ Interview with *Byungoo Kim*, Professor of Nuclear Engineering at Korea Advanced Institute of Science and Technology, *Daejeon*, and a former senior researcher at Korea Atomic Energy Research Institute, on 23 March 2011

computer codes. Professor *Byungoo Kim* further explains the background reasons for this target of 95% rather than 100%:

Those three components are the most expensive and difficult technologies amongst the nuclear power components. In addition, we did not have any demand for RCP and MMIS in power plants other than nuclear reactors. Furthermore, a dozen computer codes belong to US national laboratories, such as Argonne National Laboratory and Oak Ridge National Laboratory, rather than CE. We may need to localise them in the future. But you should keep in mind that we also need well-known foreign firms, such as Westinghouse, as a strategic partner in export projects to maximise utilisation of their networks in the global market. So, the dependence on the US firms for those technologies is not that much negative and even necessary for keeping the partnership.⁴⁴

After the abrupt change of licensors, KEPCO and CE made a nuclear technology transfer agreement in 1987. The technology transfer based on the global market contingency is pronounced among various factors of Korea's successful indigenisation of nuclear technology. Without a virtual collapse of the global nuclear market and the subsequent financial crisis of CE in the 1980s, it would not be possible for the Korean HEI to get a nearly full scope technology transfer from foreign suppliers. The Korean nuclear community, including KHIC, could exploit such a condition by creating a new reactor construction contract for the first time after the 1986 Chernobyl accident. In effect, even the official review of the Korean MER, which took charge of the nuclear indigenisation programme, denied the efficacy of the previous nuclear indigenisation policies, including

⁴⁴ Interview with *Byungoo Kim*, op. cit.

early education. It points out that 'previous policies and programmes had been fragmented and unsystematic and lacked proper evaluations' (MER, 1988: 335).⁴⁵

In addition to the global market condition, KEPCO's financial assistance played a crucial role during the technology transfer process. *Unghan Lee*, a former quality control manager at several nuclear reactors of KEPCO, explains the contribution of KEPCO's financial mobilisation for all aspects of the reactor technology transfer from the US donors to the Korean recipients. His explanation also hints at the extent to which the scope of technology transfer could reach as an option of a single commercial nuclear construction contract with a financially troubled nuclear vendor, namely CE:

KEPCO had to subsidise all the technology transfer expenditure on behalf of KHIC, KAERI and KOPEC when *Yonggwang* unit 3&4, the reference reactors of Korean Standard Nuclear Reactors, were contracted in 1987. I clearly remember that KEPCO offered KHIC 25.5 billion won for reactor equipment, 9.8 billion won for turbine/generator, KAERI 28 billion won for reactor system design, and KOPEC 26 billion won for plant design. Putting the technology transfer expenditure into the contract was a violation of regulations on budget & account of KEPCO, in effect. But it was justified by government with the rationale that those suppliers would lower the costs of design and equipment in the future nuclear power projects, and KEPCO would be a major beneficiary. In this way, each of the participant firms could send around 200 engineers and staff members to the US for training under the supervision of CE, GE and S&L, respectively.⁴⁶

In this way, the total expenditure for the PWR indigenisation programme, including the actual project cost for *Yonggwang* reactor 3&4, was US\$ 2.5 billion, in 2013

⁴⁵ It should be noted that most of previous Korean nuclear reactor indigenization programs were handled by Science and Technology Agency (STA)

⁴⁶ Email interview with *Unghan Lee*, op. cit.: p. 124

dollars. If the reactor construction cost is excluded, the net expenditure for technology transfer would be only US\$ 0.82 billion, including training costs for Korean participants and the transfer commission for CE's reactor design System 80. Furthermore, the technology transfer also brought the inclusion of CE's new reactor design 'System80+' into the Korean Next Generation Reactor (KNGR, later the name was changed as APR1400), which made Korea's first nuclear export (Table 4.13).⁴⁷

Table 4.13 Public Expenditure for Nuclear Indigenisation in 1986–'95 (in 2013 US\$ Million)

	Firms	Yonggwang 3&4 Project	Training & Commission	Foreign Licensor	Sub- Total
Design Transfer Commission	KEPCO		605.4	CE	605.4
Plant Design	KOPEC	n.a.	63.6	S&L	63.6
Reactor System & Equipment Design	KAERI	134.5	68.5	CE	203.0
Reactor Equipment	KHIC (Predecessor of Doosan)	457.4	62.4	CE	519.8
Turbine Island		354.7	24.0	GE	378.7
Balance of Plant		734	n.a.	Mixed	734
Sub-Total		1,680.6	823.9		2,504.5

Source: Author's elaboration from an email interview with *Unghan Lee*, *op. cit.*: p.124

Development of APR1400 Reactor based on System80+

The Korean nuclear industry started to develop its next generation nuclear reactor (KNGR) in 1992. During this process, CE supported the KAERI through the inclusion of major 'System80+' design features into the KNGR design, such as two-loop systems, a reactor water storage tank, and a human-system interface. The architecture and

⁴⁷ When CE made a contract for the *Yonggwang* 3&4 project with KEPCO, CE applied US Nuclear Regulatory Commission certification of its new reactor design System80+ in 1987 and received the certification in 1997. Although 'System80+' reactor was never built in the US market and the certification expired 2012, its major design features were applied to the Korean APR 1400 design (see Section A2. in Appendix Chapter A).

engineering (A&E) division of KAERI minuscule into the KEPCO's subsidiary A&E, namely KOPEC, while CE was merged by ABB, the Swedish/Swiss firm, during the technology transfer process. Although the technology transfer of 'System80+' to Korea was officially confirmed by the Technology Cooperation Agreement (TCA) between ABB-CE and KEPCO in 1997, the main design features of the design were already transferred to Korea from the early 1990s.⁴⁸

In detail, the TCA between KEPCO and ABB-CE in 1997 consisted of a licence agreement (LA), support work agreement for KNGR development programme, and business cooperation in the global nuclear market. This 10-year broad agreement created a development path for Korean nuclear technologies (KAERI, 2003). In particular, the agreement offered KEPCO a blueprint and related data on a newly developed 'System80+' design by ABB-CE, a base for Korea's APR1400 reactor design. The LA renewed the licence for transferred technologies and guaranteed permanent rights of the licence, while agreement on cooperation in technology development and global market business opened a window for Korea's nuclear exports (Ahn & Han, 2000; KAERI, 2003; KHNP, 2013).

The development process was completed in 2000 and the design was certified by the Korean safety regulator in 2002. The first APR1400 reactors were built at Shin-Kori site. Total public R&D expenditure for this programme was only 233 billion won, equivalent to US\$274 million in 2013's price (MOTIE, 2000b). Even KEPCO's overall financial support for miscellaneous R&D programmes are added, the total R&D expenditure is minuscule. For instance, as a major source of nuclear R&D funding in Korea, KEPCO spent KRW265.5 billion, equivalent to US\$ 313 million in 2013's price, for 189 nuclear R&D programmes between 1984 and 1998.

⁴⁸ Interview with *Byungoo Kim*, op. cit.

Table 4.14 Reactor Technology Transfer from CE Designs to Korean Designs

American Design	Korean Design	Indigenisation Period	Reference Reactor
CE System 80	KHNP OPR 1000	1987–1997	<i>Yonggwang 3&4</i>
CE System 80+	KHNP APR 1400	1992–1999	Shin-Kori 3&4

Source: MOTIE 2000b; Interview with *Byungoo Kim*, *op. cit.*

After the technology indigenisation programme and subsequent completion of the reference reactor (*Yonggwang 3&4*) and first Korean standardised reactor (*Ulchin 3&4*) construction projects, the KHIC won most of the contracts for main nuclear equipment, previously subcontracted to CE. Table 4.15 depicts the gradual progress of KHIC's status from a subcontractor to a main contractor, to virtually a monopoly contractor in continued nuclear construction projects. *Doosan*, a successor of KHIC, also joined in the subsequent reactor construction projects as an NSSS equipment supplier from *Ulchin 5&6* to APR1400 reactors. Nevertheless, *Doosan's* role has been limited in only NSSS equipment supplier rather than an independent reactor vendor due to the lack of capabilities in A&E.

Table 4.15 Main Equipment Supply of Pressurised Water Reactors in Korea

Reactor	Capacity (MW)	NSSS Contractor	Turbine/Generator Contractor	Operation
Kori 1 (Turn-key)	587	WH	GEC	1978
Kori 2 (Turn-key)	650	WH	GEC	1983
Kori 3&4	950x2	WH	GEC	1985/'86
Yonggwang 1&2	950x2	WH	WH	1986/'87
Ulchin 1&2	1,000x2	Framatome	Alsthom	1988/'89
Yonggwang 3&4	1,000x2	KHIC/CE	KHIC/GE	1995/'96
Ulchin 3&4	1,000x2	KHIC/CE	KHIC/GE	1998/'99
Yonggwang 5&6	1,000x2	KHIC	KHIC	2002
Ulchin 5&6	1,000x2	<i>Doosan</i>	<i>Doosan</i>	2004/'05
Shin-Kori 1&2	1,000x2	<i>Doosan</i>	<i>Doosan</i>	2010/'11
Shin-Wolsong 1&2	1,000x2	<i>Doosan</i>	<i>Doosan</i>	2011/'12
Shin-Kori 3&4 †	1,400x2	<i>Doosan</i>	<i>Doosan</i>	2016/'18

Source: Sung and Hong 1999; MOTIE 2015

†Note: Actual operation of Shin-Kori 3&4 was delayed 3 years, respectively, due to the quality certification forgery scandal in 2013 (see p.119-120).

Catching-up Policy Through Electricity Supply Planning

Government nuclear technology catching-up policies were not limited to public R&D and technology transfer contracts. The MER's intervention in the decision-making process of electricity supply planning also played a vital role in the 1980s and 90s. The technology transfer process materialised through the *Yonggwang* 3&4 project, and the transferred technology was standardised through the *Ulchin* 3&4 project in this period. Securing investment into the two projects in KEPCO's energy supply plan was crucial to the technology catching-up process and should not be taken for granted given that socioeconomic conditions were unfavourable to nuclear power throughout the 1980s.

Nuclear power, the most capital-intensive energy technology, incurred high capital costs to the Korean state, which still heavily depended on external borrowing,

whereas its competing technology, namely coal power, enjoyed low coal prices throughout the 1980s. In screening public investment projects, the Economic Planning Board's (EPB's) rates on capital cost, such as the opportunity cost of capital and discount rates, were applied as a unified guideline in the decade.⁴⁹ The application of such rates on the electric power supply planning process would easily screen out nuclear power. The World Bank, as the biggest lender to Korea at that time, pointed out the Korean the Energy Ministry's practices for nuclear power programmes and their negative implications in the 1980s:

However, for some capital-intensive energy producing or energy using projects *the opportunity cost criterion* has not always been rigorously applied due to 'strategic' reasons. As the size and capital requirements of these projects is large, these *exemptions* have major macroeconomic consequences, crowding-out more productive investments, and increasing the cost of capital to other users. Projects in this category include the *nuclear power programme*, expansion of steel-making and oil stockpiling. While the magnitude of these investments and their long maturity might warrant a modest deviation from an opportunity cost based on current tight capital market conditions, the current evidence is that the deviation has been very substantial and thus very costly to the national economy (World Bank, 1985: 2, *italics added*).

As World Bank stated, the MER decision-makers exempted or modified the application of such capital cost rate guidelines in power plant construction programmes in the 1980s. By modified application of the discount rate guidelines, deviating from the EPB guideline, the MER's 'strategic' intervention was exercised during KEPCO's electricity supply planning processes in the 1980s. There is a snapshot showing how they deviated from the guideline for nuclear power programmes.

⁴⁹ Economic Planning Board (EPB) was a powerful steering government organization for Korean state's economic policy planning and management mostly during the 1970s and 1980s.

As the Table 4.16 shows, if MER had applied EPB's guideline discount rate, 10% in the late-1980s, all the nuclear units would have been screened out, favouring coal power units in the electricity supply plan, which covered a period from 1990 to 2001. In order to secure the nuclear units for technology transfer and standardisation programmes, KEPCO applied a favourable discount rate of 8% and then slightly modified the final numbers under MER's supervision. The final planned capacity for nuclear power, 4,700 MW, includes *Yonggwang 3&4* (2,000 MW) and *Ulchin 3&4* (2,000MW) together with a smaller CANDU reactor (700 MW) (Jhun, 1991). In this way, the government's nuclear catching-up policies have been reflected in the electricity supply plan and have played a crucial role in terms of 'learning by doing' through repeated construction projects.

Table 4.16 WASP Results and Actual Electricity Supply Planning in 1988

	Discount Rate 10%		Discount Rate 8%		Adjusted Plans	
	Unit Size (MW)	Unit No.	Unit Size (MW)	Unit No.	Sub-total (MW)	Share
Nuclear	0	0	1,000	10	4,700	32%
Coal	500	27	500	8	8,800	60%
Oil	500	3	500	2	1,155	8%
Others	0	0	0	0	2,363	16%
Total					14,708	100%

Source: Adapted from Jhun 1991: 238

Note: WASP stands for Wien Automated System Planning Package. The software system was initially developed by Oak Ridge National Laboratory to meet IAEA's requests for the market survey for nuclear power in developing countries in the early 1970s (IAEA, 1986). With several updates, the software has been used for electric utilities' power generation capacity expansion planning in various countries.

First Nuclear Export Case in 2009

The Korean nuclear consortium's award in the UAE's international nuclear reactor bidding in 2009 was shocking news to the global nuclear power market. Considering the presence of global frontier nuclear OEMs in the bid, such as Westinghouse/Toshiba, AREVA and GE-Hitachi, it was a remarkable catching-up story. The construction project of four APR1400 reactor units will be completed by 2020.

Although the overall contract was led by KEPCO, *Doosan* was the biggest beneficiary of the export contract. *Doosan's* NSSS, including a steam generator and reactor vessel, has a major share of UAE nuclear projects in terms of economic values. Out of the total project price, US\$ 18.6 billion, *Doosan's* share is the biggest, about US\$ 3.9 billion. Although *Doosan* used to export replacement steam generators on an occasional basis, mostly to the US market, the UAE project has the major share of the company's entire NSSS export history. Other than *Doosan*, *Samsung* and *Hyundai* took a substantial share of the total project as civil engineering firms. Toshiba/Westinghouse also joined as a subcontractor of steam turbines and technical consulting for the project after it was screened out during the first round of bid.

Unique aspects of the project were the presence of Toshiba/Westinghouse and Korea Power Engineering Company(KOPEC), the Korean A&E firm. Although Toshiba/Westinghouse was screened out during the first round of bid, it joined as a subcontractor of steam turbines and technical consulting for the project. It is related to special licence issues and will be analysed below. Another unusual aspect is that A&E contract was given to KOPEC, a subsidiary of KEPCO, rather than *Doosan*. It shows the weakness of the Korean HEI, given that all the global nuclear vendors have their own A&Es (Table 4.17).

Table 4.17 The Role and Share of Participants in the UAE Nuclear Project

	Scope	Contractors	Price (\$Billion)
Equipment & Architecture	NSSS & steam turbine	<i>Doosan</i> (with Toshiba as a subcontractor)	3.9
	Architecture & engineering	KOPEC	n/a
	Technical assistance & royalties	Westinghouse	1.3–2
Construction	EPC	KEPCO & KHNP	n/a
	Civil engineering	<i>Hyundai</i>	3.1
		<i>Samsung</i>	2.5
Training	UAE staff	KHNP	n/a
Initial Operation	Nuclear fuel	KNF	1
	Operation & maintenance	KHNP & KPS	1.2
Financing	Project financing ⁵⁰ (failed at finding investors)	KEPCO	n/a

Source: Berthélemy and Leveque 2011, Ex-Im Bank of the United States 2012

The success factors of the surprising nuclear export by the Korean consortium became a global issue. The most frequently addressed factors are having the cheapest price, short construction lead time, and the world's highest capacity factor (CF) of nuclear fleets (Berthélemy and Leveque, 2011; World Nuclear Association, 2011). In particular, price and operational performance need to be explained.

First, regarding the price of the whole nuclear project, KEPCO played a major role as a leader of the Korean consortium for the bid. As a domestic monopoly user of *Doosan's* reactor equipment and as a parent firm to KOPEC, it could effectively exercise its position to lower the price. In particular, KEPCO's *de facto* monopoly status of all the domestic construction firms in the electricity business gave it irresistible power in cutting all the

⁵⁰ Although KEPCO spent more than five years for seeking funding from private investors, it failed to find them. Eventually, the financing problem was resolved by direct loans from UAE government and Korean Export-Import Bank in October 2016.

engineering and construction prices. It virtually ‘twisted the arms of all the participant firms to drastically cut all the prices up to nearly zero-margin level’.⁵¹

Second, its world’s highest capacity factor, above 93% on average in the 2000s, reportedly impressed the UAE government. Right after the bid, both the UAE government officials and the KEPCO consortium acknowledged that the high capacity factor of Korean nuclear fleet was a high priority, along with the project cost and construction lead time (World Nuclear Association 2011; Berthélemy & Leveque 2011; Kane & Pomper 2013).⁵²

Efficacy of the Nuclear Export

The efficacy of Korea’s first nuclear export could be evaluated based on dependence on a foreign OEM, its contract price and future market prospect. First, the discounted price, compared to competitors’ bids, other than the capacity factor of Korean reactors, was a major success factor of the UAE deal. Its aggressive approach to the bid raised criticisms, however. Its lowest price amongst international competitors, which was about US\$ 18.6 billion—nearly half price of AREVA’s bidding⁵³—would inevitably lead nearly to a zero-margin return.⁵⁴ This lack of profit is more striking when one considers that the Korean consortium subcontracted expensive equipment and technology services to Toshiba/Westinghouse, equivalent to nearly 10% of the total construction project (US Ex-Im Bank, 2012). The expensiveness of the subcontract to Westinghouse/Toshiba comes from its licensing relationship.

⁵¹ Interview with *Chaeyoung Lim*, senior nuclear engineering researcher of Korea Atomic Energy Research Institute, *Daejeon*, on 21 May 2011

⁵² See also Section 4.2.4 for background of the high capacity factor

⁵³ The Korean consortium’s bid was reported as US\$16 billion lower than the AREVA’s bid (*Arabian Business Newspaper* 27 Dec 2009)

⁵⁴ Furthermore, global nuclear community warns that any delays of the construction project would lead to fatal results (Energy Economist 30 January 2012). Considering the financial package which the Korean consortium should deliver, estimated completion costs may be closer to US\$ 40 billion (Nuclear Intelligence Weekly 20 April 2012, 11 May 2012).

In addition, the LA and TCA did not allow technology transfer of computer codes for the reactor core and core protection calculator (which belong to the US national nuclear laboratories and CE, respectively) to the third party without the permission of Westinghouse, which merged ABB-CE. Thus, it is impossible for the KEPCO–Doosan alliance to export the APR1400 reactor to potential host countries who request technology transfer as a condition, such as China (KAERI, 2003). The UAE nuclear deal that did not require a technology transfer was a rather exceptional case, and it may not be replicated in the future global nuclear market, at least in the catching-up economies.

In this concern, the KEPCO–Doosan alliance has developed its own reactor design, namely the ‘APR+’ (KAERI, 2003). It also succeeded in putting the first APR+ reactor project, constructing two 1,500 MW reactors, in the country’s 7th Basic Plan for Long-term Electricity Supply and Demand in 2015 (MOTIE, 2015). As the new government announced a moratorium on all the new nuclear power projects in May 2017, however, the first APR+ project was also cancelled. Thus, it is difficult to expect the Korean HEI to be an independent nuclear supplier from Westinghouse in the global market in the foreseeable future.

After the surprising export contract, the Korean government announced its ambitious nuclear reactor export plan in January 2010. The plan includes exporting 80 nuclear reactors by 2030, which would represent 20% of the global nuclear market by the target year and US\$ 400 billion in contracts (World Nuclear Association, 2010). It seemed that Korean HEI’s three-decade saga was repaid by the export success and prosperous future. Whether the future global nuclear reactor market would expand sufficiently enough to deliver the Korean government’s export target is doubtful, however.

Furthermore, catching-up economies in Asia, such as China or India, may soon step up from being major nuclear reactor buyers to being suppliers, as they rapidly localise nuclear reactor technologies. In other words, the Korean HEI will have to face much fiercer competition in the future, with more suppliers from latecomers in a narrow

market. For instance, China was regarded by the Korean nuclear industry as a prosperous market in the 2000s but now it will be soon a competitor.

China is virtually a closed market to the Korean nuclear industry, once the Chinese nuclear industry decided to standardise its reactors based on Westinghouse's AP1000 and Areva's EPR designs.⁵⁵

The problematic reason is not only matter of design but also main equipment, including reactor vessels, steam generators, pressurisers, coolant pumps and reactor internals, that why Koreans cannot directly penetrate the Chinese nuclear market. Instead, Chinese regional monopoly heavy forging and casting firm, namely China First Heavy Industries (CFHI), will do the same job as KHIC (*Doosan's* predecessor) did in the Korean nuclear construction projects in the 1980s and 90s. Instead, *Doosan* is transferring know-how of reactor pressure vessel forgings to CFHI as a part of Westinghouse's AP1000 project deal with China. In the beginning, some steam generator and pressure vessel forgings for the two Chinese AP1000 reactors were subcontracted to CFHI (World Nuclear Association 2015). It will be soon localised by CFHI, however, as new nuclear reactor projects continue.

Although China constructed two units of Canadian CANDU and two units of Russian VVER in the early 2000s and started construction of two units of French EPR in the late 2000s, the country chose Westinghouse's AP1000 as a base of its indigenous standard reactor in 2007. In the year, Chinese state-owned HEI firms, namely China National Nuclear Corporation and China General Nuclear Power Corporation (CGN), and Westinghouse signed a deal to construct four AP1000 units in exchange of technology transfer from Westinghouse to the Chinese firms (Freebairn & Hiruo, 2017). As the construction projects of AP1000 were delayed a few years and accompanied costs increased, the Chinese government arranged the Chinese HEI firms to develop an

⁵⁵ Interview with *Chaeyoung Lim*, op. cit.

alternative standard reactor, namely HPR1000. As a result, there are no more American, Canadian, Russian and French reactors in China's new nuclear construction plan other than HPR1000 and CAP1400, a modified version of AP1000, as of 2019 (Thomas, 2017; South China Morning Post, 2019).

4.3.3. Gas Turbine Catching-Up Experiences (1991–2014)

As briefly discussed in the previous Section, several Korean *Chaebols* were preparing to enter the HEI sector in anticipation of the expiration of entry regulation in the early 1990s. The *Chaebols* put substantial efforts to efficiently catch up on gas turbine technology, one of the emerging power-generation technologies, after decade-long entry regulations. It should be noted that global gas turbine OEMs have not been eager to transfer their technology to the Korean industry, unlike in the case of nuclear technology. This reluctance is understandable in that the latter was diminishing and positioned in a buyer's market whereas the former was emerging and positioned in a supplier's market, where only a few suppliers dominate the market with numerous buyers in the world.

Although HHI and *Samsung* showed the most active engagement, their strategies differed widely. While the former focused on arranging technology cooperation with advanced foreign firms through detailed conditions of a gas turbine licence contract, the latter focused on R&D projects other than technology licences.⁵⁶

Hyundai Heavy Industries was resourceful in maximising technology cooperation through a licence relationship. The firm dispatched several directors and managers to ABB's headquarter and its subsidiaries in Zurich to arrange technology cooperation and subsequently invited three technical specialists to Seoul. *Hyundai* Heavy Industries was quite successful in arranging the detailed conditions of the licence, such as the automatic

⁵⁶ Licensed items for KHIC were quite limited in simple components such as casings of gas turbines. Thereby, details of the KHIC-GE license relationship are skipped here.

inclusion of newly developed or improved technologies and the limitless manufacturing of single-cycle gas turbines by HHI.

Although open-cycle gas turbines are less efficient than CCGTs in a commercial sense, the licensing flexibility would offer HHI more chances to learn core technologies. The licence contract covered ABB's Type 8 (46.9 MW), Type 1-EN (81.6 MW) and Type 13-E (147.2 MW) gas turbines. Other firms, including KHIC and *Samsung* could not make such a flexible technology licence at all (Lee, 1994).

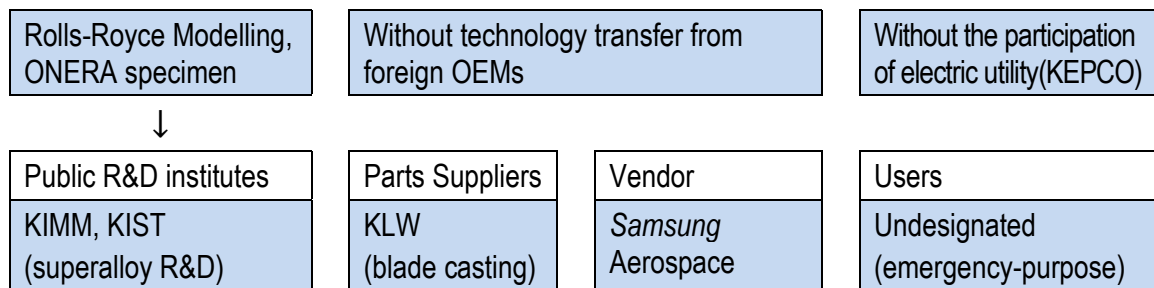
By comparison, *Samsung* Aerospace made a gas turbine licence contract with GE, which is notorious for restricting technology transfer to its licensee in the global market. Due to its arm's length relationship with GE, *Samsung* had to find a technology donor separately. After unsuccessful negotiations with American, European and Japanese gas turbine makers for technical cooperation, *Samsung* chose a small group of Russian gas turbine engineers as a technology partner in 1990. *Samsung* subsequently invited the group, namely SDC Turbine, to its public R&D programme as a technology partner (Kim et al., 1994).

First Public R&D for 1.2 MW Gas Turbine (1991–1998)

Samsung succeeded in getting government support for a small gas turbine (1.2 MW) R&D project, which started in 1991 and finished in 1998. The target of the public R&D project was a 1.2 MW emergency-purpose gas turbine and the company's official expenditure was MUS\$ 120. One of the main differences of the gas turbine R&D programme from that of nuclear power was that a user firm, namely KEPCO, did not join in the programme. Also, the emergency power plant market was neither developed nor encouraged in Korea in the 1990s. From the user side to a foreign technology donor, the programme scheme lacked crucial ingredients in the first place. *Sooyong Kim* from *Doosan* reviews limits of the programme further as below:

Samsung Aerospace's mindset was like, 'Buy out all the best components and parts from all over the world and assemble them into a gas turbine machine.' However, that does not work in a gas turbine development case and, of course, did not work. Not only integrators but also various suppliers, engineers and scientists should work together from the beginning for about a quarter-century to develop a gas turbine machine. It is a rather cooperative 'building-up' process than a simple 'assembling' of nice components and parts.⁵⁷

Figure 4.16 Limited Network for Small Gas Turbine Development Programme in the 1990s



Source: Interview with *Sooyong Kim*, op. cit.

Note: ONERA stands for Office National d'Etudes et de Recherches Aéropatiales, a French national aerospace research centre. See Accronym List for others.

Second Public R&D: Doosan's Small Gas Turbine Programme (5 MW) (2005–2011)

Firm-level efforts have changed since the ownership change of KHIC in 1998. *Doosan* adopted diversified strategies in developing the technological capabilities of gas turbines. While it kept a licence relationship with MHI, a new licensor after GE left *Doosan* in 2005, it was developing in-house capability in small gas turbines with technological assistance from a jet-engine maker in the Former Soviet Union (FSU) region.⁵⁸

⁵⁷ Interview with *Sooyong Kim*, Head of Gas Turbine Development, *Doosan Heavy Industries & Construction, Daejeon*, on 16 March 2011

⁵⁸ The engine maker is not presented here due to *Doosan's* own confidentiality issue; Ibid.

Doosan seems to have pursued a 'two-track' strategy as *Samsung Aerospace* did with GE and SDC Turbine in the 1990s. Although *Doosan* produced some basic parts of gas turbines, such as casings, and assembled complete gas turbines under MHI license, it pursued its own technology development path independently. The strategy seems inevitable in that MHI is not eager to transfer its core parts of gas turbine technology to its potential competitor. In effect, *Doosan* already experienced such licensor's defensive approach under GE's licence in the past three decades.

Although we had a cooperative relationship with GE for three decades, GE completely shut out the technology transfer option and offered us only after-market service with the expensive commission. It happens in other countries too. For example, whenever GE Saudi suffers from technical problems with gas turbines, it should entirely depend on GE. In addition, GE had a negative experience in the steam turbine licence relationship with *Doosan* in the past. When we developed and commercialised steam turbines under the GE licence, our share outpaced GE in the Asian steam turbine market. That experience seems to have made GE cut off the gas turbine licence with us in 2005 to avoid a similar situation in the future.⁵⁹

Doosan, in the 2010s, seems to have a better position than *Samsung Aerospace* had in the 1990s in that it already has a licence relationship with MHI, as well as additional technology cooperation with a gas turbine maker in the FSU region. In effect, it already has done a larger gas turbine development project with a wider range of participants in the late 2000s. *Doosan's* 5 MW Small Turbine Development Project produced four small gas turbines in total, from 2005 to 2011. It is reported that most of the components and parts are supplied by local manufacturers, except air compressors. Overall efficiency was

⁵⁹ Interview with *Chunrok Kang*, Chief Engineer of *Doosan Heavy Industries & Construction*, *Changwon*, on 14 March 2011

31%, and the emission target was NO_x at 25 ppm. About 120 engineers and researchers, including 40 from *Doosan*, participated in the development project. Four universities, namely Seoul, Yonsei, Korea Advanced Institute of Science & Technology (KAIST) and Postech, and parts suppliers, including *Samjung* Turbine and KEPCO Plant Service & Engineering (KPS), participated in the project.⁶⁰ It is estimated that a few high-temperature components of gas turbines were localised by the project (Ahn, 2014)

Third Public R&D for Large Gas Turbine (2013–2020)

The Korean government and *Doosan* Heavy Industries launched the country's third gas turbine technology indigenisation R&D programme in 2013. Initially, the project was planned to develop 100 MW (F-class), 37% energy efficiency gas turbines by 2020. Also, 70% of the components and parts are to be supplied, 100% designed by the local manufacturer. If a secondary cycle is added to the gas turbine, which means a CCGT, its total output would be around 200 MW (Ahn, 2014).

However, there have been criticisms of the initial target during government feasibility study processes that even if the project successfully achieves its development goals, the technology gap between the Korean latecomer and global frontiers would be still around two decades. The criticisms pointed out the efficacy of the 100 MW target in the global context, where large gas turbines up to 250 MW were already commercialised. Facing the criticisms, the target was enlarged to 250 MW in 2014 (Ahn, 2014). Considering the capabilities of Korean HEI that only experienced development of 5MW scale gas turbine, the sudden upscaling of the development project target is also questionable. Whether the development target is 100MW or 250MW, the Korean HEI will need a close and reliable foreign partner.

In effect, domestic gas turbine makers needed to have a foreign partner as a compulsory condition for the bidding eligibility to the public development programme.

⁶⁰ Interview with *Sooyong Kim*, op. cit.

In the beginning, the technology transfer agreement between Alstom and *Samsung TechWin* seemed imminent. The *Samsung* consortium gave up the bidding after Alstom eventually refused the technology transfer and sold its entire jet engine and small gas turbine business to *Hanwha*, another Korean conglomerate, in 2015, however. In the meantime, Alstom's gas turbine division was sold to Ansaldo Energia, an Italian state-owned gas turbine maker. In this time, *Doosan* tried to acquire Ansaldo, but the Italian government also refused the deal in 2013 (Korea EXIM Bank, 2014; Meritz Research, 2017).

Finally, *Doosan* acquired an American gas turbine repair service firm, namely ACT Independent Turbo Services, and secured participation in the development project in July 2017 (Combined Cycle Journal, 2018). The acquisition of the American specialist by the Korean latecomer is rather surprising, given that *Doosan* had to spend a substantial expenditure on the acquisition. The decision is reportedly related to the new Korean government, which has openly pledged a virtual moratorium on new nuclear power projects in Korea.

The acquisition may be a rational choice given that it is almost impossible to have a gas turbine partner in the position of direct competition in the ever-competitive global market. Also, the repair service market is as big as the gas turbine market, considering the relatively short lifecycle of major gas turbine components. *Doosan* could develop its technology capabilities based on 'learning by repairing' process with its specialist partner. It is too early to tell whether *Doosan* could leap from its current capability to the development of such a large gas turbine within a few years, however. There may be more serious issues than a foreign partner in the Korean gas turbine market.

Limit of Gas Turbine R&D Efforts and Insufficient Demand for Gas Turbines

As the global gas turbine market grows and market dominance of oligopolistic OEMs is strengthened, the chances of technology transfer to the Korean latecomer are

diminishing. Most of the interviewees did not expect a dramatic result from the current public R&D programme for the indigenisation of gas turbines. Soo-Yong Kim from *Doosan* also expressed his scepticism on enthusiastic large gas turbine R&D projects in Korea. He emphasises that even *Doosan's* small-scale gas turbine R&D investment a decade ago was a result of very hard decision-making, given the weak gas turbine demand in Korea:

A large gas turbine R&D project itself does not necessarily help us improve technology capability. Gas turbine manufacturer's own demand and conditions should be carefully considered in such a public R&D.⁶¹

A few more interviewees also pointed out the demand condition of gas turbines in Korea. In particular, Sungho Lee from KEPRI gave unexpected answers to interview questions about the effectiveness of R&D and research networks between gas turbine actors in Korea:

I do not think R&D size or coordination between gas turbine makers, public institutes, universities, etc. is the main cause of underperformance in gas turbine catching-up in Korea. Of course, we might have better R&D results if we had better material science institutes or expensive test-bed infrastructures for a demonstration of gas turbines.

However, that is not my point. I think the real problem is that most of the Korean gas turbine stakeholders do not have sufficient incentives and demand for developing the gas turbine technologies to a critical stage. For instance, we reduced designated gas turbine researchers from 15 to three a decade ago. Gas turbines' contribution to the Korean electricity market is still too small for us to invest in human resources and research funding.

⁶¹ Interview with *Sooyong Kim*, op. cit.

Particularly, the price of natural gas is too high for gas turbines to compete with nuclear or coal power in the Korean market.⁶²

Haechan kim, a former engineer of the gas turbine division of *Hyundai Heavy Industries* (HHI) also suggests the problem of domestic market demand for gas turbines. Notably, HHI was once locked out of the Korean power plant market, from 1998 to 2009, due to the second restructuring of the Korean HEI and the temporary monopoly status of *Doosan* from 2000–2009. It did not return to the power plant market after the temporary moratorium was lifted, however. *Haechan kim* points out weak domestic market demand for gas turbines in addition to a mismatch of technical specifications between domestic and the global market:

In the 1990s, we aimed at the domestic gas turbine market. Now, we find that current and future domestic market for gas turbines would be too small. We also considered the export market as an alternative. But, there is a difference in electrical system frequency between domestic and export markets; say ours is 60Hz while major gas turbine markets are based on 50Hz. So, if we build up our gas turbine technology from 60Hz in the limited home market, we may not have a good prospect for the export market either. That is why we did not restart the gas turbine business even after the temporary monopoly status of *Doosan* finished.⁶³

Table 4.18 shows the power generation costs of the major three technologies in Korea, as of 2015. The high generation cost of CCGT comes mainly from high natural gas prices. The big gap between CCGT and the other two technologies limits its position in a

⁶² Interview with *Sungho Lee*, Senior Researcher of Green Energy Laboratory, Korea Electric Power Research Institute, *Daejeon*, on 16 January 2013.

⁶³ Interview with *Haechan Kim*, a former engineer of the gas turbine division of *Hyundai Heavy Industries* (HHI) and a general manager of *Hyundai Electric*, *Changwon*, on 15 March 2011.

specific market segment, such as peak-load power generation (see Section 4.2.4 for the background of natural gas price).

Table 4.18 Economic Status of CCGT in the Korean Power Market (2015)

	Nuclear (1,400 MW)	Coal (1,000 MW)	CCGT (900 MW)
Construction Cost (KRW 1,000/KW)	2,378	1,449	904
Construction Lead Time (months)	75	58	27
Power Generation Cost (KRW/kWh)	44.6	58.6	103.7

Source: MOTIE/KPX 2015, Background Material for the 7th Basic Plan for Long-term Electricity Supply and Demand

Note: Capacity factor (CF) of all power generation technologies is assumed 80%.

4.3.4. Institutions of Korean Heavy Electrical Industry

Virtual Monopoly Status of Doosan

The repeated monopolisation of the HEI in 1980 and 1998, and the miscarriage of privatisation in 1989 locked out the Korean *Chaebols* from the HEI market. Although three famous *Chaebols* prepared to enter into the market, including investment on production equipment, contracting foreign licences, and inviting foreign specialists, they had to hand over their production assets to the state-owned KHIC or give up their market entrance to the privatised monopoly of *Doosan*.

The repeated deprivations of foreign channels, human and physical assets for HEI technologies made the *Chaebols* completely give up the market, even after the temporary monopoly status of *Doosan* expired in 2010. Although *Hyundai* and *Samsung* still participate in power plant construction projects, they are concerned predominantly with construction engineering. Therefore, *Doosan* exercises *de facto* monopoly status in the Korean HEI market without worrying too much about its domestic competitors.

Heavy Dependence on the Korea Electric Power Company

Doosan's dependence on the KEPCO, the state-owned monopoly of the ESI, is two-fold. First, KEPCO and its subsidiary firms have been major channels of power plants construction orders to *Doosan*. Although three IPPs entered into the Korean electricity market in the early 2000s, their market share remains tiny. Thus, KEPCO's technology choice and subsequent construction orders have been decisive in developing and maintaining *Doosan's* technological capabilities.

Second, *Doosan* has depended on KEPCO for A&E since the privatisation and has focused on the design and manufacturing of subsystems and power plant equipment. The unconventional division of labour was arranged by government in the early 1980s in consideration of the limited capabilities of KHIC, *Doosan's* predecessor. As an A&E subsidiary of KEPCO, the Korea Power Engineering Company (KOPEC) developed system designs of Korea's standard reactors, including OPR1000 and APR1400, and coal power plants, while *Doosan* started to develop its own gas turbine design capabilities in the early 2000s. This arrangement offers a cost-down effect of Korean nuclear reactors, while it also shows inherent weaknesses in the Korean HEI as a reactor vendor.

Arm's Length Relationship With Foreign Licensors

The Korean HEI has maintained neither long-term nor close relationships with foreign licensors in both nuclear and gas turbine technologies. Although it succeeded in contracting of technology transfer of PWRs from CE in the mid-1980s, it was rather a result of 'linking and leveraging' that switched its licence partner from Westinghouse to the financially troubled American firm rather than a close relationship. After a series of amalgamations of CE by ABB in 1989, by British Nuclear Fuel Ltd. (BNFL-Westinghouse) in 1999, and by Toshiba-Westinghouse in 2006, the Korean HEI and KEPCO had to meet Westinghouse as a licensor again. *Doosan* maintained a rather limited licence relationship with Westinghouse in component equipment of NSSS (KAERI, 2003).

By comparison, arm's length relationships with foreign gas turbine OEMs could be explained by foreign licensors' choices. General Electric's typical attitude in gas turbine technologies is to keep some distance from its licensees and prevent technology transfer all over the world.⁶⁴ Once GE left *Doosan* after a dispute over the Asian steam turbine market, MHI (the Japanese gas turbine OEM) became a gas turbine licensor of *Doosan* in mid-2005.

However, MHI also tends to keep its distance from *Doosan* regarding technology transfer issues. Instead, the two firms have agreed to have a rather gradual technology cooperation programme in proportion to gas turbine delivery performances in the Korean and the export market. For instance, the two firms would start the technology cooperation programme only after delivery of a certain number of gas turbines in Korean and foreign export markets.⁶⁵ Whether the technology belongs to the diminishing market (nuclear) or the emerging market (gas turbine), a long-term and close licensing relationship does not seem to fit with the Korean HEI.

4.3.5. Supporting Industries

Precision Casters for Gas Turbine Development

Precision casters comprise an important supporting industry to gas turbine maker, given that a new gas turbine design comes from a cooperative development process between precision casters and gas turbine makers. Although there were around 45 small and medium-sized precision casting firms, two-thirds of them hired less than 50 employees in 1990s' Korea, and actively involved firms numbered only 31. Of them, 90%

⁶⁴ Interview with *Sooyong Kim*, op. cit.

⁶⁵ Detail numbers are not presented here due to *Doosan's* confidentiality issue; Interview with *Chunrok Kang*, op. cit.

were focused on specialty steel and steel casting products, irrelevant to gas turbines or jet-engine blades and vanes. A few exceptional firms produced aluminium alloy and copper alloy casting products, but their quality was still far from that of gas turbine parts, which mostly depend on nickel-base superalloy casting products. With underdeveloped technological capabilities, they had to compete only with the low-end products market (Lee et al., 1993).

While advanced economies' jet-engine and industrial gas turbine manufacturers offer large demand for precision casting products, the Korean gas turbine market does not offer precision casters for such large domestic demand. It is not strange that Korean precision casters did not have commercial technological capabilities for such purposes until the 1990s. Instead, the Korean precision casters are reported to have focused on basic technological capabilities, including i) reducing lead time through making 'fast pattern' with appropriate price and quality, ii) systematic process simulation technology on casting process factors of solidification, iii) equipment design capability for improving process efficiency (Choi et al., 2011). Table 4.19 shows all the material which the 31 firms use for their precision casting business (Lee et al., 1993).

Table 4.19 Major Products of Precision Casters in the 1990s' Korea

Product Metals	No. of Firms	% (No. of Firms/Total Response)
Specialty Steel	28	90%
Cast Steel	22	71%
Cast Iron	1	3%
Aluminium-Base Alloy	9	29%
Cu-Base Alloy	6	19%

Source: Lee et al. 1993

Note: The Table shows a result of multiple choices by the casting firms in an industrial survey in 1992

Nevertheless, a few Korean precision casters did catch up to the basic level of technology for modern gas turbine equipment. One of them was Korea Lost Wax (KLW),

a small firm that started with only 40 employees.⁶⁶ Initially, it was established as a Korea-Japanese joint firm in 1979, making engine parts for Japanese industrial sewing machines. *Seafoong Chang*, the founder of KLW and a former manager of a construction firm who was personally fascinated with Korean traditional casting technologies, started to learn rather simple precision parts technologies, such as valves, from the Japanese partner Hayashi Lost Wax and sent several employees to Japan for training.⁶⁷

Once it built its own production capability and performed at a lower error rate than its Japanese partner, it shifted its attention from sewing machines to larger and advanced markets. It introduced the first vacuum induction melting furnace (VIM) in Korea in 1988. The VIM is needed for high-end precision casting processes, mostly used for parts of jet engines and gas turbines. The ‘vacuum’ condition of the equipment offers a superior environment for removing impurities such as oxygen and nitrogen contents from the casting process, which air melting processes for commodity steel products, such as the EAF, cannot match.

It was surprising news to other Korean casting companies since there was not such a high-end market in Korea at that time. There were rumours that KLW would go into bankruptcy due to the financial burden of the expensive VIM equipment. But the decision-making of our CEO proved an excellent choice later.⁶⁸

After the introduction of VIM, it established its own technology research centre in 1989 and started to invest in in-house R&D with an annual research expenditure of about

⁶⁶ The firm’s unique name came from a typical precision cast technique, called ‘lost wax’, which shapes ceramic mould for various complex 3-dimension shape products.

⁶⁷ Interview with *Byungmoon Chang*, director of Korea Lost Wax Technology Research Center, *Sihwa Industrial Complex*, on 7 & 8 March 2011.

⁶⁸ Ibid.

10% of its revenues. It aimed at precision casting technology including, jet-engine parts for aeroplanes. After several years, the small firm surprised the Korean defence equipment market by winning a precision casting subcontract from Pratt & Whitney for the 'Korean Fighter Jet Project', which selected F-16 air fighters, over *Daewoo Precision Engineering*, a subsidiary of the prominent *Daewoo Chaebol*, in 1992. Its investment into new production equipment and in-house R&D had paid off.⁶⁹

When we attended the bidding process, we brought a sample of engine parts while *Daewoo Precision Engineering* brought with only a blueprint. I openly argued to the government examiners that even if there had been *Kim Woojung*, the CEO of *Daewoo Chaebol* at that time, in the bidding venue he would choose K LW rather than the *Daewoo* subsidiary firm.⁷⁰

In the following years, it acquired quality certification for the Turbine Air Seal on PW4000 engines from Pratt & Whitney (P&W), system approvals from Bell Helicopter and GE Aerospace, respectively. It took advantage of technical assistance from P&W until 2001, as well. It also developed its technological capability in gas turbine blades and vanes from the manufacturing of foreign OEM products, such as aero-derivatives of GE, namely the LM2500, in the 1990s (Korean Institute of Metals and Materials, 1994). Thanks to the accumulated experiences with major jet-engine OEMs, it now supplies blades and vanes for various commercial aeroplanes of Airbus and Boeing.

Regarding land-based gas turbines, it defeated another *Chaebol* firm, *Samsung Aerospace* (a predecessor of *Samsung TecWin*), in a competitive bid for KEPCO's gas turbine blade repair contract in the early 2000s. It was a remarkable achievement, since the small firm, with only around 150 employees at that time, performed in the project with

⁶⁹ Interview with *Byungmoon Chang*, *op. cit.*

⁷⁰ From a TV interview of *Hanvit Broadcasting* (a Korean local cable channel) with *Seafoong Chang*, the CEO of K LW, aired on 30 June 2014

higher production quality than *Samsung Aerospace*.⁷¹ In effect, the repair market for gas turbine blades and vanes is sizeable. Subsidiary GENCOs of KEPCO and Korean private IPPs operated 124 gas turbines altogether, as of 2010. They paid KRW 160 to 180 billion annually, around US\$140–160 million in 2013 price, for repair and replacement of gas turbines blades and vanes to foreign gas turbine suppliers in the early 2010s. The replacement cost is large for the operators, given that the cost is equivalent to the price of four gas turbine units (Ahn, 2014).

As foreign OEM's superalloy technologies for gas turbine blades and vanes were continuously improved with superior materials and higher turbine inlet temperature, the cost of repair and replacement of the components also rapidly increased. Thus, KRW's involvement in the repair market is important for the overall catching-up strategy of the Korean gas turbine community, especially when domestic HEI, namely *Doosan*, and other precision casters could not meet the quality requirements (KEPRI, 2003).

For instance, starting in the early 2000s, foreign gas turbine OEMs began to exercise predatory measures to lock out Korean precision casters from domestic gas turbine maintenance business, including repair and replacement of blades and vanes. Considering that one of the main catching-up strategies of KRW has been reverse engineering, it is not surprising that the firm is vulnerable to lawsuits on IPR infringement. Although the interviewee did not confirm whether there was an actual IPR lawsuit case against KRW, he mentioned there have been informal threats of a lawsuit from a foreign OEM.⁷² Also, the foreign OEMs started to apply long-term (typically more than five years) exclusive maintenance contracts at a discounted price with Korean gas turbine users, including IPP and KEPCO's subsidiary GENCOs. At times, the Korean precision casters are faced with sudden upgrades of gas turbines blades and vanes by the

⁷¹ Interview with *Byungmoon Chang*, op. cit.

⁷² Ibid.

foreign OEMs after the Korean firms localise existing blades and vanes. *Byungmoon Chang* explains an example:

In some years of the 2000s, we developed D, E and N class blades and vanes through a collaborative development programme with KEPCO and our products were installed in one of GENCOs' CCGTs. After two years of commercial operation, however, the OEM suddenly upgraded the gas turbine with a different configuration set of D & E-class blades and vanes from existing 115 blades configuration to 85 blades. The OEM upgraded the gas turbine at a nearly zero-margin price. Instead, it shared the increased revenue from the improved fuel efficiency of the gas turbine with the GENCO in each year. Then, the D and E blade technologies we developed were instantaneously abandoned in the Korean market.⁷³

Although Korean precision casters tried to make a link with a new technology source from advanced countries in order to improve its technology base of precision casting, soon they realised there is a tremendous hurdle to do so. Two Korean precision casters, for instance, tried to negotiate a cooperative development of the technology with advanced foreign precision casters such as Howmet and the Precision Castparts Corporation (PCC) in the US in the mid-1990s. Both failed to do so, however, owing to unacceptably high-technology commission requests (Korea Institute of Machinery and Materials, 1998). The frustration of 'technology donor searching' efforts amongst Korean precision casters was not only a matter of technology commission but also a matter of strategic control of the US Department of Defence. *Bumsoo Kim from the Korea Electric Power Research Institute (KEPRI)* suggests the background reason:

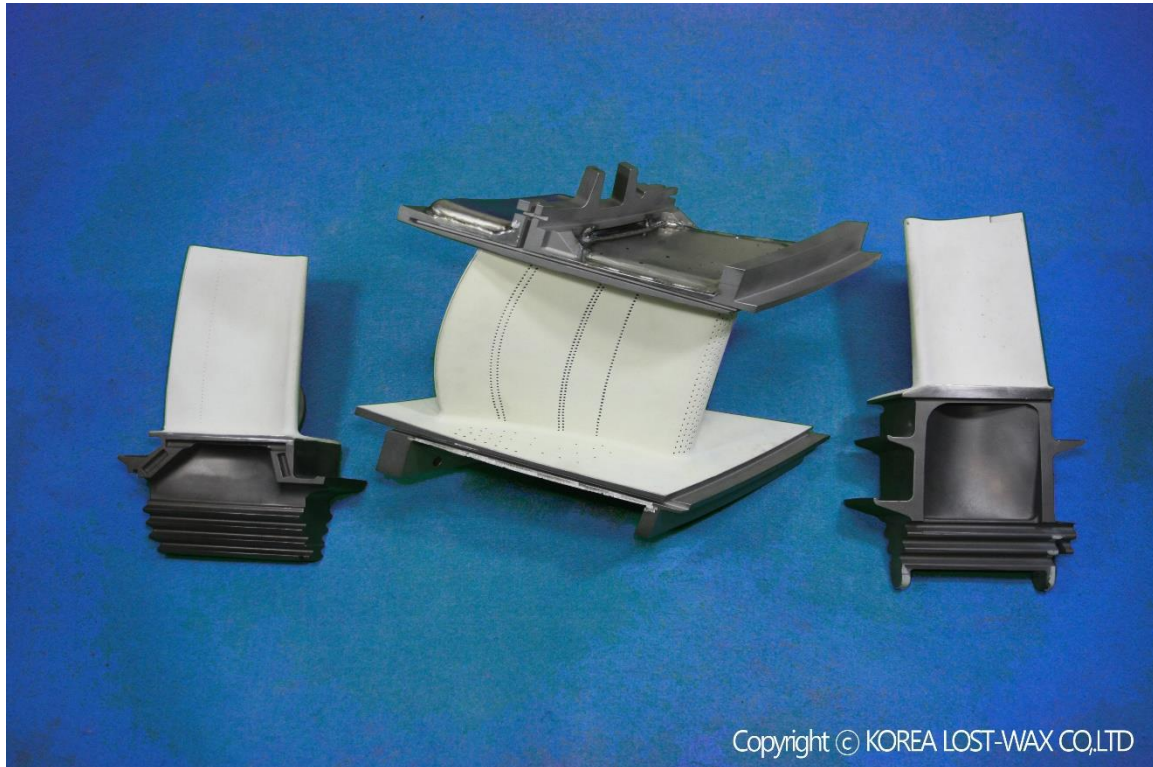
⁷³ Names of the CCGT, the OEM, and the year of development are not presented here due to the firm's confidentiality issue; Interview with *Byungmoon Chang*, *op. cit.*

The refusal of the cooperative development request should not be misunderstood as a mere problem of technology commission. In effect, those US precision casters are involved in jet-engine development programmes for the US Department of Defence. Most of their contracts with foreign firms are strictly regulated by the US government with a concern of technology transfer to foreign countries. It is highly probable that their refusal to the request has been already decided from the beginning.⁷⁴

Nevertheless, K LW developed precision casting technology for ‘501F class’ gas turbine’s blades and vanes through its in-house efforts along with a recent public R&D programme in 2013 (see Section 4.3.6). It was a crucial achievement in that K LW upgraded its precision casting technologies from outmoded equiaxed, or conventional casting (CC), to directionally solidified (DS). Although DS technology does not match with single crystal (SC) technology of the global frontier OEMs, such as GE, it implies K LW’s competitive capabilities given that one of the three global OEMs, namely MHI, still applies DS technology to its gas turbines from F-class to latest J-class versions (Figure 4.17).

⁷⁴ Interview with *Bumsoo Kim*, a senior researcher of Korea Electric Power Research Institute, *Daejeon*, on 10 March 2011

Figure 4.17 Korea Lost Wax's Directionally Solidified Blades



Source: Courtesy of Korea Lost Wax

However, its involvement in the domestic gas turbine market has been effectively locked-out by conservative domestic users, namely KEPCO's GENCO subsidiaries. The public ownership of the GENCOs and tight business regulations prevent them from applying the not-yet-commercialised blades to their gas turbines. If the blades cause damage to GENCOs' gas turbines, for instance, the tight business regulations, including public enterprise management evaluation system, would punish the managers of GENCOs. Thus, K LW inevitably gave up the domestic market and shifted to foreign niche markets, such as the Middle East region. Although it has already delivered several sets of blades and vanes to the Middle East region, the market size is quite limited.⁷⁵

⁷⁵ Interview with *Byungmoon Chang*, the director of K LW Technology Research Centre, Sihwa Industrial Complex, on 8 September 2017. Details of the importing countries and the power companies are not presented here due to K LW's confidentiality issue.

Thereby, KLW does not get enough benefit from its 'home market' despite its relatively advanced capabilities, compared to its HEI partner and other precision casters in Korea. This situation originates from the limited role of gas turbines in the Korean electricity supply market. Given that the domestic price of natural gas fuel for gas turbines has been kept high by KOGAS, the state-owned monopoly wholesale natural gas firm, gas turbines have always been regarded as a peak-load technology. Daily start and stop (DSS) operations are known to dramatically reduce the life cycle of gas turbine equipment and increased the cost of gas turbine further. Thus, a vicious circle between high natural gas prices, unstable operation, additionally increased cost of gas turbine generation, and state-ownership of GENCOs has limited the overall demand of gas turbine in Korean electricity market (see Section 4.3.4 for the background and Section 4.4.2 for the effect). In this regard, KLW's efforts to catch-up advanced blade precision casting technologies have been effectively suppressed, and it could not enter the commercialisation stage of decent precision casting technologies in the domestic market.

Specialty Steel Firms for Steam Generator Tubes Supply

Since the *Yonggwang 3&4* project was completed in 1995, the Korean monopoly HEI firm, KHIC, and later its successor *Doosan*, started manufacturing NSSSs, including a reactor pressure vessel, pressuriser, steam generator and main pipelines for nuclear power plants under the licence of ABB-CE (KAERI, 1994).⁷⁶ KHIC and its specialty steel suppliers, such as Sami, recognised the necessity of localisation of the steam generator tubes, which account for nearly 50% of the total steam generator price. While there have been a few stainless-steel seamless pipe and tube manufacturers, such as Sami, in Korea,

⁷⁶ Combustion Engineering went into near bankruptcy due to collapse of nuclear power plant market in the US and was sold out to ABB in 1989.

nuclear steam generator tubes made of superalloys need more complex process technologies, which cover 27 process stages.⁷⁷

Only a few Korean firms including Sami, Kia Specialty Steel, and Seoul Steel produced specialty steels in the 1970s. Pohang Steel Co. (POSCO), the biggest Korean steelmaker based on BOF or an integrated mill, also started a specialty steel business in the late 1970s for products suitable for mass production. The four firms kept production and development activities until the late 1990s. At this time, only material products for nuclear equipment which Korean specialty steelmakers could supply were limited to forging products, plates and some pipes. They did not have the manufacturing technology, such as vacuum re-melting, for steam generator tubes, which have a 1 mm wall thickness and about a 10 mm diameter. The country has had to depend on imported Japanese seamless pipes and tubes. For example, 78% of the imported pipe and tube products in 1992 came from Japan (Sami Specialty Steel, 1995).

In the meantime, Sami joined in a public R&D programme for steam generator tube indigenisation under supervision of KAERI from 1993. Although it succeeded in developing alloy 600 steam generator tubes for a test purpose in the mid-1990s, it could not commercialise the products. After the Asian Financial Crisis in the late 1990s, the four were reduced to two, namely POSCO and *Sea Vesteel*. Except POSCO, the three Korean specialty firms were not well equipped with finance and technology enough to survive the crisis. Sami also went into bankruptcy due to its massive investment in new factories abroad when the country faced the crisis. After the bankruptcy, Sami became *Changwon Specialty Steel* as a subsidiary of POSCO. While it had certain capabilities in manufacturing seamless pipes in general, it could not commercialise high-value products, such as steam generator tubes. Seamless pipes are the pipes without any welding parts to reduce the chance of degradation. Although steam generator tubes can be categorised in

⁷⁷ Interview with *Sunkyo Jung*, former Director of Technology Development Department, KEPCO Nuclear Fuel, *Daejeon*, on 23 January 2015.

the seamless pipe products, the tubes need additional characteristics to withstand high temperatures and highly corrosive environments, such as nuclear power coolant systems. Despite continued efforts to develop the tubes under government-sponsored R&D programmes, it could not commercialise it even in the 2000s.

Although *Doosan*, successor of KHIC, has evolved as one of the global suppliers of pressure vessels and steam generators in major nuclear power markets such as China and the US, it should depend on foreign firms, such as Sandvik from Sweden, Sumitomo from Japan, and Valinox from France, for its steam generator tubes supply. All efforts by the specialty steel firm to localise manufacturing technologies of the tubes failed as of 2018.

After repeated failure to commercialise through government-sponsored R&D programmes, the development role was shifted in 2011 from KAERI to KEPCO's subsidiary nuclear fuel supplier, KNF. It planned to commercialise the tube by 2017. The KNF was already familiar with similar types of products such as nuclear fuel rod claddings, made of zirconium alloy with thin walls. Since the firm already developed the claddings, which also needed to withstand high temperature and high corrosive environments, it expected that it could also develop steam generator tubes.⁷⁸

Nevertheless, it seems that it is still far from commercialisation success in that its initial foreign partner, Sumitomo Metal from Japan, scrapped a KNF-Sumitomo joint-venture production plan when the Japanese firm decided to cease to expand its production capacity in 2012. Sumitomo Metal's cancellation of the plan came from a discouraging market forecast that the global demand for steam generator tubes would stagnate after the Fukushima nuclear accident in 2011.⁷⁹

⁷⁸ Interview with *Sunkyo Jung*, op. cit.

⁷⁹ Ibid.

4.3.6. Public Programmes for the Supporting Industries

Public R&D on Precision Casting for Gas Turbine Blades

In contrast to the electric-intensive commodity metal industries, specialised metal industries in Korea have been suffering from weak institutions. Although there have been repeated development efforts from the early 1990s through to the end of the 2000s, public R&D programmes on the specialised metal technologies have failed to indigenise both the gas turbine blade precision casting and nuclear power's steam generator tube quenching.

It is the Korean Institute of Science & Technology (KIST) that started superalloy R&D in 1979, under a government grant without any gas turbine and superalloy industry in Korea. The development programme was carried out based on the computer aided design method developed by Japanese researchers. The KIST developed several cast superalloys for turbine blade applications through benchmarking of the Japanese analytical technique. However, the research efforts could go no further when there was not enough industrial demand for superalloys and government initiatives in Korea.

After a decade, the Korean superalloy development programme restarted in 1992 under the government-sponsored Highly Advanced National project. It was inter-twined with the Korea Fighter Project, which offered an 'offset project' to domestic precision casters such as KLW in the early 1990s, as explained in the Section 4.3.5. Through this opportunity, KLW could develop its production capability in gas turbine blade precision casting. In addition, KLW participated in a cooperative public R&D project for the development of 501F Class gas turbine blades and vanes in 2009, and reportedly developed blades and vanes for the demonstration purpose (KETEP, 2014; MKE, 2009). Nevertheless, the developed blade precision casting technology could not be commercialised in both of new gas turbine and gas turbine repair markets, owing to *Doosan's* inferior capability in modern gas turbines and foreign OEMs' new strategy in the repair market, respectively.

Although certain Korean precision casters and public research institutes continued to invest effort into localising gas turbine blades and vanes in the 2000s, such investment has hardly achieved fruitful results. One of the main reasons for the unsatisfactory results arises from the tendencies of global gas turbine OEMs, which still have their business merits in the gas turbine repair and parts replacement market as much as the new gas turbine market and use their certification for quality assurance as an obstacle to discourage latecomers from catching-up on parts technology and mass production. Unfortunately, most of the Korean public institutes and manufacturers have focused on the development of prototype blades and vanes, without the concept of certificates established by the global OEMs.⁸⁰ The certification issue reminds that there is a substantial limitation in public R&Ds on the gas turbine blades without a close relationship between domestic HEI firm and foreign licensors.

Public R&D Programmes on Steam Generator Tube Technologies

Sami and KAERI launched a collaborative R&D project on alloy materials for steam generator tubes in 1993. Their research reports in 1994 and 2002 show successful results with prototype steam generator tubes based on outmoded alloy 600, and alloy 690 materials, respectively. Neither prototype tube produced any fruitful results in terms of commercialisation, however, due to reliability and complex manufacturing process issues. In 2011, the leading role of the development project was shifted to the KNF. Since the nuclear fuel manufacturer succeeded in indigenisation nuclear fuel cladding and since the cladding has a small-diameter seamless pipe shape similar to steam generator tubes, the developers have the optimistic prospect of successful indigenisation by 2017 (KAERI, 1994; KETEP, 2008; Park CH, 2013).

⁸⁰ Interview with *Byungmoon Chang*, *op. cit.*: p.159

4.4. Sectoral Institutions of ESI and Catching-Up Performances

4.4.1. Sectoral Institutions of ESI and Nuclear Power Catch-up

The Korean case shows that the core institutions of the ESI have shaped the successful catch-up of nuclear power technologies. First, the state-owned monopoly status of KEPCO played a crucial role in the nuclear technology transfer process. Its abrupt change of the technology links from the incumbent licensor, namely Westinghouse, to financially troubled CE in achieving the technology transfer contract and the package deal of technology transfer from NSSS to A&E demonstrate a dramatic aspect of 'linking and leveraging' of the Korean nuclear latecomers. The swift financial mobilisation of KEPCO for supporting all the process of the technology transfer from reactor blueprints to the overseas training programmes of all the Korean subcontractors also shows the crucial role of the state-owned ESI firm.

Second, the tight business regulations secured preconditions for 'learning by repetition' of constructing the same design reactor and the rapid indigenisation and standardisation of the transferred reactor technology. Energy ministry's alteration of the long-term electricity supply plan deviating from the national guideline of public investment and its stiff regulations of electricity pricing for specific electricity-intensive industries, which induced constant growth of base-load demand, has established essential preconditions for continuous new reactor orders. The remarkable learning performance of the HEI firm (KHIC), public nuclear research institute (KAERI) and A&E subsidiary (KOPEC) during the short-term standardisation process cannot be explained only by the firms' 'absorptive capability' without the tight business regulations on the ESI.

Third, even after the rapid standardisation, tight business regulations enabled the first nuclear export case in 2009. The monopoly status of the ESI allowed the cheapest bidding in the international competition for the UAE nuclear project by 'twisting arms' of

all the Korean subcontractors to lower overall prices down to nearly zero margins. The Korean subcontractors had to follow KEPCO's command and control in the project to guarantee participation in future projects at the monopolised home market. In this way, the tight business regulations on the ESI more than offset the weak capability of the Korean HEI firm in the whole nuclear catching-up process.

However, repeated failures in indigenisation of steam generator tubes show the weakest link of the ecosystem of the Korean nuclear latecomers. Although there have been repeated public R&D programmes for more than two decades, the specialised suppliers could not follow the nuclear catching-up trajectory. The steam generator tubes should withstand the most vulnerable area of PWRs, namely pressure boundary, in which highly corrosive conditions and the large pressure differential between primary and secondary coolant loops are pronounced. It reveals the limits of the role of firm-level capability in explaining Korea's nuclear catching-up success.

On the other hand, loose safety regulation and practices contributed to the world-record operating performance of Korean nuclear fleets in the 2000s. The regulatory response to the steam generator tube rupture (SGTR) event and continued lax oversight of nuclear equipment transactions were shown as evidence. The operating performance became one of the primary track records in the UAE nuclear export case. It is difficult to expect, however, that the world-record operating performance would sustain facing strengthened regulatory practices, which are the aftermath of the Fukushima accident.

Besides the weakness of *Doosan*, the KEPCO–*Doosan* alliance needs to solve a more serious issue to become an independent nuclear supplier in the global market. The technology of APR1400 reactors is not free from Westinghouse's intellectual property of 'System80+' design. The issue became self-evident in the UAE export case, in which the KEPCO consortium offered a subcontract of technology consulting with a huge commission to Toshiba/Westinghouse despite such tight price-cutting efforts for the bidding. To become a completely independent vendor from the Westinghouse

technology, the KEPCO–*Doosan* alliance developed its own reactor design, namely ‘APR+’ (see Section 4.3.2.).⁸¹ The Korean ESI-HEI alliance will need to secure another series of a new construction project to commercialise the new design in the Korean market under increasingly strict safety regulations, however.

4.4.2. Sectoral Institutions of ESI and CCGT Catching-Up

Although there have been continued catching-up efforts including repeated R&D programmes and technology transfer negotiations with foreign gas turbine OEMs by Korean HEI and its supporting industries, ESI’s institutions heavily constrained their efforts. The same tight business regulations and loose environmental regulations that offered favourable conditions to nuclear power have limited the CCGT catching-up efforts. The tight business regulations, including the gas fuel contracts of KEPCO, and the loose environmental standards and regulatory practice on coal power effectively limited overall demand of gas turbine in Korea in terms of new orders and operation.

Furthermore, Korean CCGTs suffered from more maintenance problems since their role in the Korean electricity market was limited in the peak-load power source and thereby had to repeat ‘start-up and stop’ daily. This frequent repetition of start-up and stop severely degraded thermal parts and reduced the life cycle of CCGTs. Ironically, CCGTs’ superior technological aspects and superior load-following ability made the technology more expensive and unattractive in the Korean electricity supply market.

It is quite different from other countries’ cases, where CCGTs are utilised as a base-load, or intermediate-mode at least. Although it is CCGTs’ technological competitiveness that can meet peak load on short notice, too frequent involvement in responding to peak loads deteriorated its components much earlier than its designed life in Korea. For

⁸¹ However, recent political events, such as the newly elected Korean government’s moratorium on all new nuclear projects in 2017, have made commercialisation of the new design impossible in the foreseeable future.

instance, several life-cycle analyses of gas turbines report that the lifecycles of gas turbine blades in the DSS mode are less than a quarter of those in a load-following mode, which is a typical operation mode of gas turbines in competitive electricity markets (Isaiah et al., 2015, 2016).

Table 4.20 Share of Start and Stop Mode by Technology in the 1990s Korea⁸²

Technology	DSS	WSS	Low load Operation	Total
Nuclear Power⁸³	None	None	None	None
Coal Power	None	3%	9%	3%
Heavy Oil Power	23%	31%	34%	28%
CCGT	77%	26%	17%	43%
Total	100%	100%	100%	100%

Source: KEPCO, 1992.

Although there is a warranty of ‘equivalent operating hours’ by CCGT OEMs, gas turbine blades are reported to show much shorter lifetimes than the warranty duration when they are operated under peak-load mode or cycling mode. *Sungho Lee from KEPRI* interpreted the same phenomena below:

Most of the CCGTs imported by KEPCO and its subsidiaries in the 1990s and 2000s were designed for base-load or intermediate purposes by global OEMs. However, CCGTs in Korea have mainly operated in a peak-load mode. The ‘daily start and stop or DSS’ mode caused gas turbine components, such as turbine blades, to deteriorate in less than half of their designed life cycle. To repair and replace the damaged blades and related parts over around 120 CCGTs, the Korean operators should pay nearly the equivalent of 3 to 4 gas turbines to the foreign OEMs every year. This mismatch between technical

⁸² DSS stands for daily start and stop, whereas WSS stands for weekly start-up and stop.

⁸³ Nuclear power’s case was added by the author for readers’ understanding.

specifications of imported CCGTs and operational modes of the Korean utility, in addition to high gas fuel price, alienated CCGTs from the Korean electricity market.⁸⁴

Thus, the economic life cycle of CCGTs in Korea is 20 years, whereas it is 40 years in other countries, such as the US and Japan (Cho, 2008; IEA, 1998). The mismatch between the imported base-load purpose CCGTs and DSS mode practice in the Korean market is confirmed by a Korean IPP.

We had a dispute with a foreign OEM about our gas turbines over the responsibility of turbine blade replacement cost a few years ago. The supply contract guarantees that effective lifecycle of the first stage blades meets 25,000 equivalent operating hours and is extended another 25,000 hours after inspection and repair processes. During the inspection, however, the blades were so severely damaged that we could not extend the lifecycle at all. Although the supplier should take the cost burden of replacement according to the contract, the OEM pointed out the frequent 'daily start and stop' operation practices of CCGTs in the Korean electricity market as an exceptional cause of the unusual early degradation. After a negotiated resolution of the dispute, we paid 50 per cent of the replacement cost.⁸⁵

The mismatch between CCGTs and the Korean electricity market does not end here. The premature degradation of gas turbine blades and subsequent disputes led to foreign OEMs to lock into the repair and replacement service market, in which Korean precision casters could learn foreign technologies and develop their own capabilities. The deputy director of the Korean IPP explains this new situation.

⁸⁴ Interview with *Sungho Lee*, op. cit.

⁸⁵ Interview with a deputy director of a Korean Independent Power Producer on 15 May 2015. Due to the firm's confidentiality issues, name of the interviewee, the firm, and the OEM are not presented here.

After the dispute, both sides agreed to make a 10-years, long-term maintenance service contract from the next gas turbine import deal. The contract will require our firm to make a fixed payment during the contract term in exchange for unlimited liability in repairing and replacement services from the foreign OEM. This kind of contract gives the foreign OEM an exclusive right in the repair service market at the expense of domestic repair service providers.⁸⁶

Although the long-term service contract between CCGT OEMs and users is not a Korean-specific way of transaction, the omnipresent premature degradation of gas turbine components in Korea made gas turbine users follow foreign OEMs' guide. This makes the gap between foreign OEMs and domestic latecomers, including *Doosan* and precision casters, bigger. In this context, active in-house research efforts and better performances of the Korean precision caster, namely KRW, compared to its nuclear counterpart, such as Sami or POSCO specialty steel, the chances for the precision caster to accumulate technological capabilities have been limited.

4.5. Chapter Conclusion

The Chapter shows that historically ingrained institutional factors of the Korean ESI have been shaping the context for success and failure of the two power generation technologies in Korea. On the one hand, the tight business regulations of the state-owned monopoly ESI have been pronounced in the successful catching-up process of Korean nuclear power despite the limited role of the HEI firm and its specialised suppliers. The regulations played a key role in 'linking and leveraging' for technology transfer, securing new construction projects for the rapid standardisation of the transferred reactor

⁸⁶ Interview with a deputy director of the Korean IPP, op. cit.

technologies, and controlling of bidding and overall project process for the first nuclear export case.

However, the tight business regulations effectively limited overall demand for CCGT despite repeated public R&D programmes and relatively successful performances of the specialised supplier. Persistent cross-subsidy from the ESI to the city gas sector has increased the cost burden of CCGT and effectively discouraged public and private demand for CCGT technology development.

On the other hand, the lax safety standards and regulatory practices effectively encouraged operational performances of nuclear power and offered the globally recognised track records. Catching-up efforts in steam generator tube technologies by supporting industry have been marginalised by KEPCO, and the efforts were left only a few public R&D programmes without KEPCO's involvement. By comparison, the loose environmental regulations discouraged environmental competitiveness of gas turbine compared to its competitor such as coal power in the Korean electricity market.

While technology catch-up policies including public R&D programmes do not exhibit consistency in explaining the contrasting catch-up experiences, focusing on effects of regulations on ESI seems to offer better explanations. As a result, the Korean user-supplier co-evolution effectively strengthened operation, construction, and technology catch-up of nuclear power technology, whereas it weakened those of CCGTs. Thus, the sectoral institutions of user framework offer a better position than the strength of specific technology catch-up policies in explaining the successes and failures of catch-up across nuclear power and CCGT technologies.

Table 4.21 Institutional Scheme of Korean ESI and Technological Impacts

	Business Issues	Environmental Issues
Institutional Environment (Property)	- Nationalisation of ESI by Military Coup (1961)	- Massive Poisoning Deaths due to Household Heating Coal (1960s–80s)
Governance (Contract)	- Tight Control of Business Activities (Fuel Contracts and Pricing)	- Lax Emissions and Safety Regulations of ESI for Price Concerns
Operational Practices	- Cross-subsidy from CCGTs to City Gas - Aggressive TOU Pricing for Commodity BMIs	- Rules often Exempted for Coal Power - Serious Nuclear Safety Issues are Repeatedly Dismissed
Technological Impacts	- CCGTs' Increased Fuel Cost Caused Vicious Circle - Continued Growth of Base-load demand for New Nuclear Projects	- CCGTs' Role Limited by Coal under Lax Regulatory Practices - Operational Performance of Nuclear Enhanced by Lax Regulatory Practices

Source: Adapted from Williamson 2000

Chapter 5. The Japanese Case

5.1. Introduction

This Chapter clarifies critical reasons of how and why the Japanese HEI could shift from catching-up to nuclear power to gas turbines. It illustrates how user-producer co-evolution of HEI and the ESI has been shaped in Japan, and focusses on how a set of institutions of the ESI, rather than explicit catch-up policies, such as public R&D and energy supply plans, have affected the user-producer co-evolution in favour of gas turbine technology, which is currently overtaking nuclear power.

Section 5.2 analyses Japanese ESI and its business and environmental regulations based on a historical perspective. **Section 5.3** describes Japanese HEI's brief history and catching-up performances in nuclear power and gas turbine. **Section 5.4** analyses effects of the ESI's institutions on catching-up performances and the ESI-HEI relationship.

5.2. Electricity Supply Industry

5.2.1. Structure of Japanese Electricity Supply Industry

The Japanese electricity supply system has quite unique characteristics in terms of the regional division by electric frequency (50/60Hz), regional private monopoly utilities, designated wholesale utilities, and quite a big self-power generation capacity of manufacturing industries. The unique characteristics have co-evolved with sectoral institutions and have heavily influenced technological choices of the Japanese ESI regarding nuclear power and CCGTs. Although a detailed background and other aspects are analysed in later sections, they need to be briefly explained here.

The Japanese electricity system has been divided in two different geographic markets according to different electric frequencies, namely the *Kansai* area (the western region of Japan) where the standard of 60Hz is applied and the *Kanto* area (the eastern region) where 50Hz is applied. This regional division of electric frequency began in the early twentieth century, when Japan introduced Western electricity systems. In the early period, the Osaka area introduced the American system (60Hz) while the Tokyo area selected the German system (50Hz), and the division has remained the same for more than a century. Thus, all the electrical equipment, including power plants have had to be adapted to their regional frequencies.

As of the mid-1990s, nine private utilities, including the major three of Tokyo, Kansai and Chubu Electric Power Co., were given a monopoly status to supply electricity to each one's assigned region. After Okinawa was returned to Japan in 1972, the number of the regional monopoly utilities was increased to ten. Although the major share of wholesale electricity has been supplied by the regional monopolies (about 75%), other electricity suppliers supplement the rest of electricity, such as wholesale electric utilities, self-generation by heavy industries, and specified suppliers mostly owned by local governments.

In addition, electric-intensive industries, such as steel, oil, chemical and petrochemicals, and paper and pulps also are involved in power generation activities for their own auto-generation or as a joint-venture with one of the regional monopolies. Therefore, they have also installed on-site power plants in their industrial complexes. Their capacity has been more than 10% of the country's total power plant capacity for the last three decades of the twentieth century and reached 16.5% in 2008. These industrial users' generation increased to 35% of their own electric demand and about 10% of the country's total power supply in the mid-2000s (IEA, 2011).

As of 2016, the Japanese electricity market is in the last stage of the liberalisation process, which means regional monopoly markets will disappear, and a competition

system across the regions will be introduced. While the wholesale market opened for IPPs after 1995, retail market liberalisation has been gradually introduced. For example, the retail market for large customers (2MW or more) was liberalised in 2000, and the retail market of commercial and industrial customers (50kW or more) was liberalised in 2005. Residential markets, which account for a 37% share of the Japanese electricity market, once confined to each region's monopoly, was liberalised in April 2016.⁸⁷

Table 5.1 Structure of Japanese Electricity Supply Industry in the mid-1990s

Categories	Examples of Firms	Share of Capacity
Regional Monopoly Utilities	Ten utilities with major three, namely Tokyo, Kansai and Chubu electric power companies	75%
Wholesale Electric Utilities	J-Power (successor of EPDC, 67 thermal power plants), JAPCO (4 reactors)	12%
Self-Generation by Industries	Steelmakers, oil refineries, chemicals, paper and pulps etc.	10%
Specified Suppliers	Municipal councils	3%

Source: Author's elaboration from Sharon Beder, 1998

5.2.2. A Brief History of Japanese Electricity Supply Industry

Post-war Period: Realisation of Matsunaga Scheme of ESI

On the verge of the World War II, during the Pacific War, the Japanese military government consolidated all the private utilities into the Japan Electric Power Generation and Transmission Company (*Nippon Hassoden KK*, hereafter *Nippatsu*) in order to rapidly mobilise the Japanese ESI for its war economy in 1939. Although a few influential leaders of the Japanese ESI, such as *Yasuzaemon Matsunaga*, resisted the nationalisation, they could not prevail over the wartime military state. Matsunaga, who managed various Japanese utilities during the inter-war period and was known as a determined liberalist, retired

⁸⁷ Interview with *Osamu Kimura*, Research Economist, Socioeconomic Research Center, Central Research Institute of Electric Power Industry, Tokyo, on 2 February 2011

from his management position in utilities after the nationalisation (Samuels, 1987; Kikkawa, 2006).

However, as soon as the war ended, state control of the Japanese ESI was under the pressure of a re-organisation policy instituted by the Supreme Commander for Allied Power (SCAP). First, SCAP ordered the abolition of the National Mobilisation Law, which governed many of the controls and regulations on the Electric Power Industry Law during the war, in September 1945. Second, SCAP designated *Nippatsu* and the nine distribution firms as “excessively concentrated companies” under the “De-concentration Law”, enacted in December 1947. Third, in 1949, SCAP invited Matsunaga to be chair of the Electric Industry Reorganisation Council (*Denki Jigyo Saihenseibi Shinjikai*) under consideration of his clean wartime record and his consistent position against state control of the ESI (Samuels, 1987).⁸⁸

However, from the beginning, the reform process was not at all smooth. Japanese interest groups including steel industry leaders, *Nippatsu* officials, MITI bureaucrats, the labour union, the communist party and the Diet Cabinet, as well as the majority of the Council, led by Miki Takashi, the president of Nippon Steel, tried to maintain the *status quo* of the nationalised utility. Matsunaga, nevertheless, succeeded in dissolving *Nippatsu* into nine private regional monopolies, thus replacing state control of the electric industry with an independent regulator, namely the Public Utility Commission. The reform was realised with dedicated support from the SCAP including General Douglas MacArthur’s direct instruction to Prime Minister *Shigeru Yoshida* in 1950 despite the Japanese government’s fierce resistance (Samuels, 1987; Kikkawa, 2006).

⁸⁸ Matsunaga proposed a historic blueprint of the Japanese electric supply industry in his 1928’s manifest, “*Denryoku Tosei Shiken*’ (My View of Electric Power Regulation)”. His suggestion can be summarized as i) Nine Regional Private Monopoly Utilities, ii) Vertical integration of generation, transmission and distribution businesses in each region, iii) Establishment of National Public Utility Commission. For details, see Samuels (1987) and Kikkawa (2006).

In addition, Matsunaga himself was designated as acting chair of the National Public Utility Commission in 1950 and contributed to the decision-making regarding electricity prices in the early 1950s. Between 1950 and 1953, heavy industries such as iron and steel and chemicals, which expanded their production capacity as a result of the Korean War economic boom, aggressively demanded that the government and the Public Utility Commission reduce allowed electricity tariffs. Fearing the revival of state control, however, Matsunaga proposed a 76% increase of the electric rate and the introduction of foreign capital in May 1951. Although SCAP approved only a 30% increase of electric rate, it also provided 6.2 billion yen in Counterpart Aid⁸⁹ assistance to the nine private utilities in August 1951, thus endorsing Matsunaga's proposal (Kikkawa, 2006; Samuels, 1987).

In effect, the Yoshida government and the majority of the Diet started to prepare a bill to create a new national electric power development company with strong support from heavy industries that expected subsidised electricity. Matsunaga, however, again resisted the plan to nationalise the Japanese ESI. Under the post-war regime led by SCAP, Matsunaga finally realised his pre-war reformist scheme of a Japanese electricity supply industry against strong resistance from heavy industries and MITI bureaucrats who wanted to keep a national ESI and low electricity rate under state control. Although there have been external events, such as the two Oil Crises in the 1970s, his scheme fundamentally shaped the institutional backbone of Japanese ESI until today (Kikkawa, 2006).

Dodge Line: Financial Reform and Post-war Electric Power Development

As explained above, in the early 1950s, Matsunaga, as the first and last acting chair of Japan's Public Utility Commission, abruptly initiated a major increase of the electric rate twice despite strong resistance from large steel industries and MITI. How his actions

⁸⁹ US Aid Counterpart Fund Special Account was a representative aid method of the US government in rebuilding and reforming post-war European and Japanese economy under control of US government.

could be accepted and executed need further explanation. The unique institutional background of post-war Japan gives an explanation to some extent.

Immediately after World War II, Japan suffered a steep inflation rate due to a serious shortage of commodities. By the end of the 1940s, after various efforts by the Japanese government, the inflation rate fluctuated around 300%. Having faced the Cold War Era, including the confrontation with the FSU, the US Truman administration sent Joseph Dodge, President of Detroit Bank, as a Special Ambassador to Japan in February 1949 to rapidly rehabilitate the Japanese economy and to make the country a strong geopolitical partner in the region. Dodge, a fundamental free-market advocate, ordered harsh austerity measures to terminate inflation in Japan. His austerity policy package was called “Dodge Line”. Although there are various versions of his instructions to the Japanese government in the literature (Kagami, 1995; Metzler, 2013), the four principal demands commonly found are below:

- Balanced and consolidated budget: a zero balance on all accounts should be maintained, and all special accounts should be brought into the general account.
- Elimination of hidden subsidies, including price controls.
- No further extension of the borrowing power of the Reconstruction Finance Bank, a predecessor of Japan Development Bank.
- Unification of multiple currency exchange rates at JP ¥ 360 to USD 1.

As a result of this macroeconomic reform package, the inflation rate immediately decreased by 30% in 1949. Although the subsequent economic shock was quite severe and immediate recession was expected in Japan, the surprising breakout of the Korean War in 1950 and the subsequent ‘wartime economic boom’ eliminated concerns of economic recession. More importantly, it sustained and backed up Matsunaga’s institutional reform of Japanese ESI, including the world’s highest electricity price.

World Bank's Loan to Japanese Electric Industry

The Japanese government designated the coal, electric power, steel and chemical fertiliser industries as key energy and materials industries, so-called “priority industries”, in its effort to reconstruct the Japanese economy during the post-war period. In 1946, it also established the Reconstruction Finance Bank (RFB), a predecessor of the Japan Development Bank (JDB), in order to lend funds to the designated industries. Even when the RFB's fund was not available, the Bank of Japan, in cooperation with the Economic Stabilisation Board, financed those designated industries.

In 1951, once SCAP withdrew from Japan along with the direct US financial aid (i.e. the Counterpart Fund), Japan joined the international financial community, including the World Bank and IMF, in 1952. During this transition, the source of Japan's major foreign financial aid shifted from the US Counterpart Fund to the World Bank Loan and US Export-Import Bank, which initiated a provision of aid loan to Japan from 1953 and 1956. The first three provisions of loans from the World Bank to Japan through JDB, totalling USD 40 million, aided Japanese electric utilities which suffered a shortage of financial resources in reconstructing and expanding their electricity supply systems during the post-war period.

In the fiscal years of 1951-1955, when the shift occurred from the US Counterpart Fund to the World Bank Loan, financing the electric power industry was JDB's highest priority, for a total of JPY 117.4 billion (about USD 1.86 billion in 2016 price), or 46% of JDB's total financing during this period.⁹⁰ Amongst this financing to the ESI, JPY 104.5 billion was sent to nine utilities while the remaining JPY 12.9 billion was sent to industrial firms (mostly steelmakers) which operated their own auto-power generators (JDB/JERI

⁹⁰ Although the funding size seems rather small compared to the overall size of Japanese economy in the post-war period, its ‘signalling effect’ was large enough to induce additional funding from private banks. See Stiglitz and Uy (1996) for details regarding the ‘signalling effect’ of the Japanese public banks.

1994: 151). This snapshot of financial and economic reconstruction during the post-war era in Japan reveals the seriousness of the Japanese electric shortage.

Additional financing for on-site, auto-power generation industries (primarily heavy industries) shows that electric power resource development by electric utilities could not meet the surging demand for electricity, even with major financial support. Therefore, it is understandable why Matsunaga drove such large increases of the electricity rate during his two years as acting chairman of Japan's short-lived Public Utility Commission. Due to those consecutive increases, the Japanese electric rate was already the highest in the world beginning in the early 1950s (Kitazawa, 1984).

In conclusion, massive inflation rates in the late 1940s, a harsh austerity policy, the economic boom during the Korean War, the chronic shortage of electricity, and massive financial aid for electric power resources development during the post-war period explain how and why Matsunaga's increase of electricity prices could be accepted and endured. Although there have been additional electric price increases during the global energy crisis of the 1970s and the ESI restructuring policies initiated in the late 1990s, the post-war economic condition and institutional system as explained above fundamentally shaped the basic structure and practices of the Japanese ESI. Salient results of the institutional reform are analysed and discussed further.

5.2.3. Demand Condition of ESI: Basic Metal Industries

Aluminium Smelters

In the early 1970s, the Japanese aluminium industry was the world's second-largest producer with an annual capacity of 1.64 million tonnes. However, the oil crisis, followed by electricity price increases and global economic recession, made the Japanese aluminium smelters reduce their domestic production capacity by 98% from the mid-1970s to 1990. Eventually, only a single smelter with a capacity of only 64,000 tonnes remained in operation. The dramatic change was the result of the rapid and voluntary

shift of the industry overseas, where much cheaper electricity and alumina were offered (Uriu, 1996).

Although the Japanese government established a basic stabilisation plan, so-called *Tokuanho*, to support the aluminium industry, it hardly worked and was nearly meaningless in guiding the industry in an effective adjustment process. Instead, the industry itself voluntarily adopted a near-total closure of domestic production. The government policy was a rather passive response to the industry's request and even tried to slow down the restructuring process (Peck et al., 1987; Uriu, 1996). There are several background reasons for this exceptional industry exit process.

First, although the Japanese aluminium industry already had adjusted to the most expensive electricity in the world beginning in the 1950s, the two oil crises made the country completely lose any possible price competitiveness. Although the Japanese smelters had the most energy-efficient smelting plants in the world, their production costs were nine times those of Canadian firms backed up by abundant hydroelectric power, and three times those of American firms in 1980 (Samuels, 1983:496). According to a Japanese survey, the Japanese smelters had to pay 15-17 yen/kWh for electricity while Canadian and US counterparts paid the equivalent of 1-1.5 and 3-5 Yen/kWh, respectively, in the early 1980s (Kimura, 1983; Sheard, 1991).

Furthermore, Japanese ESI did not offer a special price scheme to the country's most electric-intensive industry, namely the aluminium smelters, such as a long-term electricity supply contract which is widely practised in most aluminium-producing countries. The long-term special electricity price for aluminium smelters in those countries is typically less than half of the average price for the industry. Considering the share of electricity cost in total aluminium production costs ranged from 41 to 51%, the big gap of electricity prices between Japan and its North American counterparts was devastating to the Japanese smelters (Michal, 1984; Peck et al., 1987).

Second, domestic users of aluminium ingots and final consumers, such as aluminium sheet producers and automobile makers, also faced fierce price competition in the global and domestic markets. This situation made protection of the Japanese aluminium smelters through a high import tax or other subsidies almost impossible in domestic politics (Goto, 1988:116-117). Also, aluminium ingots became an international commodity, freely available at international market prices when the London Metals Exchange began to trade aluminium ingot in 1978 (Uriu, 1996:180).

Third, it was relatively easier for the Japanese aluminium industry to move its production capacity abroad technically, politically and financially. Due to technical simplicity, the six aluminium smelters employed less than 14,000 workers, the smallest labour force amongst the Japanese industries at that time. Thus, the political burden that the industry had to bear for its swift move was much smaller than any other industries under pressure of adjustment in Japan. In addition, all the smelters were tied to major *Keiretsu* firms and the *Keiretsu* supported their subsidiary firms' shift abroad by financing and absorbing a portion of laid-off labours from the smelters (Sheard, 1991).

Therefore, the smelters could easily create international joint ventures abroad to produce much cheaper aluminium ingots. The smelters mostly invested in Canada, Brazil, the United States, Australia and New Zealand, where there is a massive capacity of cheap hydropower or raw materials. In 1977, even before the Japanese government set any reduction target for domestic production capacity, the smelters had already established overseas facilities with an annual capacity of 1.24 million tonnes, much larger than domestic capacity.

Electric Arc Furnace (EAF) Steelmakers

While the most electric-intensive industry quickly chose to exit the market in the 1970s, the second most electric-intensive industry, namely EAF steelmakers, struggled to survive the restructuring during the decade of the energy crisis. As a result of

restructuring, 69 EAF firms in 1977 reduced to 37 in 2010. Those firms are generally categorised by their financial support mechanisms, including 16 *Keiretsu* member firms which have the major share of the Japanese EAF market, four trading firms' affiliated with EAF firms, and 17 independent firms which do not have either relationship. All the *Keiretsu* member EAF firms have been under control of their fellow, much larger, BOF firms (Peck et al., 1987; Lee, 2011).

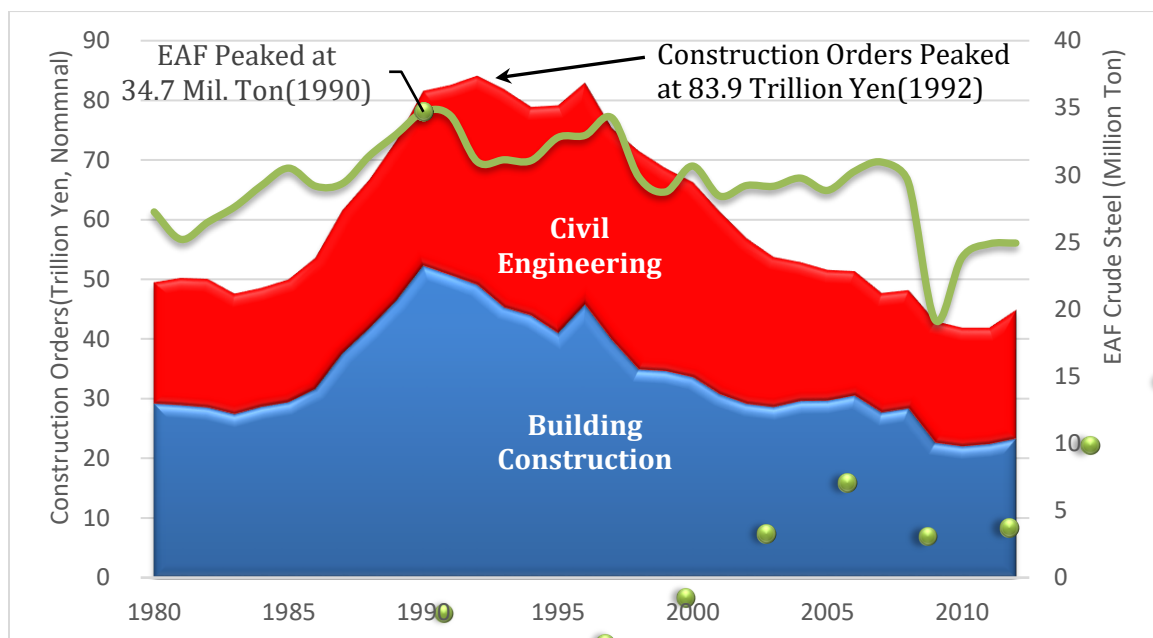
The business of EAFs mostly depends on the domestic construction market on the demand side, while it depends on scrap steels and electricity as major inputs on the supply side. In this sense, the Japanese EAF industry has suffered cycles of boom and bust due to domestic construction market fluctuations. On the supply side, while it has always enjoyed cheap, relatively high-quality scrap steel from the excessive 'home-grown' scrap steels from large *Keiretsu* BOF steelmakers, it also has suffered from the world highest electric price since the 1950s.

Since 1970, on the verge of a global energy crisis, the Japanese EAF industry had gone through several major cycles of boom and bust. Repetitive Japanese governments spending on public construction projects and the biggest market of EAF steels created intermittent booms. Nevertheless, the booms quickly became busts. In the late 1970s, the Japanese government established a re-adjustment policy for "troubled" energy-intensive industries. The "Law of Temporary Measure to Stabilise Specific Industries in Recession" (*Tokuanho* in Japanese) which sought to facilitate the restructuring of suffering industries was passed in 1978 and was in effect until 1987. Along with the aluminium industry, the EAF steel industry was also included by the law (Peck et al., 1987; Uriu, 1996).⁹¹

⁹¹ The industry was also specified as a target of restructuring policy in the "Temporary Measure on Restructuring of Specific Industries" in May 1983. The measure includes rationalization of investment, inhibition of new production facility and early closure of redundant facilities (Kim 1994).

In effect, *Keiretsu* EAF firms already voluntarily initiated the reduction of production and requested the government to enforce the ‘cartel policies’ in the late 1970s.⁹² Although independent EAF groups, such as Tokyo Steel, were against the *Keiretsu* initiative and expanded their production during the 1980s, the saturation of Japanese construction market in the early 1990s eventually restructured the Japanese EAF industry. Indeed, total investment in the construction of household, public infrastructure and non-household buildings peaked in 1993 and has never recovered. The total EAF production followed suit (Lee 2011, World Steel Association 1983-2013) (Figure 5.1).

Figure 5.1 Trends of Construction Market and EAF Steel Production in Japan



Source: Author's elaboration from World Steel Association 2014, and Ministry of Land, Infrastructure, Transport and Tourism 2014

With the decline of the construction market, it was inevitable that the ratio of Japanese EAF production to total steel production in Japan diminished from its peak of

⁹² Contrary to Anti-Cartel Regulation concept in the Western economies, the Japanese *Keiretsu* collectively controlled production of steels to maintain price of steels under government protection during the 1970s' global recession. See Uriu (1996) for details.

33% in 1996 to 22% in 2010. Both in absolute and relative production terms, Japanese EAF production performance is worse than it was during the second global energy crisis of 1978 while the world average EAF production ratio has remained around 30% for the past two decades. Although Japanese EAF pioneered the structural beam market in the world, the share of the Japanese EAF production fell far below that of global EAF production levels with the world highest electric price and the end of the domestic construction boom (Figure 5.2).

It is interesting that EAF steelmakers consumed more electricity than BOF counterparts by 56% even when their crude steel production was less than half of BOF steel production in 2000 (Table 5.2 and Figure 5.2). While BOF steelmakers showed stable electricity consumption from 1994 to 2010, EAF steelmakers reduced their consumption by one-third during the same period. The reduction seems to reflect the EAF industry's restructuring effect.

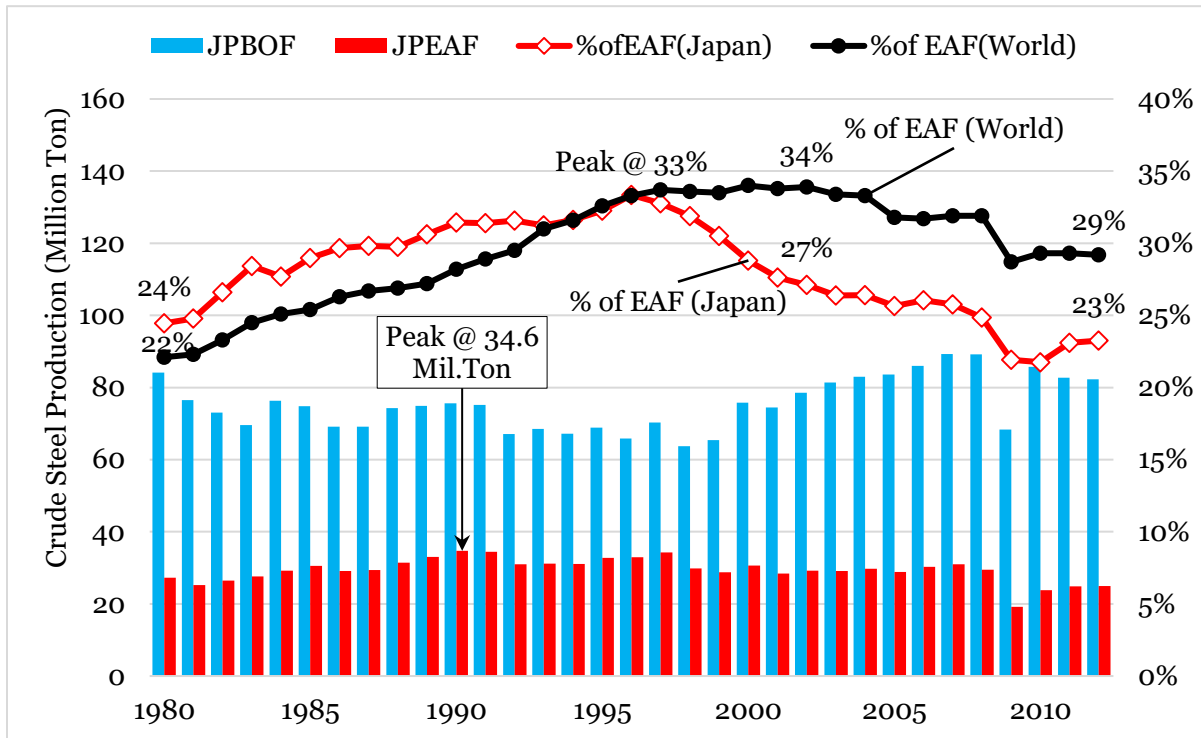
Table 5.2 Electricity Consumption of BOF and EAF Steels in Japan (GWh)

	Purchased from Utilities & IPPs		Self-Power Generation ⁹³
	BOF (including Blast Furnace)	EAF	
1994	8,023	14,866	18,766
2000	7,015	10,977	5,891
2010	8,028	9,814	5,284

Source: Author's elaboration from the Ministry of Economy, Trade and Industry, Japan 2001 & 2011

⁹³ Although the original data do not show each self-power generation of BOF and EAF, year 2000's data show that BOF and EAF generated 2,297GWh and 3,594GWh, respectively.

Figure 5.2 Rise and Fall of Japanese EAF Steelmakers in 1980-2010



Source: Author's elaboration from the World Steel Association (WSA)'s <Steel Statistical Yearbook > 1983, 1993, 2003 & 2013

5.2.4. Strong Autonomy of ESI Business

Highest Electricity Prices in the World

As explained in Section 5.2.2, Matsunaga's reform of the Japanese ESI, despite fierce resistance from steel industries and MITI during the post-war period, made the Japanese electric price the world's highest beginning in the 1950s. The price was drastically increased again during the global energy crisis of the 1970s. Naturally, it should have been difficult for electric-intensive BMIs to survive with such price in the 1970s and 1980s.

The electricity prices of the nine private utilities are regulated by METI (successor of MITI) based on the Electricity Utilities Industry Law. In particular, “Total Cost of Service Method” is stipulated in Article 19 of the law, and it defines that electric utilities’ tariff should be authorised by METI and the price and relevant supply contract should reflect “proper costs, based on efficient business management, plus fair return”. The “proper costs” consist of environmental treatment costs for wastewater, exhaust gas and other pollutants as well as expenses for labour, fuel, maintenance, and depreciation. The “fair return” is calculated according to the rate base method by multiplying business assets invested, including power generators and transmission lines by a certain rate of return, for example, 4.4% on average in 1998 (Cruz et al., 2002).

However, METI’s regulation on electric prices is limited only in relative difference amongst the nine regional monopoly utilities based on a “Yardstick Assessment” which induces “performance competition” amongst utilities. When each of the utilities files its prices with METI, the ministry compares the utility to its own past performance and to the performance of the other utilities. The costs for each utility are assessed based on whether the utility is in the bottom third, middle third, or upper third of the range. Amongst the three groups, the bottom third group, which is most efficient or most improved, is allowed to receive revenues equal to the value of their costs while the middle group is allowed to receive revenues up to 99% of the value, and the upper third group are allowed to receive only 98% of the value (IEA, 1999; OECD, 1998).

Other than the regulation based on performance competition, the Japanese government has not been able to directly control electric prices even when drastic price surges occurred, for instance, during the two oil crises. Electricity prices in Japan had increased by about 50% in 1973, after 20 years of price stability. The increases have been much greater for industrial users than domestic consumers, in particular (Surrey, 1974: 229).

Since the 1970s, a few additional factors contributed to the already high electric prices. First, the world strictest emission regulations and the Air Pollution Control Law, which allows local government to set even stricter limits than the national government's standards, resulted in increased expenditure on emission control technologies and measures (IEA, 2003; OECD, 1999).

Second, the world's strictest nuclear safety regulations forced the Japanese utilities to go through exceptionally tight safety inspections on the scope, depth, intervals, and judgement of defects. The utilities are required to have an overhaul, such as repair and maintenance, every 12 months in principle, with a one month grace period, although longer intervals for efficient fuel exchange cycles, typically 18 months, have been practised in most countries (OECD, 1999). As a result of the institutional and physical conditions, Japanese customers take the burden as explained below:

- **High generation and transmission capital costs:** Japan has the highest investment costs for nuclear, gas and coal power in OECD. Expensive land, compensation payments made to local communities and high safety standards (including earthquake resistance) contribute to increased costs. Very high technical standards for equipment compared with other countries force prices up and limit the number of competitors.
- **High fuel costs:** Japanese utilities pay 20% more for oil, 80% more for coal, and more than double for natural gas costs than the OECD average.
- **Low load factor:** The load factor in Japan (the ratio of average electricity demand to the annual peak demand) is extremely low in comparison with other industrialised countries, principally because of air conditioning use. Each 1% decrease in the load factor increases the costs of service by approximately 1% (IEA, 2003).

Voluntary Introduction of Natural Gas

Amidst the severe environmental issues, the oil crisis of 1973 made the Japanese government urgently encourage electric utilities to diversify fuels from oil to alternatives,

mostly coal and nuclear power. The intended fuel-switching process, however, has been hindered by problems in finding acceptable sites for nuclear and coal power plants (Nemetz et al., 1984). In this sense, natural gas-based power plants played an important role by providing the electric utilities with a way to avoid public resistance and strict regulation on air pollution even a decade before the commercialisation of large and high-efficiency CCGTs in the mid-1980s. *Osamu Kimura* from the Central Research Institute of Electric Power confirms the difference between natural gas from other alternatives in the fuel diversification efforts in Japan:

Since the Oil Shocks in the 1970s, electric utilities have tried to diversify fuels from oil to nuclear and coal. But both options suffered from siting problems for different reasons. Utilities faced persistent public opposition against nuclear power while they found extreme difficulties to meet strict environmental regulation on SO_x and NO_x emission for coal power plants. In this sense, gas turbines were much favoured in Japan.

Although major utilities still favour coal power and the government repeats ambitious nuclear construction planning, lengthy and tight environmental assessment procedure retarded their preference. Also, technical handicaps of nuclear and coal, such as relatively slow response to load change, limited such options.⁹⁴

Thus, it was electric utilities who obtained major LNG purchase contracts from various Asian and Middle East countries from the early 1970s.⁹⁵ As a result of the utilities' initiative, LNG's share in terms of power capacity and generation in the Japanese electricity market soared from a mere 2% and 1.6% in 1970 to 16.2% and 16.4% respectively in 1983, even before Tohoku Power started operation of Japan's first CCGT in 1985 (Figure

⁹⁴ Interview with *Osamu Kimura*, op. cit.

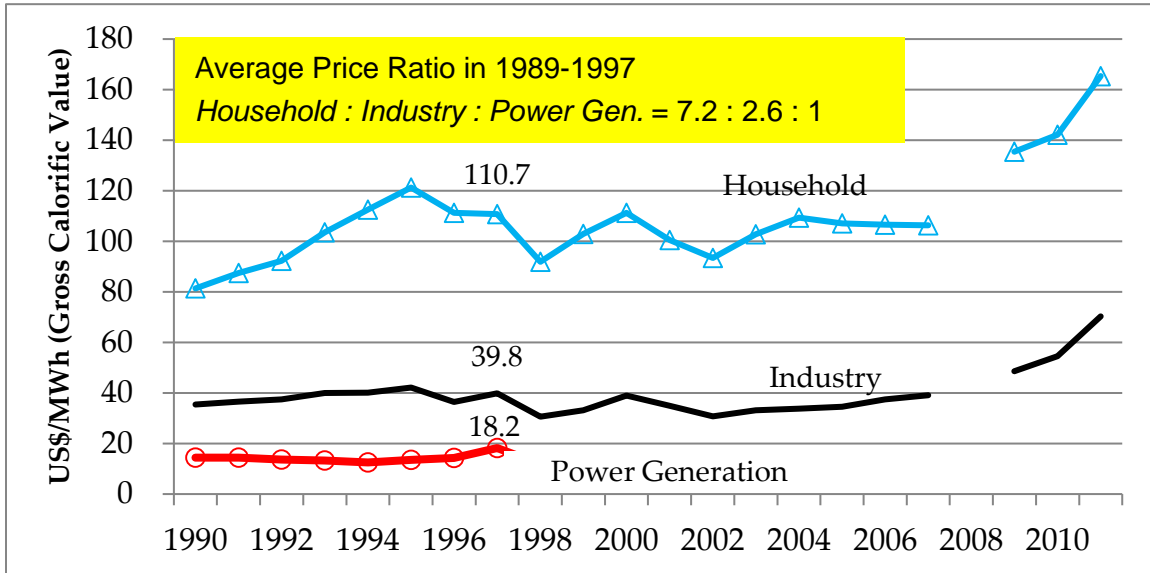
⁹⁵ In effect, Tokyo Power pioneered introduction of LNG including transportation, re-gasification, and distribution networks in Japan from 1969, and other utilities followed the suit.

5.3 and 5.4). Considering that the total capacity of gas turbines domestically delivered in Japan until 1983 was only 3.5 GW when total gas power capacity was 23.4GW, most LNG power plants in operation in 1983 were conventional gas boiler power plants rather than gas turbines (Gas Turbine Society of Japan, 1984).⁹⁶ Thus, it can be said that LNG fuel was used predominantly for steam turbines, which are less energy-efficient, by electric utilities under strict emission regulation until the early 1980s, paving the way for the commercial success of CCGTs in Japan.

Furthermore, utilities' voluntary introduction of gas for power generation invited the American gas turbine OEM, namely Westinghouse, with its technological and manufacturing capacity from the US market, which was under an embargo on natural gas use for new power plants between 1975 and 1985 (Watson, 1997). The problematic decade pushed Westinghouse to leave its home market, and it transferred most of its gas turbine business to its Japanese partner, MHI in 1987 (Unger & Herzog, 1998).

⁹⁶ Total capacity of gas turbines manufactured by Japanese firms from 1948 to 1983 was 13.8GW including 10.2GW for export according to GTSJ 1984 report.

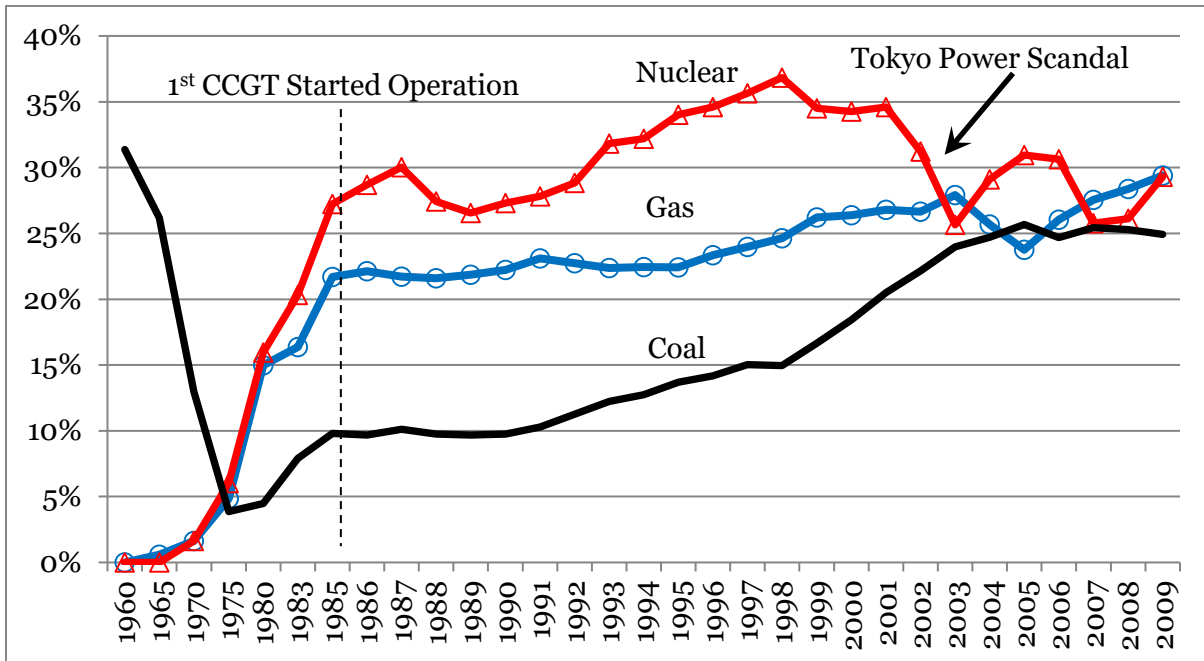
Figure 5.3 Average Natural Gas Prices by Sector in Japan



Source: Author's elaboration from IEA's Energy Prices & Taxes 1999, 2008 and 2013

Note: The price information for the power generation group in Japan has not been reported since 1998. Also, all price information of 2008 was not reported.

Figure 5.4 Fuel Mix in Japanese Electricity Market (% of supply)



Source: Author's elaboration from Japan Nuclear Safety Organization 2004 & 2013, *Operational Status of Nuclear Facilities in Japan 2004 & 2013*

5.2.5. World's Strictest Environmental Regulations

Regulatory Change in Emission Control After Yokkaichi Verdict

Numerous Japanese HCI firms established the '*Kombinato*' type of industrial complex, which integrated material processes and power plants at one site for maximising energy and resource efficiency in the late 1950s. This approach caused serious environmental issues, however, such as "*Yokkaichi Asthma*", an outbreak of asthma cases around the '*Showa Yokkaichi*' petrochemical-power plant complex in the 1960s along with "*Itai-Itai Disease* (Cadmium poisoning)", "*Niigata Minamata disease* (Methyl-mercury poisoning)" and "*Kumamoto Minamata Disease*", resulting in the "Four Major Pollution Episodes" in Japan (Schreurs, 2002).

Although MITI and relevant ministries initially submitted the "Smoke and Soot Control Law" to the Diet in 1962, based on studies of emission control laws in the US, Germany and the UK, the law was limited in that it provided solutions only to smoke and heavy deposits (Schreurs, 2002). It did not significantly reduce sulphur dioxide (SO₂) emissions and applied only to designated areas without a penalty clause for violations and was based on a standard that could be met by merely building more stacks or diluting concentrations with fresh air. Naturally, the law and subsequent implementations hardly appeased public anger. Adjacent residential areas already regularly experienced SO₂ concentrations of over 0.5 ppm and subsequently witnessed around 1,200 residents identified as "*Yokkaichi Asthma*" patients. While the main concerns of the ministries had been the protection of relevant industries from environmental disputes until the 1960s, civil actions by affected inhabitants and following rules of courts in the early 1970s significantly changed the direction of government regulations (Hashimoto, 1989; Wallace, 1995).

The ruling on the "*Yokkaichi Asthma*" case in July 1972 recognised defendant's responsibility for the disease and pointed out negligence in failing to use the best available technology to control emissions as well as the misconduct in siting of the 'refinery-

petrochemical-power plant complex'. The verdict directly affected regulatory policy on power stations in Japan. It immediately induced the ratification of the Pollution-Related Health Damage Compensation Law and the government's stricter administration of the air pollution laws (Cruz et al., 2002; Hashimoto, 1989).

Facing the legal change in addition to nationwide public discontent, the Japanese government heightened environmental regulations on coal and high sulphur oil power plants in the early 1970s.⁹⁷ As a result, Japanese government's emission standards changed from mere imitation of that of foreign countries in the 1960s to the most stringent emission standards in the world in the mid-1970s (Nishimura & Sadakata, 1989; Schreurs, 2002).

Furthermore, the Air Quality Control Law established in 1967 allowed local governments to set their own emission standards and to exert authority in power plant site permission. Indeed, local authorities imposed much stricter measures on electric utilities to reduce emissions even lower than the national standards. When electric utilities dismissed such local requirements, they had to face local residential referendums and often withdrew their construction projects. To meet such additional local requirements, utilities had to i) switch high sulphur and/or nitrogen fuels to cleaner fuels, ii) introduce combustion modification technologies and iii) develop both de-sulphur and de-nitrogen technologies, such as selective catalytic reduction (SCR) from the 1970s (Ando, 1983; Nishimura & Sadakata, 1989).

Table 5.3 shows the tightening of national NO_x emission standards on steam turbine plants in the 1970s. Although gas turbines were exempted from the national standards in the period, they still needed to meet strict local standards equivalent to standards on gas boilers (Table 5.4). In order to meet the local standards, the utilities

⁹⁷ Outbreak of massive photochemical smog and subsequent health effects on thousands of junior high school students in Tokyo area in 1970 also spurred the regulatory change.

required HEI firms to apply combustion modification as well as the SCR technologies. Table 5.5 shows performances of the emission control technologies. As a result of the strict local requirements, Japanese utilities' overall environmental performances advanced much further than their European and American counterparts in the 1990s (Figure 5.5).

Table 5.3 Changing National Nox Standards on Power Plants (ppm, % of O₂)

		1973	1975	1977	1979	1987	
Gas (5%)	Boilers	130	130	100	60	60	
Oil (4%)		180	150	130	130	130	
Coal (6%)		400	300	300	300	200	
Gas Turbine (15%)		Exempted from national standards					70
		(Local standards set at 10~15 ppm in selected areas)					

Source: Aoyama & Mandai 1984, Ministry of Environment 1990.

Table 5.4 Examples of Local Nox Standards on Power Plants in 1979 (ppm)

	Central Government	Local Government	Actual Emission	Abatement Method
Gas Boiler	60	10	8	CM + SCR
Oil Boiler	130	25	20	CM + SCR
Coal Boiler	400	170	160	CM + partial SCR

Source: Ando 1983, "Nox Regulation on Stationary Sources in Japan": 2

Note: CM = Combustion Modification, SCR = Selective Catalytic Reduction

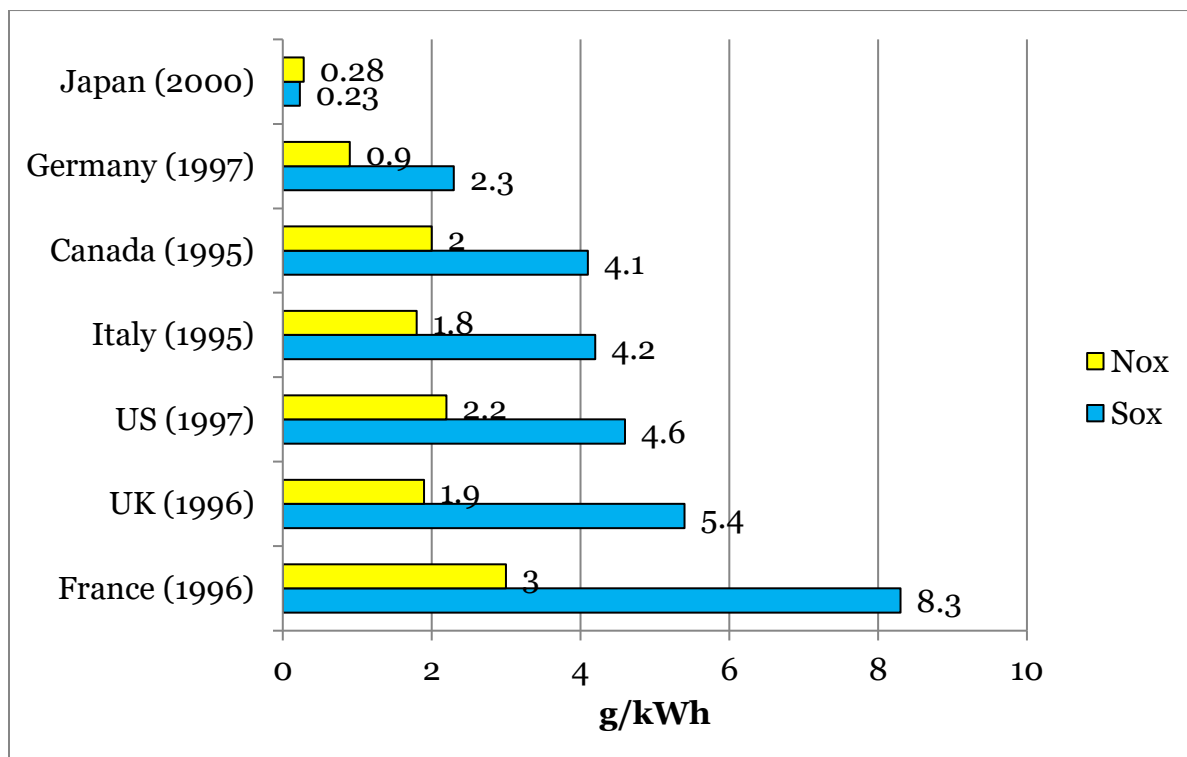
Table 5.5 Nox Abatement Technology Performances in the late 1970s (ppm)

Boiler fuels (% of O ₂)	Outlet NO _x Concentration, ppm			Percent of Control Effects		
	Before Abatement	After CM	After CM+SCR	CM	SCR	Total
Gas (5%)	200	50	10	75%	20%	95%
Oil (6%)	300	100	20	67%	27%	93%
Coal (4%)	600	250	50	58%	33%	91%

Source: Ando 1983, "NO_x Regulation on Stationary Sources in Japan": 2

Note: CM = Combustion Modification, SCR=Selective Catalytic Reduction

Figure 5.5 Environmental Performance of Fossil Power Plants by Country



Source: Author's elaboration from Federation of Electric Power Corporations 2008

Public Concerns, Leaks and Change of Nuclear Regulation in the 1970s

Public concern regarding pollution issues and subsequent regulatory changes were not only limited to fossil power plants but also affected nuclear power's siting and safety regulations beginning in the 1970s. For instance, local protests against the construction of the Hokkaido Power's Kyowa-Tomari nuclear power plant delayed construction by sixteen years. The protests were mainly organised by local fishermen who feared the impact that coolant water used for cooling of the plant would have on their catch. As a result, the utility was forced to modify its siting plans (Schreurs, 2002). Although the average lead time to gain public acceptance of nuclear power plants in Japan was only two to three years in the 1960s, it reached fourteen to fifteen years in the 1980s (Lesbirel, 1998).

Regarding safety regulations, when Japanese HEI firms almost completed indigenisation of the first-generation reactor technologies in the early 1970s, electric utilities faced serious corrosion issues of nuclear power equipment. The problems were generic—for example, primary water stress corrosion cracking (SCC) which caused steam generator tube deterioration of PWRs and inter-granular stress corrosion crack problems of BWRs. The deterioration of pipes and tubes of both reactor designs caused frequently unplanned shutdowns of reactors sometimes for several months or even years. Thereby, they exacerbated the poor economic performance of reactors, namely their capacity factor.⁹⁸

Until the early 1970s, Japanese nuclear safety regulators had used US regulatory guidelines as benchmarks for their safety regulations. For example, the sampling inspection method was the norm in the utility inspection of steam generator tubes as usual in other industrialised countries. The steam generator tube leakage incident at Mihama unit 1 in 1972, however, raised public concerns regarding nuclear safety issues and

⁹⁸ Interview with *Takuya Hattori*, President, Japan Atomic Industrial Forum, Inc., Tokyo, and Former Vice President of Tokyo Electric Power, on 5 February 2011.

changed the norm. Mihama unit 1 (340MW) of Kansai Electric Power Co. (Kansai Power hereafter) had suffered from repeated leakages of primary coolant water in the steam generator tubes since its commercial operation in 1970. In June 1972, the utility experienced steam generator tube leaks of Mihama 1. After temporary shutdown and repair of the degraded tubes, it reopened the reactor soon after (Ono, 1973; Stevens-Guille 1975). Tube leakages and degradation, however, recurred in July 1974. The leakage caused the suspension of the commercial operation of Mihama 1 for five years and nine months. It could then begin test operations on April 19, 1980.

In responding to the event, MITI's regulatory body stipulated strengthened regulatory criteria for the steam generator tubing inspection in 1980 (MITI, 1980).⁹⁹ According to the amended Technical Standard of the Electric Utility Industry Law (MITI Notification No. 501), a 'degraded tube' could not be used, and the scope of inspection was expanded from sampling to all the tubes with full-lengths from end to end (Yashima, 1991:6.2-4/11). The definition of the 'degraded tube', as well as 100% inspection, indicate the strength of the regulations. Most OECD countries had been using the US Nuclear Regulatory Commission's standard as a benchmark, such as '40% loss of steam generator tube wall thickness', in defining the 'degraded tubes' (IAEA, 1997).

Japan has been the only country that applies that "No Flaw" principle since the 1970s. The term "flaw" is interpreted to mean any indication (crack, pit or general wall thinning) greater than the background noise level in high-frequency electric detectors.¹⁰⁰ Furthermore, the definition of "flaw" addresses signals even lower than background noise level when indications are attributable to stress corrosion cracks (SCCs) or inter-granular attacks (IGAs). In such cases, utilities should inspect the tubes more thoroughly with

⁹⁹ Former Nuclear & Industrial Safety Agency (NISA) of the Ministry of Economy Trade & Industry (METI, the successor of MITI) had been responsible for nuclear power safety regulation until the Fukushima nuclear accident in 2011.

¹⁰⁰ The electric detector, namely Eddy Current Test (ECT), cannot distinguish flaw signals up to 20% of wall thickness from the background noise of the tubes. Thus, an actual criterion is 20%.

advanced inspection methods. (Clark & Kurtz, 1988; IAEA, 1997, 2011; Shizuma, 1992; Yashima, 1991).

Thus, the “no flaw” principle is not at all ‘lip service’ given that the principle applies to the limit of flaw detection technologies. It indicates the strictest level of regulation on inspection of steam generator tubes amongst nuclear power countries. For instance, German nuclear safety regulators allow up to 50% of wall thinning while the French do not have explicit criteria for steam generator tube inspection (IAEA, 1997). Further details of inspection and repair criteria of the tubes under Technical Standard of the Electric Utility Industry Law (MITI, 1980) are presented below:

- **Inspection Interval:** Prescriptive regulation of inspection frequency enforces Japanese utilities to overhaul reactors every year, at least every 13 months.¹⁰¹
- **Inspection Boundary:** 100% tubes and full-length inspection if a leak or any flaw was detected during the previous cycle. If there was no leak or flaw in the previous cycle and inspection, 30% of sampling inspection is allowed.
- **Flaw Acceptance Criteria:** “No Flaw” principle on steam generator tube inspection and operation.
- **Leakage Monitoring and Limits:** No leak is allowed during operation. If more than 120% radiation on average is detected, the reactor should be shut down.

¹⁰¹ In effect, all types of power plants including coal, gas and nuclear power in Japan should follow this 13month overhaul interval regulation according to Electric Utility Industry Law.

Table 5.6 Steam Generator Tube Inspection Guidelines in Nuclear Countries

Bases	How Implemented (Repair Criteria)	Country
No detectable flaws or leakage	No wall thinning (virtually no defects over background noise level, which is 20%)	Japan
Flaws limited to a size which is calculated not to burst during normal operation and accident conditions	Often 40% of wall thickness	USA, Canada
	50% of wall thickness	Germany
	Use conservative analysis methods supplemented by 100% inspections of affected areas and tight leak rate limits	Spain
Flaws limited to a size so that there is a <i>low probability</i> of tubing burst during accident conditions	Use conservative analysis methods for each degradation mechanism (degradation specific management)—no explicit safety factors but aggressive inspections	France
Set defect size based on allowable risk of rupture during steam line break	Estimate the probability of rupture for each defect, and require sum for all defects to be < allowed limit (e.g. 1%)	Sweden

Source: IAEA 1997

Steam Generator Tube Rupture Accident in 1991 and Industry Response

Japanese PWRs experienced more serious degradation issues later, namely the SGTR accident at Mihama unit 2 in 1991. In effect, despite previous efforts to improve the chemistry of secondary coolant water and maintenance techniques including sleeving and plugging of the Alloy 600 steam generator tubes, Kansai Power eventually decided to replace the whole steam generators with an alternative material, namely Alloy 690, after the rupture accident (Yashima, 1993). In addition, it caused Mihama unit 2 to be shut down for three and a half years for in-depth analysis of the accident and steam generator replacement (Japan Atomic Industrial Forum, 1993, 1994).

Table 5.7 Steam Generator Tube Leaks in Japanese PWRs in the 1970s and 80s

Year		Reactor	Leak Rate (ℓ/hour)	Causes	Location
1972	Jun.	Mihama 1	70	Wastage	Support plate
1974	Jul.		1.6		
1975	Jan.	Mihama 2	4	Fretting	Above tube sheet
	May	Genkai 1	80		
1977	Jan.	Takahama 1	1.6	IGA/SCC	Tube sheet crevice
1979	Oct.	Mihama 2	-		
1981	Sep.	Ohi 1	0.5	SCC	Tight U-bend
1982	Mar.	Mihama 1	0.1	SCC	Tube plug
	Jul.		0.08		
1983	Feb.	Mihama 2	0.55	IGA/SCC	Tube sheet crevice
1991	Feb.	Mihama 2	Rupture (2,600 ℓ/min.)	Anti-vibration bar	Top of tube support plate

Source: Togo, 1984; MacDonald et al., 1996

Note: IGA = Inter-Granular Attack, SCC = Stress Corrosion Cracking, T.S.= Tube Sheet

Utilities' Effort to Overcome the Strict Regulations

In Japan, nuclear power plants are required to have an overhaul and refuelling every 13 months, unlike other countries which allow their operators longer fuel cycles (typically 18 months). Furthermore, the world's strictest inspection and repair criteria for steam generator tubes forced Japanese utilities to have longer inspection periods, typically more than three months, while utilities in other countries, including Korea, are allowed to have a much shorter inspection period, typically around one month. It means that it is almost impossible to increase the capacity factor of Japanese nuclear power plants over 80%, excluding test operation (OECD, 1999; Institute of Energy Economics Japan, 2011). Indeed, in the entire history of reactor operation, Japanese utilities have only operated their nuclear reactors above 80% of a capacity factor for a few years in the late 1990s (Figure 5.6).

Therefore, the low operational performances created immense concern for Japanese ESI and HEI because that low performance was directly deteriorating the economic performance of the utilities and the track record of Japanese reactors in the global market. In order to improve their capacity factor, Japanese utilities had to reduce either the length of periodic inspections or loosen the compulsory 13-month interval of periodic inspections. An industry leader's keynote speech at the Japan Atomic Industrial Forum (JAIF)'s annual conference in 1984 shows how much Japanese ESI has been concerned about the issue (JAIF, 1984):

The availability factor¹⁰² cannot possibly be above 75% in Japan, because we spend more than 90 days for periodical inspections, much longer than in European countries and the United States. This long inspection period is a big hurdle facing the availability factor. By improving the work environment and increased mechanisation and automation, the periodical inspection time should be reduced to less than two months.¹⁰³

On the other hand, utilities have urged the government to loosen the compulsory maintenance regulation, which has required nuclear reactors to shut down every 13 months for inspection and maintenance since the late 1980s. The regulation is quite strict compared to other countries' practices. The US regulator allows operating cycles of 18 to 24 months, for instance. Increasing the length of operating cycles from about 13 months to 18 months would increase a few percentage points of capacity factor or availability factor. Thus, the industry association, JAIF, aimed to increase the average capacity factor of nuclear power to about 85% by 2020 and 90% by 2030 through regulatory changes

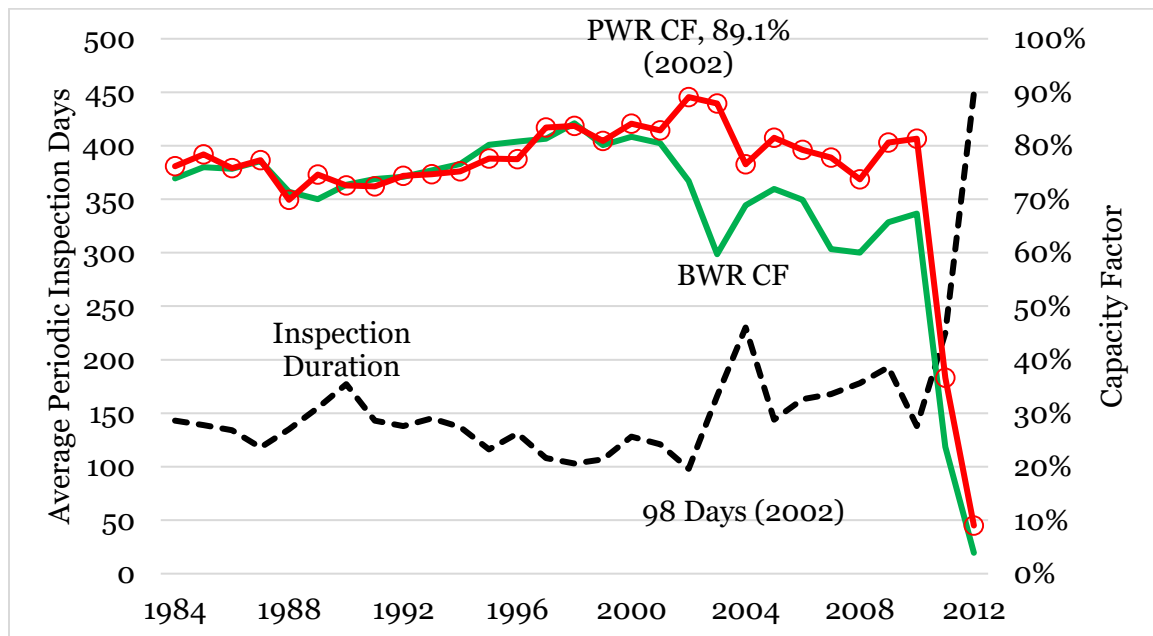
¹⁰² Availability factor (AF) is a ratio of hours which a power plant is on line to total hours in a given period while capacity factor (CF) is the ratio of actual electricity generated to the energy that could have been generated at continuous maximum power operation during the given period. Nevertheless, the AF also indicates the overall operational performance of nuclear power as CF does.

¹⁰³ *Hiromi Arisawa*, Chairman of the JAIF, Keynote speech at the 17th JAIF Annual Conference, *Atoms in Japan*, March 1984: 4

allowing longer-cycle operations of 18 months or more (Japan Atomic Industry Forum, 2010).

However, Tokyo Power's inspection data scandal in 2002 resulted in nationwide public discontent on the Japanese utilities' nuclear safety management. The scandal revealed that Tokyo Power's falsification of reactor safety inspection records during 1990 and 1991 was sealed by the utility for a decade. Under the pressure of public anger and subsequent government investigation and preventive measures, Japanese utilities' efforts to loosen the regulation did not materialise (METI, 2007). Instead, forced outage of numerous reactors for in-depth inspection dramatically decreased the overall capacity factor of Japanese reactor fleets in the mid-2000s (Figure 5.6).

Figure 5.6 Performance of Japanese Reactors Limited by Strict Inspection



Source: Author's elaboration from Japan Nuclear Energy Safety Organization 2014

Note 1. The figure shows the average annual periodic inspection duration of all PWR and BWR reactors excluding Tokai-1, the only Gas-Cooled Reactor in Japan.

Note 2. The dramatic decrease of capacity factor in 2012 is a result of the shutdown of 53 reactors out of 54 reactors for safety checks and maintenance after the Fukushima nuclear accident in 2011.

Regulatory Change After the Fukushima Nuclear Accident

The Japanese government established a new independent nuclear regulatory agency, Nuclear Regulation Authority (NRA), substituting the former Nuclear and Industry Safety Agency in 2012 as a countermeasure of nuclear safety after the Fukushima nuclear accident in 2011. NRA developed new and more stringent regulations that were enacted in 2013. The new regulations require utilities new evaluations of earthquakes, tsunamis, tornadoes etc. and additional countermeasures against tsunami, fire, internal flooding, and the loss of a large area of the nuclear power plants due to natural hazards or terrorisms (NEA, 2017).

Although the Japanese government publicly announced to continue to use nuclear power as an important baseload power source, it is a challenging issue in that the more stringent regulations, cost increase associated with retrofitting reactors to meet the regulations (METI, 2014). Among 54 nuclear reactors in Japan, five reactors were permanently shut-down due to the new regulations and following cost increase. All of the six Fukushima Daiichi units were permanently shut down too. This makes the total operable reactors 43 units in Japan. Utilities had applied to the NRA for a review of the safety systems of 28 units among the 43 units for conformance with the new regulatory requirements and only nine of them went to restart as of 2018 (World Nuclear Association, 2018).

Even looking at the performance of the nine reactors, the capacity factor has never been improved. The average capacity factor of four reactors which experienced planned inspection outages from 2016 to 2018 was 79%, compared to 92% of average US reactor fleet in 2017. The difference mainly comes from the long duration of periodic inspections. The Japanese reactors spent 101 days, while US counterparts spent only 35 days for inspection on average. (Yamaguchi, 2018)

5.3. Heavy Electrical Industry

5.3.1. Sectoral Institutions of the HEI

Post-war Period FDI Regulation and Technology Transfer Guidance

During the post-war period, the Japanese government encouraged technology transfer from advanced foreign firms to Japanese firms, while effectively blocking foreign firms' equity investment through lengthy and stringent case-by-case screening procedures based on the Foreign Investment Law (FIL) of 1950. The MITI, as a gatekeeper, decoupled technology issues from capital investment, and only allowed technology transfer in the form of patents, licences and expertise. At the same time, the Ministry of Finance blocked equity investment and foreign efforts to control Japanese firms including merger and acquisitions, while it allowed only foreign loans (Cohen & Zysman, 1983; Maison, 1992).

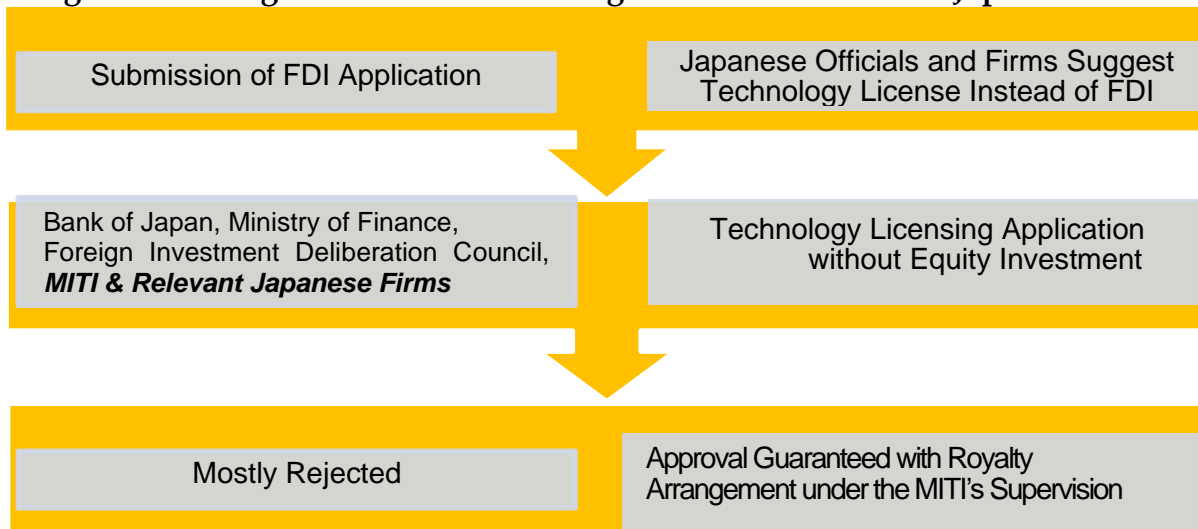
When foreign firms indicated their intention to submit their investment applications to the Japanese FDI, they were told by Japanese officials or industrial leaders to modify or cancel their applications. Instead, they were persuaded to offer technology licensing with minimal effort and guaranteed approval under the FIL even before they submitted a formal application. When prospective foreign investors ignored such informal suggestions and went through the formal application process, their applications mostly failed. First, they had to submit an application to the Bank of Japan, then it passed to the Foreign Investment Deliberation Council (FIDC), which decided whether or not to validate individual investment proposals under the FIL. After a final decision by the FIDC, the Bank of Japan would notify the applicant of the result (Cohen & Zysman, 1983; Maison, 1992).

As a result of the *de facto* government-industry coalition backed by the *de jure* screening process, most of the applications were rejected. Rather than sell their own products in Japan, what foreign firms could do was simply sell their technologies and

settle for royalty payments for the use of their technology, mostly under the MITI's guidance (Figure 5.7; *de jure* process on the left, *de facto* process on the right). In this way, neither capital investment nor technology allowed foreign firms to control their Japanese counterparts in the post-war Japanese market. The virtually closed market institution gave Japanese firms not only stable domestic markets but also advanced foreign technologies without foreign intervention (Cohen & Zysman, 1983; Maison, 1992).

With this 'seamless' FDI blocking system and technology licence settlement, Japanese HEI firms enjoyed easier technology transfers from advanced licensors. The MITI imposed unique indigenisation guidance on foreign licensors and domestic licensees. According to this guide, once they imported the first unit of power technology, Japanese licensee HEI firms had to be able to localise all the components and subsystems from the second unit of the same power technology. Without meeting this condition, the MITI did not allow power generation technology license contracts between foreign and Japanese HEI firms. Mitsubishi Heavy Industries could obtain technology transfer of key components and subsystem technologies, such as gas turbine rotor technology, when it formalised a license contract (Sakuraka, 1997).

Figure 5.7 Foreign Investment Screening Processes in Post-war Japan



Source: Author's elaboration from Cohen and Zysman 1983 and Maison 1992

The Liberalisation of FDI Regulation and its Impact

After a temporary exemption treatment from the General Agreement on Tariffs and Trade (GATT) in the 1950s, Japan faced the Kennedy Round of GATT in 1959, which urged the removal of such discriminatory import restrictions. Following the Kennedy Round, the Japanese government formulated the General Plan for Trade and Exchange Liberalisation, which outlined overall trade liberalisation within three years. Subsequently, the MITI removed quantitative restrictions on trade in 1963 and implemented most of the GATT rules, including Article 11, in 1964 (JDB/JERI, 1994; US Congress OTA, 1991). In this way, the Japanese government's withdrawal from the post-war regulation of FDI and technology transfer guidance resulted in significant implications for Japanese HEI firms in establishing their nuclear and gas turbine technology development.

Notably, there has been a clear difference in licensing strategies between the two major HEI licensors in Japan, namely Westinghouse and GE. While Westinghouse has been rather approachable in transferring its nuclear and gas turbine technologies to its licensors worldwide, GE has been always strict in technology transfer and 'bossy' with regard to its licensees.^{104, 105} The intersection between the MITI's technology licence approval pattern and the two global HEI OEMs' contrasting licence strategies heavily influenced the catch-up performance of Japanese HEI firms.

¹⁰⁴ Author borrows the term, 'bossy', from a discussion with Professor Jim Watson at University of Sussex about GE's relationship with its Japanese gas turbine licensees, Toshiba and Hitachi. GE's controlling tendency in relationship with its licensees can be observed in the nuclear power case as well. While Westinghouse allowed its gas turbine and PWR licensees, including Combustion Engineering, EDF, KEPCO, and MHI, independence and direct competition with itself in the global market once they completed technology indigenisation, GE hardly did so in relationship with its gas turbine and BWR licensees, including Toshiba and Hitachi.

¹⁰⁵ Interview with *Chunrok Kang*, op. cit.: p. 145

Impact on Nuclear Power Technology Catch-up

Nuclear power plants in Japan are supplied by the big three HEI companies, namely MHI, Hitachi and Toshiba. Although the impact of technology guidance on nuclear power catch-up performance of Japanese HEI firms is not as salient as in the gas turbine case, differences in degrees of freedom amongst the three companies are somewhat similar to that seen in gas turbines. Mitsubishi Heavy Industries completed its indigenisation of pressurised water reactor technologies through a close tie with Westinghouse in the late 1970s and early 1980s, while the other two companies have been restricted by GE. These two firms developed BWR technology but had been constrained by GE's strict licence control for many years.

Impact on Gas Turbine Technology Catch-up

The combination of the MITI's 'one firm per one technology transfer' approval strategy and the two foreign licensors' contrasting strategic preference was more pronounced in the gas turbine case. The timing of the MITI's withdrawal from licence approval practices based on the FIL, as well as the technology licence contracts between Japanese HEI firms and the two American licensors, explains a great deal. While Westinghouse entered into a gas turbine licence contract with MHI in 1961, GE established a contract with Hitachi only in 1964 when the Japanese government lifted FDI technology licence package regulation. In effect, GE also entered into a computer technology licence with Toshiba in 1964 (Boulton et al., 1992).¹⁰⁶ It appears that GE strategically waited until the Japanese government lifted the FDI technology licence package regulation to secure its control over its Japanese licensees across various sectors during the transitional period.

Although Hitachi entered a co-production contract with GE in 1964, it could not insert such a demanding technology transfer option into the contract (Sakuraka, 1997).

¹⁰⁶ It should be noted that a computer industry was another strategic sector, together with HEI, targeted by MITI during the post-war period.

Tokyo Shibaura Electric and its sub-licensees, predecessors to Toshiba, signed a gas turbine licence contract with Brown Boveri in 1958, but the licence was limited to manufacturing and marketing without technology transfer options (ABB, 2005). Although Toshiba switched its licensor to GE in the 1980s, it would not have expected to have a technology transfer option from the ‘bossy’ licensor.

Table 5.8 Major Japanese HEI Firms’ Turbine Licence Contracts¹⁰⁷

	Licensor	Country	Technology	License Duration
MHI	Westinghouse Int’l Technology Cor.	US	Steam Turbine	1952-1989
			Gas Turbine	1961-1996
Hitachi	GE	US	Steam Turbine	Early 1950s
			Gas Turbine	1964-
Toshiba	Brown Boveri	Swiss	Steam Turbine	-
			Gas Turbine	1958-1982
	GE	US	Gas Turbine	1982-

Source: MHI, 1990 and Ikegami, 2009

5.3.2. Japan’s Nuclear Technology Catch-up Performance

Daunting Experiences of Early Nuclear Reactor Catch-up Policies

Encouraged by the ‘Atom for Peace’ initiative of the Eisenhower administration in the US in 1953, Japanese government officials established the Atomic Energy Commission (AEC) and the Science and Technology Agency (STA) based on the ‘Atomic Energy Basic Law’ passed in the mid-1950s. What Japanese government acted as a player from the beginning, however, was an unsuccessful choice of commercial reactor technology such as Gas Cooled Reactor (GCR) by the STA, and later Canada Deuterium Uranium (CANDU) reactor by the MITI. While the CANDU reactor idea was abandoned, a small,

¹⁰⁷ Ishikawajima Shibaura Turbine, together with Ishikawajima-Harima Heavy Industries, previously made a gas turbine license contract with Brown Boveri, but was merged into Tokyo Shibaura Electric, a predecessor of Toshiba, in 1961.

single GCR was constructed in 1966. Unfortunately, this resulted in high costs, due to early cracks and the difficulty of repairing and replacing defective equipment. Japanese private utilities were against the government's choices given that commercially proven American reactors, namely PWRs and BWRs already existed in the 1960s (Samuels, 1987).

In the meantime, private HEI firms including Mitsubishi, Hitachi and Toshiba made their own choice of commercial reactors with American OEMs, namely Westinghouse and GE. Mitsubishi group's 25 member firms established Mitsubishi Atomic Power Inc. (MAPI) as a nuclear engineering firm in 1958. Subsequently, MAPI agreed to a PWR technology license contract with Westinghouse in July of 1959, and the contract was approved by the Japanese government in September 1961 (MHI, 1990). The two-year delay was a typical aspect of the technology transfer negotiation process between domestic firm-government alliances and foreign licensors based on the FIL, which was omnipresent in the post-war era Japanese market (see Section 5.3.1).

Mitsubishi Heavy Industries' Catch-up to 'the 1st Generation PWRs' in the 1970s

Mitsubishi Heavy Industries' PWR technology catch-up process followed its fossil power technology indigenisation pattern in the 1950s, which means if a first unit was built by foreign firms, MHI reviewed all the technology and built the second unit itself. This began with the Mihama unit 1 (340MW) order from Kansai Power in 1966. The order was divided into Westinghouse as a main contractor of the NSSS and MAPI as the main contractor of the turbine island in 1967. In the meantime, MHI acted as a subcontractor of Westinghouse for production of containment vessels and balance of power-related pipes. In preparing the construction, MHI sent numerous engineers and staff members to Westinghouse headquarters in the US for their training in designing and operating PWR reactors with the intention of technological accumulation in the 1960s (MHI, 1990).

Following the first unit order, Kansai Power ordered its second PWR (500MW) from MHI in May 1968. From the second unit, MHI localised almost all component

technologies, equipment and system technologies. Once there was a second unit of this kind, the main contractor of the project was changed from Westinghouse to MAPI, and MHI designed and produced most of the reactor equipment and components while Westinghouse only designed some primary system equipment such as steam generators. This pattern was repeated three times following each scaled-up PWR, including Mihama 1 and 2 of the 340~500MW class, Takahama 1 and 2 of the 800MW class and finally Oi 1 and 2 of the 1,100MW class (MHI, 1990) (Table 5.9).

Facing rapid power demand growth, Kansai Power ordered Takahama 1 in May 1970. Takahama 1 was 826MW and a 'three-loop plant', namely three steam generators and three coolant circulation loops. In other words, it is different from Mihama 1 and 2, which have a two-loop design. In this situation, Westinghouse acted as a main contractor again. This time, MHI learned the larger design as quickly as it could get an order of the second unit, Takahama 2, from Kansai Power in December of the same year. Moreover, it indigenised the reactor core structure and control rod drive mechanism (CRDM) through the construction of this unit, and its overall PWR technology indigenisation rate jumped from 76% to 95% in the case of Mihama unit 2. Mitsubishi Heavy Industries reported that it localised 95% of PWR technologies through Takahama 2 in 1975, and with Genkai 2 in 1981 reached 99% in terms of its share of total economic value (MHI, 1990) (Table 5.9).

As technology transfer gradually progressed, Westinghouse finished its direct involvement in the nuclear construction projects with the final order as a main contractor from Kansai Power for Oi 1 and 2 in 1972. After the order of Oi 1 and 2, MHI became a supplier of full scope PWR technologies from system design to equipment in all subsequent PWR orders in Japan. Nevertheless, MHI continued efforts to absorb new PWR technologies from Westinghouse. It opened MAPI's resident office near Westinghouse's headquarter in Pittsburgh and let MAPI arrange training of MHI employees for design, production and operation under Westinghouse's supervision.

From this continued close relationship, MHI evinced the intention for an efficient licence relationship with Westinghouse for new technologies in future (MHI, 1990).

Mitsubishi Heavy Industries claims that it improved reliability and capacity factors through its first phase programme, which included seven reactors from Genkai unit 2 and Tsuruga unit 2. Also, MHI claims that it increased the technology indigenisation rate to 99% in 1981 through the application of its own RCP, expanded application of automatic systems, reduced employees' radiation dose and improved designs for easier maintenance and repair (MHI, 1990) (Table 5.9).

Nevertheless, MHI suffered from a lack of new orders from the mid-1970s to the mid-1980s due to the decreased growth rate of electricity demand and local resistance. It focused on cost reduction through modification of its reactor design. From a series of reviews aimed at minimising cost, MHI constructed seven more PWRs, including Tomari 1&2 of Hokkaido Power, and Genkai 3&4 of Kyushu Power in the 1990s. Despite the early and wide scope technology indigenisation of reactors, stress corrosion crackings (SCCs) of steam generator tubes remained as a serious concern (MHI, 1990; Mishima, 1990; Miyake & Mukai, 2003).

Table 5.9 Progress in Indigenisation of Pressurised Water Reactors by MHI

Utility	Reactor	Unit No.	Size (MW)	Commercial Operation	Main Contractor	Equipment Supplier							
						Reactor System	RV	RC	SG	ST			
Kansai	Mihama	1	340	1970	W/MAPI	W/MHI	CE	W	CE	MHI			
		2	500	1972	MAPI	MHI/W		W	W				
		3	826	1976	MHI	MHI		MHI	MHI				
	Takahama	1	826	1974	W/MHI	W/MHI		W	W				
		2	826	1975	MHI	MHI		MHI	MHI				
		3&4	870	1985									
	Oi	1	1,175	1979	W/MHI	W	W	W					
		2	1,175	1979									
		3	1,180	1991	MHI	MHI	MHI	MHI					
		4	1,180	1993									
Kyushu	Genkai	1	559	1975					MHI		MHI	MHI	MHI
		2	559	1981									
		3	1,180	1994									
		4	1,180	1997									
Sendai	1	890	1984	MHI	MHI	MHI	MHI						
	2	890	1985										
Shikoku	Ikata	1	566					1977	MHI		MHI	MHI	MHI
		2	566					1982					
		3	890					1994					
Hokkaido	Tomari	1	579					1989					
		2	579	1991									
		3	912	2009									
	Tsuruga	2	1,160	1987	MHI	MHI	MHI	MHI					
		3&4	1,538×2	Deferred									

Source: MHI 1990; Miyake and Mukai 2003

Note: W = Westinghouse, CE = Combustion Engineering, MAPI = Mitsubishi Atomic Power Inc., MHI = Mitsubishi Heavy Industries, RV= Reactor Vessel, RC= Reactor Core, SG = Steam Generator, ST = Steam Turbine.

Stress Corrosion Cracking of Steam Generator Tubes and Subsequent Upgrades

Although the first-generation American PWRs and BWRs had better experiences than the British GCR, it was still too early to see the chronic material problems, namely SCC of tubes and pipes (see Section 2.2.1). Mitsubishi Heavy Industries had to face numerous coolant leak events due to SCC of steam generator tubes and long years' worth of shutdowns of Mihama unit 1. The cracking and coolant leaking issue at Mihama unit 1 amidst public anger regarding overall environmental pollution issues induced the strengthening of safety regulations regarding nuclear reactors as well. Thanks to the strengthened regulation, the average capacity factor of Japanese PWRs fell from 72% to 43% between 1971 and 1973 and remained at around 50% until the end of the decade (Japan Nuclear Energy Safety Organization, 2014; MacDonald et al., 1996; Togo, 1984).¹⁰⁸

In order to solve the SCC problems alongside other operational and maintenance problems, MITI launched public R&D programme, namely the Light Water Reactor (LWR) Improvement and Standardisation Programme, in 1975. The programme was aimed to standardise LWR designs in three phases by 1985. In its first and second phases, the existing BWR and PWR reactors were modified to improve operational and maintenance performances. MHI participated in the programme with assistance from Westinghouse. Solving the SCC problems of steam generator tubes was a priority issue of these public programmes. Out of US\$190 million (\$436 million in 2017 price) for total reliability test R&D budget, US\$61 million (\$194 million in 2017 price) was spent on the SCC issue of steam generator tubes between the mid-1970s and early 1980s (Taniguchi, 1985). Technological improvements regarding the safety of the steam generator tubes are summarised below:

- Coolant water quality from phosphate treatment to all volatile treatment;
- Structural modification of the tube supports and anti-vibration bars;
- Application of more corrosion-resistant materials, e.g. Alloy 690 instead of 600;

¹⁰⁸ In effect, BWRs in Japan also suffered from serious coolant pipe cracks and leaks during the same period, but the thesis does not cover BWR issues in detail.

- Improving manufacturing methods from rolling to hydraulic expansion to restrain residual stress of tubes (Miyake & Mukai, 2003).

In the third phase, MHI planned to increase reactor design size up to 1,350MW in 1980. It co-developed the reactor with Westinghouse in addition to cooperation with five electrical utilities, including Kansai Electric Power Company. As a result, its Advanced Pressurised Water Reactor (APWR) was certified by the Atomic Engineering Test Centre, the MITI's nuclear power technology institute, in 1987 (MHI, 1990; Taniguchi, 1985). Later, the APWR design was scaled-up to 1,500MW class and was applied to Japan Atomic Power Co. (JAPCO)'s Tsuruga unit 3&4 construction plan in 2004. Furthermore, MHI developed 1,700MW class APWR design targeting the US and European nuclear reactor markets in the late 2000s (IAEA, 2004).

In effect, the APWR was one of development target reactors in the US Advanced Light Water Reactor programme, launched in 1985 and completed in 1999. It shows the technological and leveraging capability of MHI given that even its licensor, namely Westinghouse, could not complete the APWR design development during and after the programme. It also shows its close relationship with Westinghouse based on long years' technology cooperation (see Section A2 and A4.2 of Appendix A).

However, APWR reactor was never constructed anywhere in the world. Kansai Power and Japan Atomic Power have tried to build the APWR in Japan since 1989 but failed to do so. Even worse, strengthened safety regulations on seismic protection issues in the mid-2000s forced the power companies to delay the APWR construction projects (Maeda, 2010; NRC, 1992). Considering the even stricter regulations on the seismic issue after the Fukushima accident in 2011, it is unlikely that APWR has any future for commercialisation in Japan. It also suspended its design certification process of APWR in the US in 2013 (Ogata, 2013).

Table 5.10 Japanese LWR Innovation: Standardisation Programmes and Targets

Target Items	1 st Phase (1975-77)	2 nd Phase (1978-80)	3 rd Phase (1982-87)
Capacity Factor	Around 70%	Around 75%	90%
Annual Inspection Outage Duration	About 85 days	About 70 days	45 days
Reliability Improvement	Corrosion-resistant materials in Steam Generator	Improving CRDM, Nuclear Fuel	Developing ABWR and APWR, Improving Turbine Systems
Typical PWRs	Sendai 1, Tsuruga 2	Genkai 3 & 4	Tsuruga 3 & 4 (planning halted)
Typical BWRs	Fukushima Daini 2	Kashiwazaki-K 2&5	Kashiwazaki-K. 6 & 7

Source: Mishima 1990: 86

Unsatisfactory Export Performance Despite Rise in Sophistication

Despite MHI's early technological indigenisation and increased sophistication of PWRs in the 1970s and 1980s and eventual expiration of licence with Westinghouse in 1991 (Schuler et al., 2004), its export performance was limited in dozens of subsystems and equipment until the 2010s. The firm started its nuclear equipment export from a steam turbines contract with Mexico in 1972 and a reactor vessel contract with China in 1984. Export performance of replacement steam generators (RSGs) has been better than other equipment thanks to the omnipresent SCC of steam generator tubes and subsequent early degradations of steam generators in OECD countries. Mitsubishi Heavy Industries received orders for 31 RSGs from utilities in the US, France and Belgium from the 1980s to the late 2000s (*World Nuclear News*, 12 May 2010).

Although MHI put efforts into the export of nuclear reactor systems rather than component equipment, both internal and external conditions did not allow its export. Recognising some equipment export contracts with China in the mid-1980s as a signal of export conditions, MHI established its nuclear export group in May 1986. However, the

Chernobyl nuclear accident in 1986 and the appreciation of Japanese Yen to US dollars in 1985 discouraged export efforts (MHI, 1990). Mitsubishi Heavy Industries was concerned that both the domestic and major global market, such as the US, faced nuclear market saturation in the 1990s. It seems to have considered developing small reactors under 600MW for developing countries (Sato, 1991). This niche market idea has not been materialised.

Table 5.11 Nuclear Equipment Exports by MHI from 1984~2018

	RCP	RV	RVH	ST	SG
China	8	3		6	
Korea			3		
Taiwan				2	
N. America			15		6
Central & S. Americas			1	2	
Europe		1	3	2	25
Total	8	4	22	12	31

Source: MHI 2006, 2018

Note: RCP=Reactor Coolant Pump, RV= Reactor Vessel, RVH=Reactor Vessel Head, ST = Steam Turbine, SG = Steam Generator

The unsatisfactory nuclear export performance can be observed in the other major Japanese HEI firms' cases too. Although Hitachi and Toshiba have been actively involved with GE's BWR construction projects in Taiwan, their role was limited in the supply of components and equipment as a subcontractor to GE. For instance, Hitachi provided reactor containment vessels to the *Chinshan* project and spent nuclear fuel storage racks for the *Kuosheng* project in the 1970s, and reactor pressure vessel and internal reactor components for the *Lungmen* project in the early 2000s (Yoshimura et al., 2009; AEC,

2013).¹⁰⁹ They tried to improve their nuclear export performance as the main contractor of a whole nuclear construction project rather than a subcontractor from the late 2000s through either acquisition of or forming of a joint venture with foreign nuclear OEMs.

Toshiba was the first mover in shifting from a subcontractor to a prime contractor by severing the old ties with a foreign licensor and buying a new nuclear vendor. It acquired Westinghouse from British Nuclear Fuel Ltd. in 2006 and aimed at foreign nuclear export markets for Westinghouse's AP1000 PWR. Promptly, Hitachi also formed a joint venture with GE in 2007, namely Hitachi-GE Nuclear Energy, Ltd. With 80/20 share arrangement of the joint venture, Hitachi became a prime contractor in the global nuclear market and aimed at exporting ABWR reactors (Hitachi, 2012). In a similar vein, MHI also formed a joint venture with AREVA, a French nuclear OEM, in 2007 and aimed at developing and exporting jointly developed 1,100 MW PWR reactors (MHI, 2007).

As soon as Toshiba initiated a destabilisation of the Japanese nuclear HEI, it started two AP1000 construction projects in the US and formed its UK subsidiary, namely NuGen, in 2009 to build another AP1000 reactors at the Moorside site. In addition, Korea's first nuclear export case to the UAE in 2009 stimulated the Japanese nuclear community to participate in the fierce nuclear export market competition. The Japanese HEI firms, including MHI, Toshiba, and Hitachi, and nine Japanese ESI firms organised a nuclear export consortium, namely International Nuclear Energy Development of Japan Co. (JINED), under government sponsorship in 2010. The unprecedented user-producer nuclear export consortium in Japan first aimed at the Vietnamese market. The consortium made an agreement with the Vietnamese government to construct nuclear plants even without a reactor choice, whether it is PWR or BWR, in 2010. It indicates a sense of urgency

¹⁰⁹ The *Lungmen* nuclear project, which could have been the first ABWR out of Japan, was scrapped by the Taiwanese government due to safety concern and public protest in 2015. Although there are some suggestions to restart the project, the project is officially and irreversibly cancelled (Nuclear Engineering International, 2019).

that the Japanese nuclear industry felt after it was defeated by the Korean consortium in the UAE nuclear tender.¹¹⁰

Although the Fukushima nuclear accident in 2011 halted Japanese government and nuclear vendors export efforts temporarily, MHI, Toshiba/Westinghouse and Hitachi-GE Nuclear resumed the efforts. MHI, alongside its French ally, AREVA, signed a nuclear export contract with Turkey in 2013 at a heavily discounted price (about US\$ 18 billion for four reactors), in winning the competition with the Korean KEPCO/*Doosan* consortium. Also, Hitachi entered the UK nuclear market through acquiring Horizon Nuclear Power Ltd from German electric utilities in 2012 to construct two Advanced BWR(ABWR) reactors at the Wylfa site (Johnston, 2017).

However, all the nuclear export projects expected by the Japanese nuclear OEMs and the nuclear consortium eventually failed after their decade long export efforts. It is unlikely that they restart nuclear export efforts in foreseeable future considering the extent of the financial damage and cost increase of the nuclear projects they experienced. Firstly, the Vietnamese government cancelled the nuclear construction plan due to concerns with increasing construction cost in 2016 (Larson, 2016). Secondly, Toshiba's Westinghouse went bankrupt in 2017 due to the soaring construction cost of the two nuclear projects, including Virgil Clifton Summer (Summer in short) in South Carolina and Vogtle in Georgia, in the US. The bankruptcy induced Toshiba exit the nuclear market with a substantial financial loss. It also completely abandoned its Moorside nuclear project in the UK and liquidated NuGen in November 2018 after it failed to sell the subsidiary to KEPCO (Adelman & Yamaguchi 2018).

Thirdly, the construction cost of the *Sinop* project in Turkey has doubled due to enhanced safety standards after the Fukushima accident during a feasibility study, and

¹¹⁰ Interview with Yuji Takahashi, Chief Operating Officer, International Nuclear Energy Development of Japan Co., LTD., Tokyo, and Yoshihiro Tomioka, General Manager of Nuclear Power Department, The Federation of Electric Power Corporations, Tokyo, on 1 February 2011

MHI cancelled the project in December 2018, eventually. The problem was not a fear of the host country about nuclear accident risks but the heightened safety regulation after the Fukushima accident and the cost rise (Tsuji, 2018).

Finally, Hitachi also announced indefinite suspension of its Wylfa nuclear project in the UK in January 2019, leaving substantial financial expenditure for preparation works. It suffered from increased cost, a reduced subsidy from the UK government, and lack of private investors. It expected further support from the UK government and private investors, but neither side did Hitachi favour in the end. The UK government has already been criticised by the National Audit Office, the UK's national auditor, due to its generous subsidy to EDF's Hinkley Point C nuclear project and suggested much less subsidy to Hitachi's Wylfa project. Also, Tokyo Power, one of the major prospective private investors of the Wylfa project, indicated its unwillingness to participate in the project due to the soaring cost and financial risk (Hotta & Ibusuki, 2018; Ibusuki, 2018; Johnston, 2017; The Economist, 2019).

5.3.3. Japanese Gas Turbine Technology Catch-up History

Japanese gas turbine manufacturers can be grouped by the size of major gas turbine products. The big three 'heavies' include Mitsubishi, Hitachi and Toshiba Heavy Industries, who mostly supply large CCGTs to utilities, while Kawasaki Heavy Industries (KHI), Ishikawajima-Harima Heavy Industries (IHI)¹¹¹, Niigata, Kobe Steel and Mitsui Shipbuilding mostly supply small and medium gas turbines for various applications. In particular, MHI's technological leadership has been pronounced. It developed its own

¹¹¹ Among the gas turbine suppliers, IHI, KHI and MHI also manufacture jet engines for airplanes. IHI performs the most advanced jet engine blade manufacturing process technologies through its precision casting subsidiary, namely ICC, in Japan.

high temperature-resistant materials as well as a precision casting process for gas turbines through its *Keiretsu* members, including Mitsubishi Steel Manufacturing Co. and Mitsubishi Materials Co, who were predecessors of MHI Precision Casting.¹¹²

There has been a certain division of labour between the three big ‘heavies’ and other small- and medium-sized gas-turbine makers in terms of market segments. The three big ‘heavies’ concentrate on large gas turbines mainly for base-load power plants of utilities, while smaller gas-turbine makers focus on emergency purpose gas turbines for building and factory owners. Although the production of large gas turbines had been divided into base-load and peak-load markets in the beginning, large machines have been produced solely for the base-load market since the end of the 1990s (Table 5.12).¹¹³

Table 5.12 Land-based Gas Turbine Production by Japanese Makers in 1948-2003

	Delivered Year	Base Load		Peak Load		Emergency	
		Units	Output (MW)	Units	Output (MW)	Units	Output (MW)
Small	1948-03	224	72	12	6	4,957	1,777
Medium		1,019	4,597	135	1,297	2,620	4,349
Large		564	52,282	136	7,598	1	24
Total		1,810	56,956	284	8,912	7,578	6,148
Large GTs by Periods	1948-69	0	0	2	60	0	0
	1970-78	100	3,796	78	2,418	0	0
	1979-83	61	2,786	13	319	1	24
	1984-88	48	2,453	10	554	0	0
	1989-93	102	9,890	15	1,656	0	0
	1994-98	114	14,426	18	2,591	0	0
	1999-03	139	18,931	0	0	0	0

Source: Gas Turbine Society of Japan 2004

Note: Small = ~0.74MW, Medium = 0.74~22MW, Large = 22MW~.

¹¹² Email interview with *Youngsoo Yu*, Senior Researcher, High Temperature Material Department, Korea Institute of Material Science, *Changwon*, on 13 January 2015

¹¹³ Interview with *Osamu Kimura*, Research Economist, Socioeconomic Research Center, Central Research Institute of Electric Power Industry, Tokyo, on 15 February 2011

Mitsubishi Heavy Industries' Gas Turbine Licence Contract with Westinghouse

In establishing a gas turbine licence with Western firms, MHI alone enjoyed an exceptional technology transfer option from the licence contract amongst Japanese HEI firms, thanks to the timing of the contract in advance of the liberalisation of FDI regulation. Once dismantled into three heavy industry firms by Supreme Command for Allied Powers (SCAP) and re-merged in 1965, MHI's two post-war predecessors established different licensors in parallel. Shin-Mitsubishi (Central Japan MHI), after several years of its in-house R&D of gas turbines, re-established its licence relationship with Westinghouse for gas turbines in 1961 and delivered its first Westinghouse-type industrial gas turbine (12MW) for Asahi Glass's Chiba factory in 1963 (MHI, 1990).

In addition, Mitsubishi Zosen (West Japan MHI), predecessor of the current Nagasaki Shipyard of MHI, re-established a licence contract with a Swiss firm, Escher Wyss, in 1953 regarding steam and gas turbines for land-based and marine applications. Following the licence contract, it delivered its first industrial gas turbine for an air supplying locomotive of a blast furnace at Yawata Steel in 1958 (MHI, 1990).

Mitsubishi Heavy Industries initiated its technology accumulation of gas turbines under the Westinghouse licence relationship in two ways. Regarding design capability, it developed its capability through iterative feedback from Westinghouse, including imitation, trials of design and reviews by Westinghouse designers. At the same time, it developed manufacturing capability through producing industrial gas turbines for marine propulsion and machine locomotive purposes based on, for instance, the Westinghouse W-251 model (MHI, 1990).

However, the other two manufacturers did not enjoy the technology transfer option from their licence contracts. Although Hitachi began its in-house gas turbine R&D in 1949, it re-established a gas turbine licence contract with GE in 1964 only after the Japanese government withdrew from the post-war FDI regulations. Then, it delivered its

first industrial gas turbine (6MW) based on GE technology in 1966. Toshiba experienced a slightly different pattern of licensing with foreign OEMs. *Ishikawajima Shibabura* Turbine, a predecessor of Toshiba's gas turbine division, entered a licence contract with Brown Boveri, a Swiss predecessor of ABB in 1958. It delivered its first industrial gas turbine (5MW) in 1961. Having lagged behind its competitors in high thermal inlet temperature, however, Toshiba changed its licensor to GE for leading commercial gas turbines in 1982. Like the Hitachi-GE licence contract case, however, its contract also lacked the possibility of including a technology transfer option (Kimura & Kajiki, 2008; Ikegami, 2009).

Thus, the difference in technology transfer options is ascribed to the change of the Japanese government's trade regulations and subsequent change of technology licence regulations in the mid-1960s. The post-war era Japanese government's regulatory logic was to let a leading Japanese firm enter technology licensing contracts with foreign firms for technology transfer, and let the firm share the transferred technology information with other competing domestic firms (see Section 5.3.1.).

Different Strategic Interests with the Licensor Across Dual Electrical Systems

Although MHI had a better position than its domestic competitors, it also had to face conflict with Westinghouse over different strategic markets, which led to MHI's own development of MW-701B and MW-252 in the early 1970s. When Middle Eastern countries' oil field development boomed around 1970, MHI considered the Middle East an emerging strategic market for gas turbines. Most of these countries, however, had different electrical frequency systems or oil field purpose locomotive demand for gas turbines, away from Westinghouse's interest (MHI, 1990; Hoshi 2002).

Middle Eastern utilities mostly use 50Hz, unlike MHI's home market, namely the *Kansai* region (western part of Japan) or Westinghouse's home market which use 60Hz. Also, industrial gas turbines used for oil field purposes need to operate in a wide range of variations in both revolutions and loads in driving pumps and compressors for pipelines,

compared to gas turbines used for utility purposes (Watanabe, 1977). Thus, MHI had strong incentives to develop 50Hz and locomotive gas turbines. Westinghouse, however, was not eager to lead the development of both 50Hz and locomotive machines and refused to offer respective gas turbine blueprints to MHI. Instead, it indicated that it would review MHI's draft blueprint. Thus, MHI tried drawing its first 50Hz gas turbine blueprint based on Westinghouse's 60Hz W-501B machine rather than a tailored blueprint for a 50Hz system. Westinghouse's indifference to 50Hz gas turbines could be explained by the fact that its production line had been already set to produce 60Hz machines targeted to its home market, namely North America (Hoshi, 2002; Kimura & Kajiki, 2008).

By comparison, MHI had a large domestic market for 50Hz gas turbines, namely the *Kanto* region (the eastern half of Japan). It had already accumulated modification capabilities of 50Hz steam turbines for coal and oil power plants in the early 1960s, including Tokyo Power's Yokohama unit 2 in 1962 based on Westinghouse's 60Hz steam turbines. Furthermore, MHI's gas turbine production system had not yet been fixed to a 60Hz market. At that time, MHI was about to rearrange its scattered heavy electrical machinery development resources across its various shipyards in Japan. As a result of the rearrangement, MHI established a gas turbine test facility at its Takasago Machinery Works in around 1970 (MHI, 1990).

By the mid-1970s, MHI experienced half success and half failure in developing gas turbines for the 50Hz electrical networks. It succeeded in developing its first 50Hz gas turbine, namely 701B, based on Westinghouse's W-501B machine in the mid-1970s. Its first order came from Qatar's Water and Electric Power Department for 93MW gas turbine in 1975. Its first domestic order for a 50Hz gas turbine came from Hokkaido Power for the *Onbettsu* plant (74MW \times 2) in 1976. Mitsubishi Heavy Industries considers the 701B as a prototype of 701D, its first CCGT (MHI, 1990). By comparison, it failed at commercialising the MW-252 gas turbines for industrial purposes after it spent three years on the process and incurred high development costs (Hoshi, 2002; Ikegami, 2009).

Catching-up Through Modifications Across Dual Electrical Systems

In effect, the conflicting interests over different electrical systems and subsequent independent efforts to modify Westinghouse designs induced momentum for MHI's catch-up in commercial CCGTs. It began to escape from Westinghouse's licence when it modified Westinghouse's 60Hz gas turbines such as 501D into a 50Hz machine, namely 701D, together with its own air-cooled blade and low-NO_x combustor technology in the late 1970s and early 1980s.¹¹⁴ The 501 series heavy frame gas turbine had been Westinghouse's representative machine from its initial development of 501A (45MW) in 1968 to W501ATS in 2002 (Ihor et al., 2002). From the early version, it became a runway of MHI's 501 and 701 series gas turbines. This was a critical juncture in MHI's gas turbine catch-up path in that MHI developed, in turn, its own 60Hz gas turbine, namely 501F, based on 701D and its scaled-down version M701DA (MHI, 1990) (Table 5.13 and Table 5.14).

Table 5.13 Catching-up through Modifications across Dual Electrical Systems

	Power Output (MW)								
TIT (°C)	5-	10-	20-	40-	80-	120-	160-	320-	480-
800-	101		191	301					
900-			251A	501A					
1000-		M151	251B	501B	701B			50Hz Utility Purpose	
1100-					501D	701D			
1200-	MF61	MF111	MF221			M701DA			
1300-						M501F	M701F		
1400-		Industry Purpose(50/60Hz)				M501F3	M701F3		
1500-					60Hz Utility Purpose		M501G	M701G	
1600-							M501J	M701J	

Source: Author's elaboration from MHI, 1990, Hoshi 2002 and Kimura & Kajiki, 2008

¹¹⁴ MHI started independent commercial gas turbine development efforts with MW-701B based on Westinghouse 501D from 1970. MHI evaluates 701B as a prototype of MW-701D, a later version which was integrated into the first CCGT, Higashi Niigata unit 3, in Japan.

Table 5.14 Gas Turbine Sales by Electrical Frequency by MHI as of 2014

501Series (60 Hz)		701Series (50 Hz)		Small and Medium GTs	
D Class	25 units	92 units		189 units (Mostly 50/60Hz Dual Industry Purpose GTs)	
F-Class	73 units	125 units			
G Class	70 units	11 units			
J Class	26 units	2 units			
Sub-Total	194 units	230 units			
Major Exports by Region and Domestic Sales					
Americas	Europe	Mid. East & Africa	Asia	Oceania	Japan
99	39	97	188	7	183

Source: Ando, 2014: 15

When MHI developed its MW 501F series of gas turbines in the late 1980s, it invited a team of Westinghouse designers into its development group. This 150MW machine's turbine inlet temperature (TIT) is 1,350°C, and its efficiency reaches 50% with combined cycle (MHI, 1990). With the development of its own 60Hz 501F gas turbine, MHI became independent from the Westinghouse licence in terms of its technology and licence contract in 1986. This changed MHI's status from licensee to 'equal partner' with Westinghouse, and the relationship continued until 1997 when the two companies finished joint development of the first 'G' class gas turbine with the operation of a demonstration gas turbine at the MHI's Takasago Machinery Works (Kimura & Kajiki, 2008).¹¹⁵

Takasago Machinery Works, with its on-site R&D centre and manufacturing facilities, has been leading the development of various MHI's gas turbine series under the Westinghouse license since the early 1970s. For example, it developed the 25MW 2 Shaft Gas Turbine (MW-252) for industrial purposes in 1976 based on Westinghouse's W-251 design. Due to its central role in absorbing Westinghouse's technological knowledge, it has been often called '*Eastinghouse*' by its own engineers (Stoloff, 1984; Tien, 1985).

¹¹⁵ It should be noted that non-nuclear heavy electrical business of Westinghouse, including gas turbine, was merged by Siemens in 1998.

Takasago Machinery Works also collaborated with MHI's Nagasaki Institute in the 1970s in developing design technologies for compressor, turbine, air-cooled blades, combustor, shaft system and control systems. Around 1980, in supporting MHI's production of 501D, development of 701D gas turbine and the Moonlight Project's 'High-Efficiency Gas Turbine Project', it developed crucial component technologies including an air-cooled blade and researched new superalloy materials. All the results were integrated into Tohoku's Higashi Niigata unit 3 CCGT in 1984 (Kimura & Kajiki, 2008; MHI, 1990).

Re-combination of Low NO_x Combustor Under Strict Emission Standards

Mitsubishi Heavy Industries' first CCGT, namely the 701D, cannot be sufficiently explained by its modification of machine design across the dual electric frequencies alone. The 701D had a salient key ingredient that outperformed advanced American CCGTs, namely in environmental performance. As briefly explained above, MHI commercialised a dry low-NO_x combustor (DLNC) technology for the first time in the world, and its performance surpassed that of the global leaders, including GE (Aoyama & Mandai, 1984). The technology of NO_x emission control is crucial in gas turbine developments in that the formation of NO_x exponentially increases in response to the combustion temperature increase which is essential to improve thermal efficiency (Tanaka et al., 2013). It means that the NO_x control technology is a crosscutting solution area between ever strengthening global emission standards and ever-increasing combustion temperature for energy efficiency of gas turbines in the worldwide competition.

In effect, GE won the first CCGT plant contract in Japan from Tokyo Power in 1981. The 2,000MW CCGT contract for the first and second groups of power plants at Tokyo Power's Futtsu site was a breakthrough to GE given that the US and European CCGT markets were frozen in the 1980s (Watson, 1997). GE, however, faced an unfamiliar challenge, namely the stringent Japanese local NO_x emission regulations. Its 'wet-type' NO_x emission control technology which injects steam or water into the flame in the

combustor could not meet the stringent regulation. Although GE's 9001E gas turbine could lower NO_x emission to 42 ppm by using the 'wet-type' control in the Futtsu project, for instance, it could not meet the Japanese local standard which was 10 ppm. The project was delayed two years due to the emission issue, and barely met the local standard with Tokyo Power's own post-combustion technique, namely selective catalytic reduction (SCR), in 1986. The SCR was also a new technology to GE whereas it was already widely applied to the Japanese fossil power plants from the late 1970s (Angello & Lowe, 1989; Ando, 1983; US EPA, 1993) (see also Section 5.2.5).

In the 1980s' global market, conventional combustors of gas turbines input fuel and air directly into the combustion zone and created a wide variation in the air-to-fuel ratio. This irregularity induces combustion of 'localised fuel-rich pockets', which produces significant levels of NO_x emissions. In order to reduce the NO_x emission of the combustor, the global OEMs used 'wet-type' treatments which inject steam or water into the flame in the combustor. The injection of steam or water reduces the temperature of the flame and subsequently reduces NO_x emission sacrificing thermal efficiency. As NO_x emission standards were strengthened in the 1980s' US, the global gas turbine OEMs initially responded with more extensive use of steam or water injections. This response, however, causes not only further loss of energy efficiency but also substantial equipment and maintenance costs (Angello & Lowe, 1989; US EPA, 1993).

Even after the installation in 1986, GE's 9001E gas turbines suffered serious technical problems with the wet-type NO_x control. The steam injection caused various problems, such as 'flame out' or rundown of power plants, lower thermal efficiency and more frequent inspections and part replacement at additional costs (Angello & Lowe, 1989; EPA, 1993). After the saga of *Futtsu* group 1, Tokyo Power requested GE to apply dry low-NO_x combustors for *Futtsu* group 2 CCGT units and joined GE's combustor development programme as a sponsor. The company's dry combustor, however, was not developed until the group 2 gas turbines started operation in 1988 (Angello & Lowe, 1989;

Hara, 1992). Its first dry combustor in Japan was applied to Tokyo Power's *Yokohama* group 7 only in 1996 (Aizawa & Carberg, 1992; Tomlinson & McCullough, 1996). While GE and Tokyo Power suffered project delays and failure in the development of DLNC, MHI delivered the actually first CCGT in Japan in addition to its world-first commercial DLNC (Angello & Lowe, 1989).

How could the latecomer commercialise the world first DLNC surpassing the global OEMs? In effect, MHI already developed a pre-mix combustor for oil and gas boilers in the mid-1970s to adapt to the strengthened Japanese NO_x emission standards. The technology is based on MHI's "off-set premixed flame theory", a modification of the existing "premix flame combustion theory" mostly used in rocket designs by the US in the 1970s (Kawamura & Frey, 1980). While conventional combustors widely used for oil and gas boilers at that time produced a vast amount of NO_x due to their irregularity of air to fuel mixture, the premix technology contributed to substantial reduction of NO_x emission in dozens of oil and gas boiler power plants in the late 1970s' Japan, such as Tokyo Power's *Anegasaki* power plant in 1977.

Later, it was applied to coal power plants too and licensed to CE for application to coal power plants in the US (Angello & Lowe, 1989; MHI, 1990). Table 5.15 shows that MHI's premix combustion technology for gas boilers was a result of adaptation to gradually strengthened emission standards in the 1970s' Japan, even before CCGT technology was commercialised. Table 5.16 shows difference of NO_x emission standards for gas turbines between countries. It should be noted that once the DLNC technology is recognised available, a couple of regional regulatory agencies in the US, such as South Coast Air Quality Management District (SCAQMD), set more restrictive NO_x limits as low as 9ppm, which became effective from 1995 (US EPA, 1993).

Table 5.15 Gas Boiler Technology Adaptation of MHI to NO_x Standards in the 1970s

	Pre-1973	1973	1975	1977
Emission standard on gas boilers	None (180~250ppm)	130ppm	100ppm	60ppm
MHI's abatement technology	Tangential burner	Tangential + GM		PM burner

Source: Author's elaboration from Ando 1983 and MHI 1990

Note: GM and PM stand for Gas Recirculation Mixture and Pollution Minimum, respectively.

Table 5.16 International Comparison of NO_x Standards on Gas Turbine in 1984

	Turbine Capacity (MW)	National Standards (ppm)	Local Standards (ppm)
Germany	60 or larger	147	-
	less than 60	172	-
US	10 or larger	75	9 (SCAQMD 1995)
Japan	10 or larger	70 (1987)	15(Tohoku),10(Tokyo)

Source: Angelo & Lowe 1989, US EPA 1993

To overcome the issue, the global gas turbine OEMs developed 'a lean premixed combustor', which premixes the air and fuel in an air rich ratio before fuel injection into the combustion zone following the lead of MHI in the 1980s and 1990s. This results in a mixture with a very fuel-lean and uniform air/fuel ratio for delivery to the combustion zone and a minimal NO_x formation. Although all global gas turbine OEMs had initiated programmes for lean premixed combustors in the 1980s, only GE, Siemens and ABB among them had succeeded in commercialising the technology. Even Westinghouse could not develop the new combustion system and still had to depend on the 'wet-type' combustor (Bender, 2006; US EPA, 1993).

Table 5.17 shows NO_x emission performances of the conventional 'wet-type' combustors, a widely applied technology at the time, and newly developed DLNCs of the global gas turbine OEMs in 1993 in the face of strengthened US emission standards. At this stage, their newly developed DLNCs caught up with the 1984 version DLNC of MHI (Angello & Lowe, 1989; US EPA, 1993). Although the three global OEMs appear to have caught-up to MHI's 1984 version DLNC technology with the lower NO_x emissions in

1993, their lower TITs indicate their thermal efficiency was compromised for the environmental performance.¹¹⁶ Given that NO_x emission exponentially increases as TIT increases, it is doubtful if their 1993 version combustion technologies were superior to the 1984 version DLNC of MHI.

Table 5.17 NO_x Emission Control Performance of the Global OEMs in 1993

	Model	Output (MW)	Temperature (TIT, °C)	Wet Control (Steam/SCR)	Dry Control (DLNC/SCR)
GE ^{a, b}	9001E	116.9	1,085 (1988)	42/9	not developed
	9001E	125	1,124 (1991)	42/9	25/9
Siemens	V 84.2	105	1,060	55/n.a.	25/9
ABB	GT11N	83.3	1,027	25/9	25/9
Westinghouse	501D5	109	1,132	25/n.a.	not developed
MHI (1984) ^c	701D	137	1,150	-	75/15

Source: Angello & Lowe 1989^a, Pavri & Moore 2001^b, Aoyama & Mandai 1984^c, US EPA 1993: 5-136, 6-254, 6-255

Note: TIT = Turbine Inlet Temperature, DLNC = Dry Low NO_x Combustor, SCR = Selective Catalytic Reduction

Special Relationship Between MHI and Tohoku Power on NO_x Control

The special relationship between MHI and Tohoku Power must be analysed in two aspects. First, mutual trust between the two firms under uncertain conditions need to be addressed. Under the conservative culture of the Japanese utilities, it was difficult for domestic producers to supply their first commercial product to the utilities (MHI, 1990). Therefore, Tohoku's acceptance of MHI's first CCGT was unusual in the Japanese electricity market in the early 1980s. Below, *Osamu Kimura* from Central Research Institute of Electric Power Industry explains the background behind this:

Although the government initiated national technology development programmes for gas turbines, the utilities' role is more important in terms of providing a stable gas turbine market. In the early period of gas turbine

¹¹⁶ An increase of 56°C (100°F) in turbine inlet temperature, for instance, provide a corresponding 1.5~2.3% improvement in thermal efficiency of gas turbines (Soares, 2007; Huda et al., 2014).

commercialisation, Japanese utilities did not trust domestic manufacturers. However, the utilities gradually came to prefer domestic manufacturers to foreign suppliers since it was more comfortable to discuss with the domestic makers when the issues are complex, such as maintenance. For instance, when MHI developed its first CCGT (701D), the president of MHI met the president of Tohoku Power to negotiate the contract from the beginning. That is how MHI and Tohoku made their gas turbine business relationship, like a gentlemen's agreement between top decision-makers.¹¹⁷

Second, MHI's close relationship with Tohoku Power cannot be separated from the stringent Japanese local emission standards on electricity suppliers. Before 1980, Westinghouse's 'wet-type' combustors did not meet the local standards. The latecomer, thereby, needed to develop the DLNC technology based on its lean premix burner technology for gas boilers. It led MHI and Tohoku Power to tight cooperation as a developer and a sponsor, respectively. It took two years for MHI to develop the DLNC upon Tohoku's request.

After installation of the combustor, it took four months to complete final adjustments (Aoyama & Mandai, 1984; Angello & Lowe, 1989; Jeffs, 2008). The co-development process between the two firms for innovation of the DLNC was repeated several times in the face of ever-increasing turbine inlet temperature and strict environmental regulations (Matsuzaki et al., 1992). This relationship continued until the 2000s and worked as a base of MHI's further development of CCGTs. For instance, Tohoku Power's Higashi Niigata played a role of verification plant for M701G (50Hz CCGT) while MHI's Takasago workshop did so for M501G (60Hz CCGT) (Soares, 2007).

¹¹⁷ Interview with *Osamu Kimura*, op. cit.: p. 175

Table 5.18 Mitsubishi Heavy Industries' Milestones in Gas Turbine Catch-Up

Milestone	Implication	Year
Dependence on licensed Westinghouse designs (1970s)		
Development of MW-701B (50Hz) based on W-501B design GT (60Hz)	Accumulation of technological capability in 50Hz gas turbine market	1970~76
Development of 252B for industry purpose GTs based on W-251B	Accumulation of technological capability in industry purpose GTs	1974~76
Catching-up under Westinghouse licence (1978-86)		
Development of MW-701D (TIT 1,150°C, efficiency 48.8%)	World 1 st DLNC, Japan's 1 st CCGT	1984
Joined in Moonlight Project (Target: 1,300°C 'Reheat' gas turbine)	Accelerated learning in precision casting resulted in 1,250°C industry purpose GT	1978~87
Equal partnership with Westinghouse (1986~96)		
Development of MW-501F/701F (TIT 1,350°C, efficiency 57%)	Developed Multi-nozzle Combustor, World 1 st large F-class CCGT	1989
Independence from Westinghouse (1996-)		
Development of M-501G/701G (TIT 1,500°C, efficiency 59%)	World 1 st Steam Cooling Combustor, Developed MGA-1400 cast blades (DS)	1997
Development of M-501J/701J (TIT 1,600°C, efficiency 61.5%)	Efficiency Improvement (Extension of G-class technologies)	2011/14

Source: Author's elaboration from MHI (990, Akita 2001, Komori, Yamagami & Hara 2003, and Kimura & Kajiki 2008)

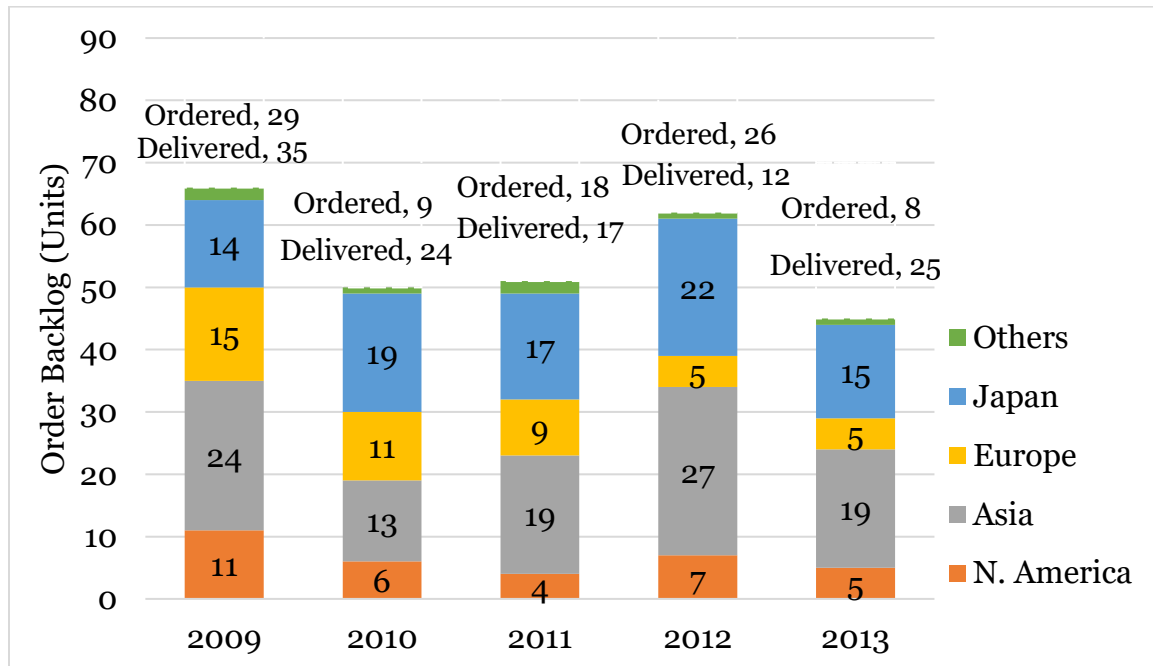
Note: TIT=Turbine Inlet Temperature, GT = Gas Turbine, DS = Directionally Solidified

Mitsubishi Heavy Industries' Performance in the Global Gas Turbine Market

With initial catch-ups of D class and F-class gas turbine technologies in the 1980s based on Westinghouse's designs, MHI became one of the three major suppliers in the global gas turbine market. While GE focuses on proven technologies such as those in the F-class, Siemens and MHI put more weight on larger scale gas turbines such as J class in the global market. According to recent market analysis, in the mid-2010s, MHI's share of the global gas turbine market in terms of gas turbine capacity is about 15%, while GE and

Siemens have shares of about 37% each (Korea EXIM Bank, 2014; Meritz Research, 2017) (Figure 5.8).

Figure 5.8 Mitsubishi Heavy Industries' Performance in the Global Gas Turbine Market



Source: Author's elaboration from Korea EXIM Bank, 2014

Although there had been a substantial gap between MHI and the two leading producers in the limited data available, this still illustrates some technical strengths and weaknesses of each OEM. Mitsubishi Heavy Industries appears to focus on larger and more efficient gas turbines while GE is more competitive in proven middle size gas turbines, such as F-class. In effect, more recent progress exposes that the division of labour comes from GE's failure in steam cooling CCGT technologies in the 2000s and the slow process of replacing the production lines with air cooling one put it behind Mitsubishi and Siemens in the latest and large CCGTs in the 2010s (see A4.2.2. in Appendix Chapter A for technical details of the steam cooling technology issue).

Despite the technology gap with the frontier OEMs, MHI's remarkable adaptation with the limited capability brought it to a leading position in the global CCGT market in terms of ordered capacity in 2018. It is the first time that MHI has taken a leading position

in the global CCGT market. In particular, its 41 per cent share compared to GE's 28 per cent and Siemens' 25 per cent in CCGTs category larger than 100MW in 2018's global market shows its competitiveness in the latest CCGTs, such as J-series and J Air-Cooled series. The direct reason for this change comes from the failure of GE's blades which broke out among its H Air-Cooling(HA) system CCGTs in 2017. The failure of blades caused shutdowns of at least 18 of 55 HA-systems in Japan, Taiwan, France and the US in 2018 and subsequent reduction of sales (Gülen, 2019; Scott, 2018, 2019).

Although GE only indicated that the cause of the blade failure is related to protective coatings of the blades without detail explanation, the blade failure occurred during the hasty transition process from its failed steam cooling technology to air cooling one (Scott, 2018). Given that GE spent an entire decade of the 2000s to fix problems of the unqualified steam cooling technology, it had to rapidly catch-up Mitsubishi and Siemens who applied the steam cooling to a quite limited area and replaced the steam cooling with air cooling much earlier, respectively. Whether the blade failure of GE HA-system is a random incident or an inevitable result of the hasty transition process, MHI's catching-up efforts with cautious technology application appear to have paid off. More details of the issue are analysed and discussed in Section A4.2.2 in Appendix Chapter A.

5.3.4. Specialised Metal Industry

Precision Casters for Gas Turbine Demand in Japan

The history of Japanese superalloy precision casters is rather short, due to the relatively late catch-up with the precision casting technologies from Western firms in the 1980s and 1990s. Most of the firms belong to *Keiretsu* families and maintain close relationships with their *Keiretsu* HEI firms, such as MHI or Jet-engine makers like IHI. Although precision casters have maintained a close relationship with HEI firms, more

than half of precision casting products in terms of turnover come from other sectors, such as automobile, machinery and aircraft weaponry.

Key component technologies in increasing gas TITs have been a material science (superalloy), process technology (precision casting), cooling technology and thermal barrier coating. Most Japanese superalloy precision casters are members of large and well-capitalised *Keiretsu*, such as the Ishikawajima-Harima Casting Company of IHI and MHI Precision Casting of MHI. Most of the precision casters were developed from the backward integration of jet-engine and gas turbine manufacturers. Ishikawajima-Harima Heavy Industries, a jet-engine and small gas turbine parts supplier, developed its blades and vanes under GE's licence. MHI Precision Casting has VIM and refining superalloys capabilities, as well as precision casting. In effect, MHI integrated superalloys in primary production of precision casting, jet-engine and gas turbine manufacturing capabilities from the 1980s (Tien, 1985).

Also, numerous Japanese leading iron and steelmakers, including Nippon Kokan, Kobe and Daido, had VIM capabilities, a crucial method for high-grade superalloy production and were able to forge superalloys from the 1980s onwards. Hitachi Metals are also in the superalloy business. Other Japanese firms established joint ventures with American superalloy firms, such as The International Nickel Company, the Cabot Corporation and the Howmet Corporation (Tien, 1985).

Nevertheless, the country's small air force defence and self-regulation on arms exports restricted the jet engine market from the post-war period onwards. Also, the Japanese superalloy makers had to import almost all superalloy ingots for turbine blades and vanes from the US due to licensing agreements with American firms and refusals to license the production alloys or even components. By comparison, the utility power plant market offered the Japanese HEI firms opportunities to continue to build technological capabilities in the gas turbine segment under American OEMs' licences (Stoloff, 1984; Tien, 1985).

MHI Precision Casting Co.

The MHI Precision Casting Co. specialises in precision casting and is engaged in the development, design, manufacture and sales of precision castings for gas turbines, aircrafts, automobiles, general machines, etc. in an integrated system. Initially, it was established as a Joint Venture between Mitsubishi Steel Manufacturing Co. Ltd. and an American firm, namely TRW Automotive Inc. in 1971. Although the two firms finished Joint Venture in 1975, their technology alliance lasted until 1986 and provided the latter a chance to improve precision casting technology capacity.¹¹⁸

It began to manufacture low pressure turbine (LPT) blades for jet engines under Pratt and Whitney(P&W)'s licence in 1985. Then, it expanded its technology scope to large precision cast blades for land-based gas turbines from the 1990s, such as production of prototype blades processed by directionally solidified (DS) and single-crystal (SC) technologies in 1991 and 1994, respectively. Although it could not commercialise SC blades, its active technology relationship with American specialist firms from TRW Automotive to P&W paved the way for MHI's flourishing catching-up performance in the global CCGT market. The precision cast division was separated from Mitsubishi Steel Manufacturing and established a Dia Precision Casting Co. as a 100% subsidiary of MHI in 1999 and then merged into MHI Precision Casting Co. in 2012 (Mitsubishi Hitachi Precision Casting, 2015).¹¹⁹

In addition, the network of various gas turbine and propulsion system manufacturing and research centres within MHI, including Takasago Machinery Works, Hiroshima Machinery Works, Nagasaki Shipyard, the Nagoya Aero Space System Works and Nagoya Guided Propulsion System, seems to offer the firm a unique advantage. The

¹¹⁸ Email interview with *Jungwoo Lee*, Deputy Director, Gas & Hydro Turbine Engineering Team, Doosan Heavy Industries & Construction, *Changwon*, on 23 January 2015

¹¹⁹ The firm changed to Mitsubishi Hitachi Precision Casting after the merger between MHI and Hitachi in the thermal power plant segment in 2014; Ibid.

firm also supplies its products to MHI's competitors such as KHI, Hitachi, Toshiba and Niigata Turbine.

Despite the rich technology networks, it seems that MHI's precision specialist firm has not yet overcome some crucial hurdles in commercialising the frontier process technology, namely SC. In developing the MF111 gas turbine in parallel with the Moonlight Project, precision casting technology was tested as a method to shape a hollow gas turbine blade with an inner coolant path, a crucial component for modern gas turbine blades. However, it was not much successful due to lack of experience with the complex shape of the inner coolant path (Akita, 2001). The hurdle in commercialising SC blades continues until the 2010s.

MHI Precision Casting's Gas Turbine Blade Catch-Up

As described in Section 5.3.3, MHI was able to shorten precision casting technology, ceramic moulds in particular, through the famous Moonlight Project in the late 1970s and 1980s (Kimura & Kajiki, 2008). In addition to the public R&D programme, MHI's precision casting subsidiary, Mitsubishi Superalloy, predecessor of MHI Precision Casting, benefitted from the long-term, stable relationship between MHI and Westinghouse in that the gas turbine technology transfer process also involved superalloy material specification, precision casting process specification, quality certification process and evaluation technology of reliability. Based on the technology transfer process and the Moonlight Project, MHI was able to commercialise its first CCGT, the 701D, for Tohoku Power in 1984 (Table 5.19).

Although catching-up with precision casting technology itself does not require its own materials and could employ imported superalloys, donor countries could constrain latecomers' future use of the materials through export control laws. Thereby, it is crucial for latecomers to develop their own superalloys, including patents of unique chemical compositions and alloy production technologies when catching-up with gas turbine

technology.¹²⁰ All of the superalloys that MHI used for the rotating blades of its gas turbines were imported from the US, such as U-520 and IN738LC, until the mid-1990.

Advanced gas turbines require heat-resistant materials as well as advanced cooling technologies. For the rotating blade material, MGA 1400 was developed through collaborative research between MHI, Mitsubishi Steel Mfg. and Mitsubishi Material Corp. MGA1400 is a nickel-based superalloy and can be used for DS casting. Compared to conventionally cast blades, the creep strength of the MGA1400 DS blade is 50 °C higher (Yoshioka et al., 2004) (Table 5.19).

Table 5.19 Gas Turbine Catch-up Trend of MHI in Precision Casting¹²¹

	Year Developed	Output (MW)	TIT (°C)	Efficiency of GT only (%)	Base Alloy	Process
501D/701D	1981/1984	114/144	1,154	31.5	U-520	Wrought
501F/701F	1989/1993	185/270	1,350	37.0/38.2	IN-738LC	Casting(CC)
501G/701G	1997	254/334	1,500	38.7/39.5	MGA-1400	Casting(DS)

Source: Yoshioka et al. 2004

Note 1: TIT= Turbine Inlet Temperature, CC = Conventional Cast, DS=Directionally Solidified

Note 2: Only 1st stage blades are considered in Base Alloy and Process columns. The bracket indicates first delivery of the product.

However, MHI has always lagged behind other global OEMs in the material application and casting technology, even from its first proprietary gas turbine in the 1980s. For example, when MHI developed its F series gas turbine in 1989, it applied conventional cast (CC) alloys while other OEMs applied DS alloys. This was repeated when MHI developed G series gas turbines in 1997. The company applied DS alloys when other OEMs applied SC alloys (Table 5.20). Even in its latest J-series, commercialised in 2011, MHI still applied DS. This was an unexpected approach in the international gas turbine

¹²⁰ E-mail interview with *Youngsoo Yu*, op. cit.: p. 220

¹²¹ Only 1st stage blades are considered in Base Alloy and Process columns. The bracket indicates first delivery of the product.

market. *Youngsoo Yu*, a senior researcher from Korea Institute of Material Science, suggests a technical-material mismatch issue as a reason:

We expected MHI would apply SC blades when it announced the development of the 1,600 °C class J-series gas turbine. Later, we learned that it still stuck to DS blades. MHI seems to have kept SC from application considering the risk of mismatch with the existing blade cooling and thermal barrier coating technologies.¹²²

Table 5.20 Materials of Gas Turbine Blades in the early 2000s' Japanese Market

		MHI	Siemens/Fuji	Alstom/KHI	GE/Toshiba
Model		701G2	V94.3A	GT26	9H System
Output (MW)	GT	334	266	265	-
	CC	489	392	401	480
Combustion Gas Temperature (°C)		1500 (TIT)	1400 Class 1230(ISO)	1400 Class 1250(ISO)	1427 (1 st Blade)
Pressure Ratio		21	17	32	23.2
Efficiency (% LHV)	GT	39.5	38.6	38.5	-
	CC	58.7	57.4	59.1	60
Coolant		Air(Steam)	Air	Air	Steam/Air
1 st Stage Blades		MGA1400(DS)	PWA1483(SC)	CMSX4 ^{mod} (SC)	ReneN5(SC)
1 st Stage Vanes		MGA 2400	Mar-M 509		

Source: Yoshida 2003: 894

Note: CC = Combined-Cycle, DS = Directionally Solidified, SC = Single-Crystal

Mitsubishi Heavy Industries' recent technology review of its demonstration stage gas turbine for 1,700 °C class implies another reason for its relatively slow catch-up performance in blade technology. It highlights the risk of casting defects during the casting process, which greatly lowers the strength of blades, as well as the high cost of rare metal, namely rhenium, as main problems of SC blades (Oguma et al., 2015). It is not clear, however, whether MHI had the capability in SC blades but avoided application, or

¹²² E-mail interview with *Youngsoo Yu*, op. cit. 220

if it did not have the capability to solve the mismatch issue. Also, the cost of the rare metal for SC blades does not explain its lagging performance in the 1980s and 1990s, when rhenium and SC blades were not commercialised on the global gas turbine market. Instead, the review reports that MHI and the National Institute for Materials Science successfully co-developed alternative SC blades without using the expensive rare metal and accompanying casting process technology without the risk of casting defects in 2015, as a part of a national R&D programme (Oguma et al., 2015). It is still too early to see the eventual results of the latest technological progress.

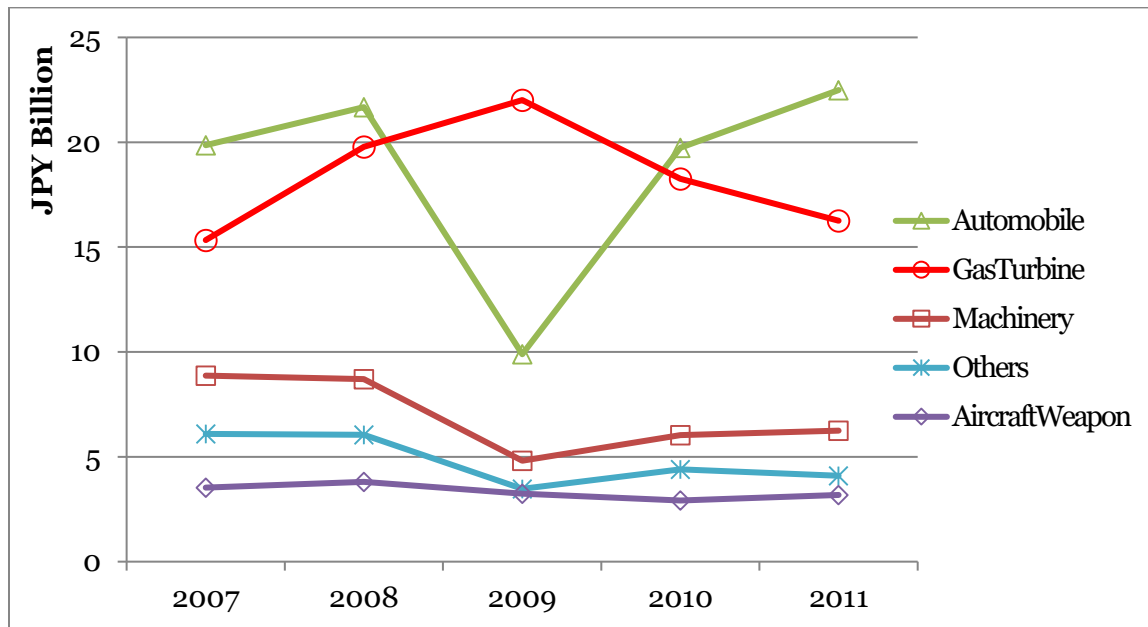
Ishikawajima Precision Casting Co.

The Ishikawajima Precision Casting Co. (ICC) of IHI is the most advanced precision caster for jet engines in Japan. Its parent firm, Ishikawajima-Harima Heavy Industries, has partnered with GE since 1951, from the beginning of the Japanese Air Force programme. The firm initially performed rapid delivery of prototype jet-engine blades, within six weeks, for instance, while GE's conventional process took nearly a year. It should be a clear advantage in developing new designs given that the engine developers need to confirm whether their new designs are 'castable' before they go further with the designs (see Section 2.3.2 for the castability issue). This experience led GE to enhance the technology relationship with IHI in further developing and producing jet engines (National Research Council, 1994).

Initially, IHI was allowed to cast only low-pressure turbine blades of equiaxed superalloy (multi-crystals) when it made the F100 Jet Engine licence agreement with GE in 1978. Although its licensed production of higher grade blades, namely DS, was refused at that time, it acquired the right in 1983. Together with this revised licence and the Japan Defence Agency's funding through its Technology Research and Development Institute, IHI made progress in the development of SC blade casting with partial success in manufacturing later (NRC, 1994).

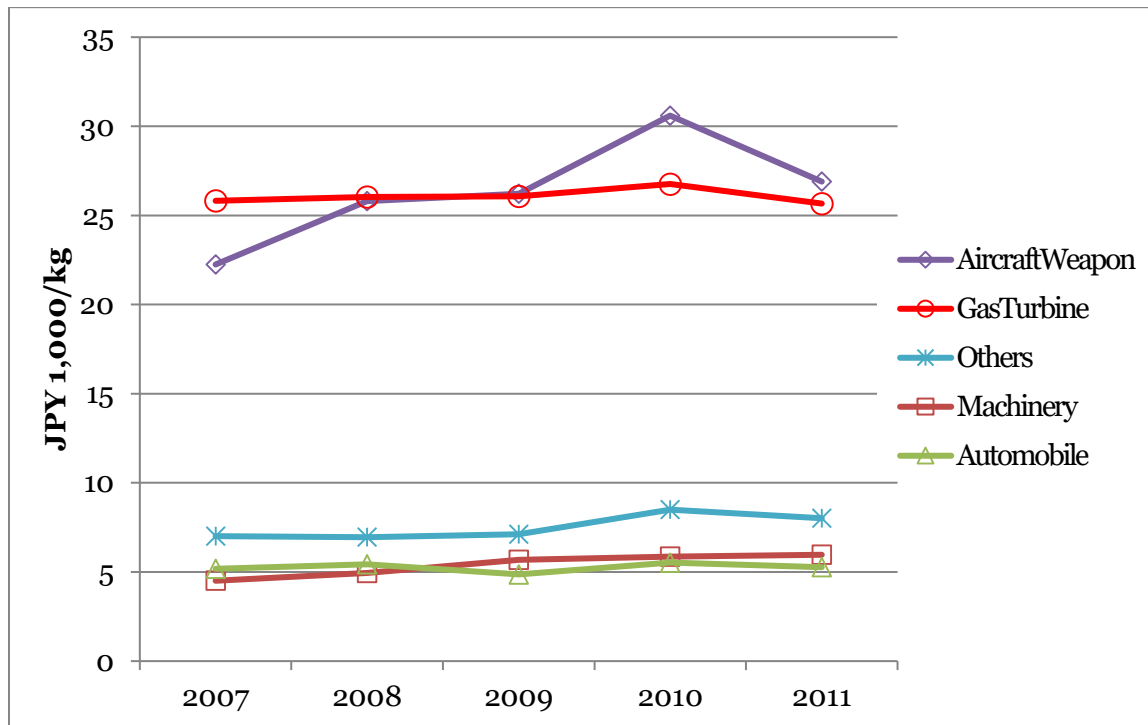
Nevertheless, IHI's progress has clear limits in two aspects. Despite the technical potential of IHI, it has little experience in the high-pressure turbine(HPT) blades which require the highest heat-resistant technologies (Nakagawa, 2004). Its entrance into the HPT market is not allowed by the international division of labour, either (see Appendix Chapter B). Second, the domestic jet-engine market has been too small for the Japanese precision casters to build-up technological capabilities (Stoloff, 1984; Tien, 1985). Although precision casting for jet engine and other weaponry is a high-value-added area as much as gas turbines, the market size has been minuscule compared to gas turbines and automobiles for the precision casters in Japan (Figure 5.9 and 5.10).

Figure 5.9 Turnover of Precision Casting Industry in Japan



Source: Author's elaboration from METI 2012, 'Yearbook of Iron & Steel, Non-ferrous Metals, and Fabricated Metals Statistics 2011'

Figure 5.10 Prices of Precision Casting Products per Weight in Japan



Source: Ibid.

Specialty Steel Industry for Nuclear Power Demand

Japanese specialty steel makers diversified as widely as global specialty steel markets, including electro galvanised steel sheets, high strength oil country tubular goods, automotive wire rods and bars and advanced stainless steels. Most specialty steel makers themselves have been part of member firms of large BOF steelmakers such as Nippon Steel, JFE Steel, Sumitomo Metal, Kobe Steel and Nisshin Steel (Tien, 1985).¹²³ Japanese specialty steel makers belong to traditional BOF steelmakers and constitute a special segment inside of this classification.

Amongst various types of specialty steels, Sumitomo Metal is one of the major producers of pipes and tubing for special purposes such as oil and gas fields, power plants

¹²³ Nippon Steel and Sumitomo Metal were merged into Nippon Steel & Sumitomo Metal Co.(NSSMC) in 2012

and chemical plants in Japan. Sumitomo Metal specialised in steam generator tube technologies for nuclear power and became a monopoly firm in the market segment in Japan. Starting from 'Sumitomo Copper Plant' in 1897, Sumitomo Metal has a long history in pipes and tubing, as described below:

- Sumitomo Metal's Steel Tube Works at Amagasaki Factory established in 1919;
- Began producing hot seamless pipes and tubes in 1921;
- Produced Japan's first stainless tubular products for nuclear power plants in 1956;
- Began exporting steam generator tubes for nuclear power plants in 1994;
- Increased production capacity for steam generator tubes for nuclear power plants in 2008.

Source: Sumitomo Metal Industries (2008)

In the 2007 fiscal year, Sumitomo Metal's Steel Tube Works performed JPY116 billion in sales in oil and natural gas development and exploration (43%), fossil fired power and nuclear power (32%) and chemical industry (25%) markets. Its share of the global market was around one-third of 1.8 thousand total tonnes in 2008. The high quality and reliability of Sumitomo Metal's Steel Tube Works are supported by its own patented original manufacturing process: 'High pressure drawing bench'. Its technical strength is in the precise size and shape of its tubes maintained through a high-pressure cold drawing method, while its international competitors, namely Sandvik from Sweden and Valinox from France, use a 'cold rolling' process (Sumitomo Metal Industries, 2008; Kusaka, 2013).

The main benefit of Sumitomo's steam generator tubes is the 'high detectability' of potential flaws resulting from the minimised background noise of the tube surface. This is a technological adaptation to the strict safety regulation of ESI, demanding the "no flaw" principle (see Section 5.2.5). During a periodic inspection of nuclear reactors, inspectors use a high-frequency electric test method, namely the eddy-current test, to detect flaws in steam generator tubes, such as cracks. If the background noise of the tube surface is not minimised during the manufacturing process, the tubes will produce more background noise above signals of potential defects during their periodic inspection. This

results in lower reliability of the inspection and longer inspection processes (Nippon Steel & Sumitomo Metal, 2013).

In this way, Sumitomo Metal's innovation is well adapted to Japanese nuclear safety regulations which require “no flaw” and “100% inspection” of steam generator tubes during periodic inspections. It reduces inspection time while improving the reliability of the inspection, while its competitors' tubes, which have more background noise, incur difficulties in effectively identifying potential defects in the tubes. Thanks to the innovative characteristics of the tubes, Sumitomo Metal's share in the current domestic markets is 100%, and one-third in the global SG tube market as of 2008 (Sami, 1994; Sumitomo, 2008: 27) (Table 5.21 and 5.22).

Table 5.21 Sumitomo Metal's Steam Generator Tube Supply Record (1969-2012)

Country	Tube Quantity (Tonne)	Steam Generator Units
US	4,941	64
Japan	2,879	54
Korea	1,507	18
China	888	13
Belgium	367	7
UAE	270	2
Total	10,852	158

Source: Nippon Steel & Sumitomo Metal 2013

Table 5.22 Performance of Global Steam Generator Tube Suppliers

	Production Capacity (km/year)	
	2008	2013
Valinox (France)	1,700 km	5,000km
Sumitomo/NSSMC (Japan)	1,500km	≈ 4,500km
Sandvik (Sweden)	1,200km	1,600km

Source: Author's elaboration from the interview with *Sunkyo Jung*, op.cit.: p.161 and Vallourec 2013

Stimulated by the rapid growth of global electricity demand and nuclear power construction projects, as well as growing concerns over climate change issues, Sumitomo Metals announced an ambitious plan in 2010 to nearly triple its steam generator tube production capacity in Amagasaki, Hyogo Prefecture, by 2013 (Sumitomo Metal Industries, 2010). Furthermore, it negotiated with Korean Nuclear Fuel Ltd. to establish a joint-venture firm for a new steam generator tube production based in Korea. The negotiation went to quite a detailed level, with Sumitomo gaining 30% share in the joint venture firm and production technology.¹²⁴

However, in the early 2010s, Sumitomo Metal had to contend with the Fukushima nuclear accident as well as an international dispute. The dispute was over the integrity issue of its tubes for MHI's eight RSGs to San Onofre Nuclear Generating Stations (SONGs), located in California. The operator of the SONGs, namely Southern California Edison, suffered from massive cracks and leaks in the replaced steam generators and sued MHI for faulty steam generators. Even further, the U.S. Nuclear Regulatory Commission undertook a field investigation of Sumitomo Metal's Amagasaki Steel Workshop for the steam generator tubes' cracking issue. According to investigation reports, the cause of the massive cracking originated from tube-to-tube frictions (US NRC, 2012).

Although the dispute was settled with minimum compensation by MHI in 2017, and Sumitomo Metal itself was not accused as a contributor to the cracking issue, it caused a serious reliability issue for Sumitomo Metal and MHI as the two SONG reactors had to be permanently shut down due to the cracking tubes. The dispute, together with sluggish global nuclear power demand in the late 2000s and the Fukushima nuclear accident in 2011, forced Sumitomo Metal to abandon its earlier plan to establish the JV firm in Korea. In particular, managers of the newly merged firm (NSSMC) between Nippon Steel and Sumitomo Metals in 2012 did not expect a prosperous future for nuclear power and scrapped the plan immediately after the replacement of previous managers. Despite its

¹²⁴ Interview with *Sunkyo Jeong*, op. cit.: p. 161

innovative tube technologies and subsequently excellent performances, Sumitomo Metal's steam generator tube segment seems to be overshadowed by the anti-nuclear atmosphere both in the domestic and global nuclear markets.¹²⁵

5.3.5. Public Research and Development Programmes of Nuclear Power and CCGT

Public Research and Development of Nuclear Power Technology Catch-Up

While catch-up efforts in commercial reactors were mostly undertaken by private HEI firms, which accumulated the technological capability through repetitive orders and with foreign technology assistance and public support, government R&D efforts have been focused on back-end nuclear fuel cycle technologies such as reprocessing and breeder reactors.¹²⁶ There has been a division of labour between the former Science and Technology Agency (STA) and the former MITI in spending on R&D expenditures across different energy technologies. While most of the nuclear R&D budget came from the STA, which contributed more than 90% of the total budget, the MITI focused on non-nuclear energy R&D, and its expenditures were much smaller than that of the STA in absolute terms (Table 5.23).

In detail, the MITI's nuclear R&D spending have focused on standardisation and safety improvement of commercial BWRs and PWRs from their 1st to 3rd phases (see page 209-215). As can be seen in Figure 5.11, total expenditures on commercial reactors between 1974 and 2011 were around US\$5.7 billion in 2013 prices. Considering technical cooperation programmes with foreign licensors, such as Westinghouse and GE, in public R&D, the public programmes included the technology transfer process in each phase of standardisation and improvement.

¹²⁵ Interview with *Sunkyo Jeong*, op. cit.: p. 161

¹²⁶ Although the thesis does not cover back-end cycle nuclear technologies *per se*, it is inevitable to address them when it comes with public nuclear energy R&D.

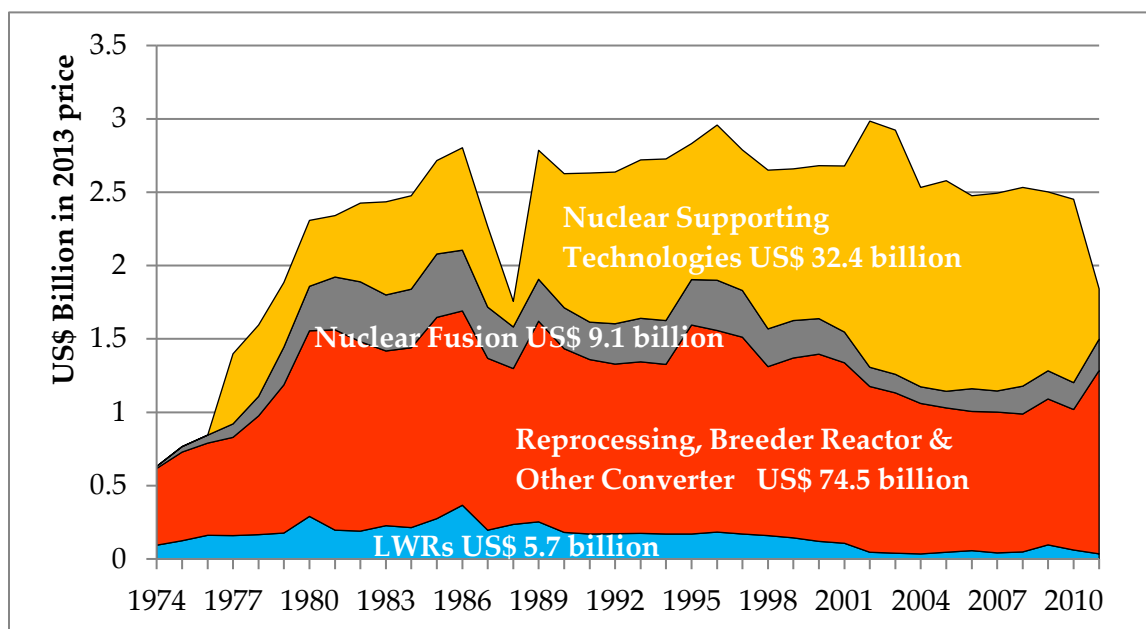
Table 5.23 The Japanese Government's Energy R&D Expenditures (¥ Billion in 1985 prices)

	Government's Total Energy R&D Spending		Total	The MITI's Contribution to Total Energy R&D Spending		Sub-total
	Nuclear	Non-nuclear		Nuclear	Non-nuclear	
1980	231.7	78.4	310.1	10.1 (4.4%)	71.2 (90.8%)	81.3
1985	280.5	91.1	371.6	25.4 (9.1%)	89.7 (98.4%)	115.1
1990	297.0	70.0	368.0	n/a		
1994	301.1	101.9	403.0	20.4 (6.8%)	92.2 (90.5%)	112.6
2000	309.0	128.0	436.0	n/a		

Source: Author's elaboration from Watanabe 2002 and IEA 2003

Note: (%) indicates the MITI's contribution to total government R&D expenditures in nuclear and non-nuclear energy technologies, respectively.

Figure 5.11 Japan's Public R&D Expenditures for Nuclear Power in 1974-2011



Source: Author's elaboration from IEA 2015

By comparison, public expenditures on 'new reactor' related R&D under the STA's supervision reached US\$74.5 billion during the same period. Despite the enormous public expenditure, all the development efforts for the new reactors, including breeder reactors

and other converter reactors, have failed to commercialise. Mitsubishi Heavy Industries, together with other Japanese HEI firms, was also involved in various government new reactor R&D programmes as a core member, including fast breeder reactors, advanced thermal reactors, high-temperature gas-cooled reactors and nuclear fusion reactors.

On a global scale comparison, Japan's public nuclear R&D spending accounts for more than one-third of the world's public spending. Even when fusion reactor R&D is excluded, Japan's nuclear R&D spending outpace that of the US, which is second, more than twice in the past four decades. It will take two more decades, however, to see whether the new reactors will be commercially viable.¹²⁷

Public Research and Development for Gas Turbine Catch-Up

Although the 'Sunshine' and the 'Moonlight' projects covered various non-oil alternative energy technologies besides gas turbine, it is worthwhile to examine the overall shape of non-nuclear public energy R&D in Japan. The MITI focused its efforts on securing an energy supply in the face of increasing oil prices in the 1970s. It initiated a new policy based on the 'Basic Principle of Industry Ecology' to increase energy security by means of R&D in new and clean energy technology. This policy led to the establishment in July 1974 of a new programme called the Sunshine Project (Watanabe, 2002).

The Sunshine Project initiated the approach of focusing on non-oil alternative energy technologies such as coal and solar energies. By comparison, the Moonlight Project was launched in 1978 to focus on energy conservation and efficiency technology. The Sunshine Project and the Moonlight Project represented 4.9% of the MITI's total R&D budget in 1974, 13.8% in 1979 and 28.9% in 1982, respectively (Watanabe, 2002).

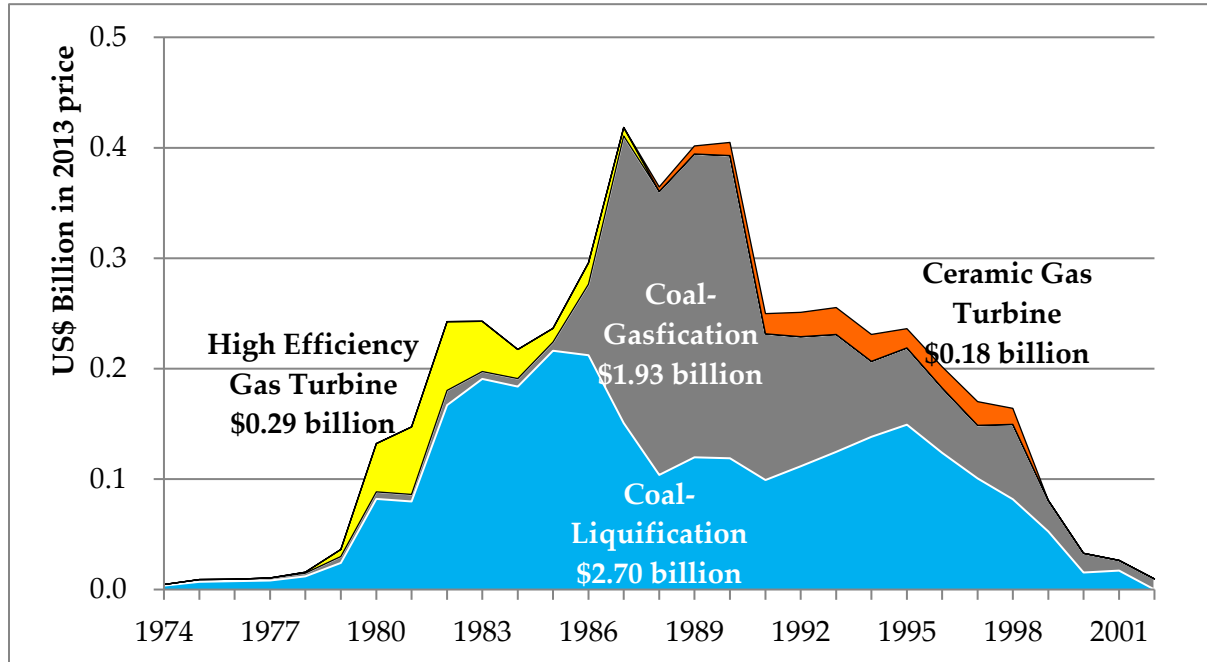
¹²⁷ Interview with *Suzuki Tatsujiro*, acting chair of Japan's Atomic Energy Commission, Tokyo, on 16 February 2011

In 1978 under the Moonlight Project, the famous High Efficient Gas Turbine Project invited not only gas turbine suppliers but also upstream suppliers, users, national material institutes and other aerospace institutes for development of gas turbines with an output power of 100MW and 55% efficiency. It invited four metal supply and fabricators and three ceramic suppliers. Although the original project target, 'Re-heat' gas turbine, was not commercialised at the end of the project, the participants gained tacit knowledge and experiences from the project, which was important resources in developing subsequent gas turbine products in the 1980s and 1990s (Kimura & Kajiki, 2008).

For instance, the each of five HEI firms could develop its own capability of component technologies such as blade cooling, superalloy and low-NO_x combustors based on generic technologies of the project, such as return-flow cooling technique, thermal barrier coating and directional solidification (Kimura & Kajiki, 2008). Gas turbines of MHI's F-class for utilities, Hitachi's 'H-25' for middle size class and KHI's 'M7A' for small-scale were based on experience gained through the project. Participants from public research institutes including the National Research Institute of Metals (NRIM) also continued superalloy development programmes and successfully extended these to develop DS and SC superalloys for gas turbine blade applications in the 1980s (Kobayashi, 1990).

However, the Sunshine and Moonlight projects did not necessarily lead to fruitful results in numerous technology cases. Even though the government spent nearly 10 and 7 times the high-efficiency gas turbine project budget for coal liquefaction and coal gasification, respectively, Japan could not commercialise the two coal-based technologies through the projects (Kimura et al., 2007). Although MHI is reported to have succeeded in its demonstration of the Integrated Coal Gasification Combined-Cycle plant using the coal gasification technology from 2007 to 2012, it is still too early to judge from its five years of demonstration experience whether it will be commercially successful (Isles, 2012) (Figure 5.12).

Figure 5.12 Public R&D Expenditure for Fossil Fuel Technologies



Source: Author's elaboration from Kimura et al. 2007

Note: The figure includes 'Sunshine', 'Moonlight' and 'New Sunshine' projects

Furthermore, even the successful high-efficiency gas turbine project has serious limitations in explaining its relative contribution to Japanese gas turbine development on several points. It is not clear whether MHI's success in commercial CCGT technology was the result of the project or of its own in-house efforts based on modification of licensed technology. First, the world's first DLNC, which symbolises MHI's catching-up to Western gas turbines, was a result of re-combining MHI's own technology based on its previous lean premix combustion technology for conventional fossil power plants in the early 1970s (Angello & Lowe, 1989; Matsuzaki et al., 1992). Second, even the biggest benefit of the project for MHI, namely the ceramic mould for precision casting of blades, was a 'time-saver' that reduced a couple of years for commercialisation rather than a 'breakthrough' type of innovation. Third, even national institutes that hosted the project did not have the necessary infrastructure, such as a test-bed plant, for verification of the

developed gas turbine, and had to depend on MHI's own facilities (Kimura & Kajiki, 2008).¹²⁸

In this sense, the public R&D programme for catch-up in large gas turbine technologies played only a supplementary role for MHI, which was already on its gas turbine commercialisation trajectory. Rather, the programme gave less-developed participants, such as Toshiba, a chance to improve their own combustor technologies and to reduce the large gap between them and the forerunner, namely MHI. It matches with Porter(1990)'s critical argument about the role of public R&D programmes and actual motivation of the participants (see page 21 for further discussion on the public R&D issue).

Limits of Public Research and Development on Superalloy Technologies

Japanese HEI and supporting firms could not have direct access to foreign superalloy production and precision casting technologies until the 1980s mainly due to US government's strict technology control policy (Tien, 1985). HEI firms had to import superalloys for precision casting of blades and vanes even when MHI developed its own CCGTs, namely the 501D/701D and the 501F/701F. Instead, public and private R&D activities, including the Moonlight Project and subsequent *Jisedai*¹²⁹ Project, dominated technological efforts of the precision casting industry in the 1970s and 80s. The former MITI, through its Agency of Industrial Science and Technology, sponsored two-stage superalloy technology public R&D programmes with the intention of supporting gas turbine and jet-engine technology development in the late 1970s and early 1980s. The first was a sub-project of the Moonlight Project, the high-efficiency gas turbine project. This project was intended to develop CC and DS superalloy materials under the leadership of

¹²⁸ MHI developed gas turbine technologies further after the Moonlight Project such as M501J with support of public R&D in the 2000s. For details see Ito et al. 2010

¹²⁹ *Jisedai* means "the next generation" in English

the NRIM. As a result of the project, the NRIM proposed several candidate alloys for the gas turbine.¹³⁰

The second superalloy public R&D programme for gas turbine, “Advanced Alloys with Controlled Crystalline Structures”, *Jisedai* Project in short, in 1981-1989 supported new materials R&D, including fine ceramics, high-efficiency separation membranes, high grade alloys under crystal growth control and composite materials. In particular, development of SC superalloy for advanced gas turbine blades and thermal barrier coatings was the main target of the subproject (Yamazaki, 1986; Yamagata et al., 1987). The project was intended by MITI to shift its policy of industrial science and technology from ‘follower mode’ to ‘pioneer mode’ (Tanaka, 1989). However, the development of SC alloy was not fruitful at the end of the sub-project.

The public development efforts for the SC superalloys for gas turbines were continued in the 2000s in the name of “High Temperature Materials 21” from 1999 to 2008 (Harada, 2010). Although the joint development programme between MHI and National Institute for Materials Science, the successor of NRIM, developed SC superalloy for gas turbine blades, namely MGA1700, it still did not reach to a commercial stage. A recent technology report of MHI acknowledges the new SC material still needs a thermal fatigue evaluation to guarantee a long-term reliability before commercialisation (Ishizaka et al., 2017). The initial target schedule of commercialisation was about 2015, but it implies it would be beyond 2020 (Harada, 2010; Ishizaka et al., 2017). Thus, the four decades’ public and private joint development efforts for commercial SC gas turbine blades still need more time for the result.

¹³⁰ Interview with Youngsoo Yu, op. cit.: p. 220

5.4. Sectoral Institutions of ESI and Catching-up Performances

5.4.1. Sectoral Institutions of ESI and Nuclear Power Catching-up

Strong Business Autonomy of Japanese ESI and Effects on Nuclear Power

Strong business autonomy of the Japanese ESI shaped unfavourable market conditions for the Japanese HEI's nuclear power catching-up efforts. The autonomous fuel choice and pricing scheme by the ESI restricted demand growth of major electricity-intensive industries. Despite Japanese government's support for major BMIs, the ESI's arm's length relationship with the BMIs and the world highest electricity price effectively restricted base-load demand growth of the electricity market, which is crucial to the new nuclear power project.

Also, the strong autonomy of the ESI disabled government's effective control over financial and organisational mobilisation in the nuclear export drive for the past decade. Although Japan established an HEI/ESI nuclear export consortium, namely JINED, in response to the Korean nuclear export case, the consortium could not enforce the private ESI firms to invest in the risky nuclear export projects. The autonomy of the Japanese ESI has been a significant handicap to the Japanese HEI in the increasingly squeezed global nuclear market, where a substantial up-front capital and organisational investment is crucial for a successful nuclear export deal.

Strict Safety Regulation of Japanese ESI and Effects on Nuclear Power

As can be seen in Section 5.2.5, the "no flaw" safety regulations on steam generator tubes have restricted operating performance of the Japanese nuclear fleets since the 1970s. Despite early reactor indigenisation in the 1970s and subsequent safety upgrade programmes, the strict regulations effectively have lowered the operating performance of the Japanese and left negative track records of the Japanese in the global nuclear market. Although a few specialised metal industry, such as Sumitomo Metal Tube Works,

developed high-quality steam generator tube technologies in adapting to the strict safety regulations and has exhibited competitive performance in the global steam generator tube market, it did not improve overall domestic nuclear fleets' operating performances except a few years in the 2000s.

In sum, combined effects of the two core regulations on the Japanese ESI effectively restricted the overall performance of Japanese nuclear power, superseding advanced capability of the upstream supplier and government's strong commitment to nuclear power. Thus, the government's nuclear power support policy had to be readjusted to a much smaller capacity target than its previous targets in every long-term energy supply plan. The ambitious government plans to promote nuclear power and delay or cancellation of actual construction projects repeated until the 2010s (Table 5.24). The initial safety regulations were enhanced by the newly established Nuclear Regulation Authority, furthermore. They put the Japanese nuclear reactors in a more difficult position with less operating reactor units, only nine reactors in 2018 (see Section 5.2.5). The effects of stringent safety regulations have resulted in unsatisfactory nuclear catching-up performances of the Japanese HEI.

Table 5.24 Ambitious Nuclear Expansion Plans of Government and Reality

Released Year		Government Targets	Actual Performance
AEC	1972	32GW by 1980	15.5 GW in 1980
MITI	1980	51~53 GW by 1990	31.5 GW in 1990
MITI	1998	66~70 GW by 2010 (480TWh, 45%) ¹³¹	48.9GW in 2010 (288TWh, 26%)
METI	2001	58.4GW by 2010 (416TWh)	
METI (3 rd Basic Energy Plan)	2010	about 68GW by 2030 (14 or more new units)	9 out of 54 reactors are operating and virtually no new nuclear reactor under construction or planned as of 2018
METI (4 th Basic Energy Plan)	2015	20~22% of total power supply by 2030	
METI (5 th Basic Energy Plan)	2018		

Source: MHI 1990, IEA 2000, Pickett 2002, METI, 2003, 2010, 2015, 2018

5.4.2. Sectoral Institutions of ESI and Gas Turbine Catching-up

Strong Business Autonomy of Japanese ESI and Effects on Gas Turbine

Strong business autonomy of Japanese ESI, established in the post-war period, led the industry independent decision making of technology and fuel choices in response to socio-economic changes in the 1970s. Facing rising oil prices and the *Yokkaichi* verdict, the Japanese ESI voluntarily developed a natural gas field in Indonesia and introduced the world first liquified natural gas(LNG) fired power plants from the early 1970s. While the Japanese government encouraged fuel diversification from oil to nuclear and coal, the gas fuel was the ESI's own choice (see Section 5.2.4).

¹³¹ The bracketed indicates planned nuclear power generation and its share in utilities' electric market. AEC stands for Atomic Energy Commission and MITI stands for Ministry of Trade & Industry.

The voluntary fuel choice of the Japanese ESI in the early 1970s was overlapped with gas fuel ban for power plants of the US and European countries between the 1970s and mid-80s. This institutional asymmetry between Japan and Western economies not only invited the troubled foreign OEM, namely Westinghouse, but also offered an early home market environment for the Japanese HEI. Although a large scale modern CCGT was not yet born in the 1970s' global market, technology transfer from Westinghouse in small scale gas turbines and markets for gas boilers power plants offered a crucial ecosystem to the Japanese HEI.

Strict Emission Controls and Co-development of Low-NOx Combustors

Strict emission regulations of the ESI led the HEI to develop NOx emission control technologies for gas boilers power plants in the early 1970s and eventually contributed to MHI's gas turbine catching-up performance in the 1980s.¹³² Later, the premixed combustion technology was modified and applied to MHI's first CCGT, namely MW-701D, for Tohoku Power in 1984.¹³³ The commercialisation of the world-first dry low-NOx combustor (DLNC) for CCGT was a new combination of a pilot diffusion flame and a lean premix flame concept with air staging which MHI already developed for gas boiler with a steam turbine from the 1970s (Angello & Lowe, 1989; Matsuzaki et al., 1992).

The achievement in the combustion technology supported MHI's gas turbine catching-up performances in two ways. First, the world-first dry combustor outperformed the global OEMs including MHI's own licenser in the 1980s. It not only made MHI independent but also highlighted MHI's entrance into the global gas turbine market. Second, the performance of the combustor technology has compensated MHI's relative

¹³² Although desulfurization technologies had been improved from the 1960s, it is not discussed in this research since it had been mostly relevant to high sulphur fuels such as coal and heavy oil rather than gas turbine.

¹³³ Also, it should be noted that several NOx emission abatement technologies such as selective catalytic reduction (SCR), developed and applied in Japan in the 1970s, were globally diffused in the 1980s.

weakness in gas turbine blade precision casting technologies. Given that the combustor technology has been crucial in meeting the strict NO_x emission standards while increasing the turbine inlet temperature and subsequently larger and more efficient gas turbines in the global market, MHI's lagged performance in the blade precision technologies has been compensated by the combustor technology. MHI's performance in the large CCGTs in the global market, such as its world-first J-class CCGT (1,600°C) in 2012, would not be possible without the low-NO_x combustor technology (Hada et al., 2012) (see Section 5.3.4 and 5.3.5).

5.4.3. Effects of Post-Fukushima Institutional Changes

Given that the Fukushima accident is a significant event and its ramifications to the Japanese ESI and HEI have been substantial, the effects of institutional change need to be analysed in this Subsection. Responding to the Fukushima nuclear accident in March 2011, the Japanese government changed the economic and safety regulations on the Japanese ESI. The immediate post-Fukushima government action was the suspension of 54 operable reactors in Japan for safety concerns, and the newly established nuclear safety regulator ordered the Japanese utilities to do safety checks and enhance safety measure as a requirement of the restart. Although 15 out of the 25 applied reactors were permitted to restart after several years of the safety review process, only nine reactors restarted operation by 2018 (JAIF 2019). Other reactors do not appear to have the prospect of the restart soon. In conjunction with the new safety regulation and subsequent supply shortage, the accident induced a substantial change in the Japanese electricity market.¹³⁴

¹³⁴ Under the power supply shortage, Japanese public went into a drastic electricity conservation programmes including limited usage of air-conditioners in the notoriously hot and humid Japanese summer season for several years. This ignited a full-scale liberalisation of the Japanese electricity market to boost power supply in a cost-effective way and to allow new entrants.

Previously, the Japanese ESI had enjoyed strong autonomy in the regional private monopoly systems and had been reluctant to the electricity market liberalisation programme. The previous market reform only opened a large industrial customer market in the 1990s and had been virtually stalled since. The accident, however, reignited the reform process to the full-scale including the huge retail electricity market of about 82 million customers. The electricity market reform subsequently had regulatory effects on the power plant bidding process. In September 2011, Japan's Ministry of Economy, Trade and Industry (METI) publicly instructed the Japanese electric power utilities to hold competitive bids including new entrants when the utilities build fossil power plants to boost electricity supply and to reduce the overall cost (Goto & Sueyoshi, 2016; Goto & Takahashi, 2017).

Accordingly, the Japanese ESI's strong autonomy and its tacit barriers to the foreign HEI firms in their power plant bidding processes were changed. The post-Fukushima regulatory change forced the ESI to open the bidding process and allow more foreign HEI firms. Okinawa Power awarded Siemens the contract of its *Yoshinoura* CCGT project while Chubu Power awarded GE/Toshiba the contract of *Nishinagoya* CCGT project discarding MHI's bid in 2012, for instance. The new regulatory environment induced the Japanese HEI to consolidate their business. The merger between MHI Power System and Hitachi Power System in 2014 was the biggest action taken by the Japanese HEI, and the new Mitsubishi-Hitachi Power System (MHPS) consolidated gas turbine, boiler and fuel cell businesses from the two firms (Japan Times, 2012).

The two HEI firms' merger was not only for defending the domestic CCGT market but also for consolidating of each one's global market network against foreign competitors such as GE and Siemens. The merger also has implications of the strategic division of labour between the two firms in the changing global electricity market where renewables are rapidly growing. MHI acquired Pratt & Whitney(P&W)'s Power Systems, P&W's jet engine-derivative small gas turbine division for a land-based gas turbine market

segement, in 2013. The acquisition offered MHI a new capability in small and rapid load-following gas turbines, which are increasingly valued in electricity grids as intermittent renewables increase globally.

On the other hand, Hitachi announced its acquisition of ABB Power Grid, which installed half of the global high voltage direct current (HVDC) transmission systems, at the end of 2018 right after it implied the suspension of the Wylfa nuclear project in the UK.¹³⁵ Hitachi, in effect, has been consistently stating that it aims at “smart-grid” business as a strategic sector since the merger discussion with MHI in 2011. It considers smart-grid is the fastest growing sector in the global electricity market, and the acquisition of ABB’s transmission business makes sense in this regard (Proctor, 2018).

However, the merger excluded nuclear business due to already established complex alliance networks in the global market. MHI had AREVA as a partner for the Sinop nuclear project in Turkey while Hitachi partnered with GE for the Wylfa nuclear project in the UK in 2012. Nevertheless, all the nuclear export projects that the Japanese HEI planned were cancelled or suspended indefinitely at the end of the 2010s (see page 216-219).

5.5. Chapter Conclusion

This Chapter presenting the Japanese case reveals that the deeply entrenched institutions of ESI, including autonomous business and strict environmental regulations, effectively constrained the performances of nuclear while it incentivised gas turbines in Japan. Despite the early nuclear reactor indigenisation, the safety regulations of the Japanese ESI continuously obstructed the HEI’s performances. Although the explicit R&D efforts to adapt to the strict safety regulations resulted in globally competitive high-

¹³⁵ HVDC is considered as an alternative grid system to incumbent alternating current (AC) transmission systems in accommodating rapidly growing intermittent renewables.

quality component technologies, the catching-up performance of nuclear power could not overcome the overall institutional constraints of Japanese ESI. The strict and lengthy periodic safety inspection constrained operating performance of Japanese reactor fleets mostly below 80% of capacity factor for the past four decades except a few years in the 2000s, while strong business autonomy of the Japanese ESI constrained growth of BMIs and base-load electricity demand, which is a crucial factor for new constructions of nuclear reactors.

By comparison, even though MHI and its subsidiary precision caster have lagged behind the rest of the global gas turbine OEMs in precision casting technologies, MHI's adaptation to the strict emission standards of the Japanese ESI from the early 1970s resulted in remarkable catching-up performances. MHI's world-first commercial DLNC technology in 1984 symbolises the adaptation process and still plays an important role as a backbone of the firm's competitiveness, compensating its relative weakness in the precision casting technology, in the global gas turbine market.

Also, this Chapter reveals that neither technological capabilities of HEI firms nor sectoral perspective on HEI explain the contrasting catching-up performances of the Japanese HEI in nuclear power and gas turbine technologies. Various public R&D programmes also show opposite pictures in terms of expenditure and resulting performances. Without attention to the institutional context of ESI, firm capabilities, HEI's own sectoral elements and public R&D programmes may lead to misinterpretation of the contrasting catching-up performances of Japanese nuclear power and gas turbine.

Table 5.25 Institutional Framework of Japanese ESI and Technological Effects

	Economic Events & Impacts	Environmental Events & Impacts
Institutional Environment	Privatisation of National ESI by Allied Power (1950)	Verdict on 'Yokkaichi Asthma' & Mihama Reactor Coolant Leak (1972)
Institutional Governance	Secured Business Autonomy in Fuel Choice & Pricing	Strengthened Emission & Safety Regulations
	Voluntary introduction of the world first LNG Power Plants Arm's Length Relation with BMIs (World Highest Price)	World strictest NOx Standards on Fossil Power Plants "No Flaw Principle" on Nuclear Safety Regulation
Technological Impacts	Prepared for Gas Turbine Technology Transfer from the American OEM, Arm's Length Relationship with BMIs Constrained Nuclear	Induced development of advanced Low-NOx combustion technologies, Constrained nuclear despite Massive R&Ds

Source: Adapted from Williamson 2000

Chapter 6. Comparison of Cases and Discussion

6.1. Chapter Introduction

This Chapter compares the two cases and elaborates generalisable findings based on pattern matching between the user sector institution approach and its rival approaches. Section 6.2 compares the two country cases based on the institutional set of ESI. The core regulations of the ESI sector in the two countries demonstrate sharp contrasts. From business regulations on electricity pricing practices and natural gas fuel transactions to environmental and safety regulations on fossil and nuclear power plants, the two countries' institutional sets of ESI sector display a clear dichotomy. Then, the Section compares the effects of the ESI institutions on the catching-up performances.

Section 6.3 compares the rival explanations with the ESI institution approach. It finds that the institutional set of ESI played a major role in each catching-up case – either supporting or constraining each technology case – regardless of specific technology public R&D programmes or relative technological capabilities of HEI and upstream supplier firms. Also, it analyses a compatibility issue between the domestic institutional set of ESI and a global window of opportunity for technology transfer from advanced foreign HEI OEMs. It finds that successful technology transfers were associated with the fitness of the institutional set of ESI to a global opportunity, whereas the mismatch frustrated catching-up performance.

6.2. Institutions of ESI and Overall Effects on Catching-Up

6.2.1. Direct Effects of Business Regulations

Concerning the business practices of the ESI, the high degree of business autonomy of the Japanese ESI allowed the utilities to charge the world's highest electricity prices and drove commodity metal industries either to exit the domestic market or to restructure their production capacity. On the other hand, this business autonomy allowed the Japanese ESI to lead overseas development of the natural gas field and LNG import contracts, which ultimately made the price of gas fuel for power generation more affordable in Japan compared to its Korean counterpart.¹³⁶

By comparison, the opposite occurred in the case of Korea. Tight government control of ESI business set the lowest level of electricity price in the OECD countries and paved the way for commodity metal industries in Korea. Moreover, from the early 1980s, the government's cross-subsidy arrangement from the ESI to the city gas sector – aimed at accelerating the gasification of the country's household heating system – resulted in an additional cost burden of natural gas for power generation, which eventually made gas turbines economically infeasible, other than as a peak-load operation in the Korean electricity market. This condition discouraged user-producer cooperation on gas turbine catching-up.

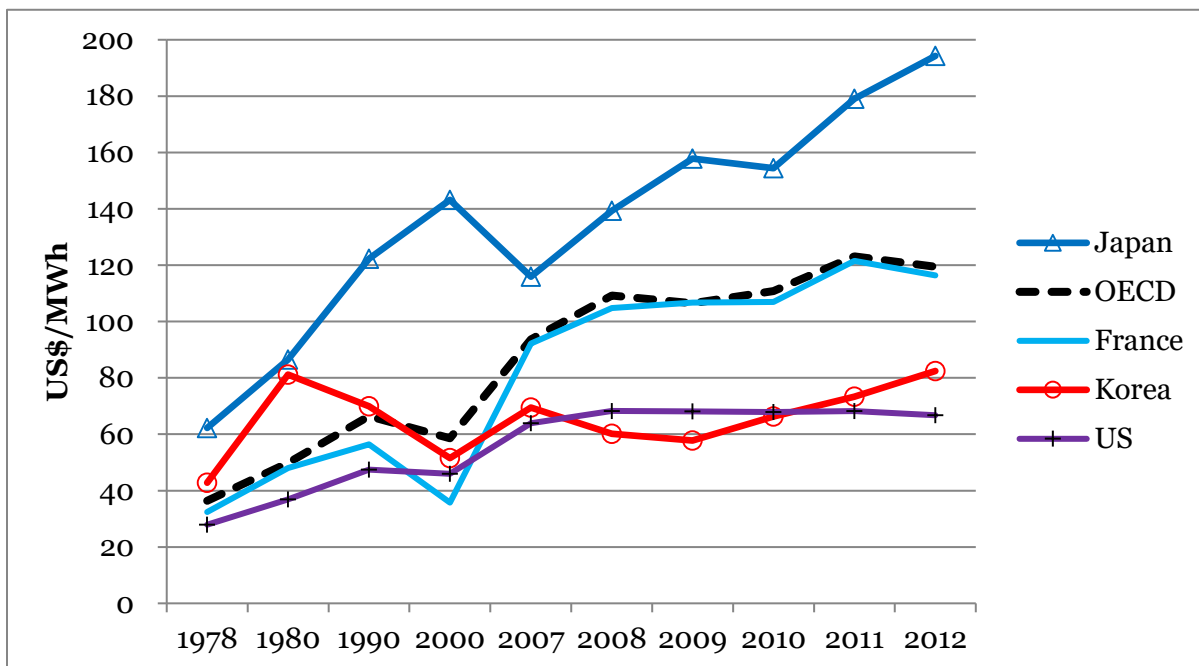
As we have seen in the Case Chapters, the two countries have contrasting electricity pricing institutions. In the post-war era, Japan's short-lived Public Utility Commission set up the world's highest electricity rates, and the pricing practices have lasted for half a century, despite the fact that the former MITI dissolved the Commission and tried to control electricity prices (see page 177 and 180). The Korean government, by

¹³⁶ Although it does not mean gas power price has been cheaper than coal or nuclear power in Japanese power market, it made gas power relatively affordable and competitive in terms of price.

contrast, has tightly controlled the prices since the 1980s (see page 99-103 and Section 4.2.4).

These contrasting institutions resulted in the Japanese ESI having the highest electricity prices, and its Korean counterpart the lowest amongst OECD countries in terms of the average price.¹³⁷ For example, the average electricity price for industry customers was US\$154.4/MWh in Japan, while in Korea it was US\$66.3/MWh, which represent the highest and the lowest figures, respectively, in the 2010 statistics relating to the 33 OECD countries. In the 2000s, only a few countries had prices comparable to those of Korea – the US or Norway, for example, which have abundant coal and natural gas resources, and cheap hydropower, respectively (Figure 6.1).

Figure 6.1 Average Electricity Prices for Industry in Japan and Korea



Source: Author's elaboration from IEA *Electricity Information* 2001, 2008 & 2014

¹³⁷ Price hikes of the Japanese case between 1980 and 2000 reflect appreciation of Japanese Yen to US Dollars in 1985 as result of a trade agreement, namely "Plaza Accord", between Japan and the US, which was reversed in 1995. Even without the currency exchange rate issue, however, Japanese electricity price has been the highest in the world since the post-war period.

With regard to electricity prices for industry customers, in particular, the Korean ESI's excessive practice of TOU pricing widened the gap between the two countries. For example, its off-peak price during night hours is even cheaper than the nuclear power generation price and has caused huge revenue losses for the utility of approximately US\$2 billion a year, while its peak price has been set up above that of gas turbine. Japanese utilities, by contrast, have not practised such an excessive TOU pricing scheme, and the liberalisation of the wholesale electricity market in 1998 made such a step more difficult to put into effect. Given the liberalised wholesale electricity market, industry customers who cannot or do not have to cherry-pick cheap off-peak electricity in aggressive TOU pricing schemes would switch their supplier for more reasonable pricing schemes.¹³⁸

It is not surprising that EAF steels have been the largest beneficiary of the price scheme in Korea, while their Japanese counterparts have been handicapped by off-peak prices that are not much different from peak prices, as well as the average world highest electric prices. In turn, the contrasting BMI growth patterns provided contrasting preconditions for a large new capacity of base-load power plants – nuclear power in particular – in the electricity market in the two countries. The relationship between the electricity pricing scheme and demand for new nuclear power capacity was more pronounced in the Korean case (see Section 4.2.4)

Table 6.1 presents the differences between peak and off-peak prices in terms of the TOU pricing scheme in the two countries. The Korean ESI displays a much greater price differential than its Japanese counterpart. Section 4.2.4 highlights that such a low off-peak price – which is even cheaper than the nuclear power generation price – originates from government intervention rather than reflecting the actual power generation cost during off-peak hours. Although price differentials decreased from 1999 to 2010 in both countries, the Korean ESI still applies excessive TOU pricing.

¹³⁸ Email interview with *Osamu Kimura*, Research Economist, Socioeconomic Research Center, Central Research Institute of Electric Power Industry, on 8 April 2015

It should be noted that monthly fixed capacity charges are added to the TOU prices. For instance, Tokyo Power charged JPY1,480/kW (\$13/kW in nominal price) while KEPCO charged KRW4,560/kW (\$3.8/kW in nominal price) for a capacity charge, respectively, to the customers in 1999 in Table 6.1. The minuscule capacity charge of KEPCO hardly affects overall TOU prices. If these charges are added, thereby, the off-peak price differential between Tokyo Power and KEPCO becomes even larger than the figures in Table 6.1.

Table 6.1 Typical TOU Pricing for Industry in Japan and Korea (US\$/MWh)

Japan (Tokyo Power)					Korea (KEPCO)			
	Nuclear price	Off-Peak(a)	Peak (b)	Ratio (a/b)	Nuclear price	Off-Peak(a)	Peak (b)	Ratio (a/b)
1999	44.0	49.2	119.0	2.4	30.7	23.7	94.1	4.0
2010	63.8	98.7	154.3	1.6	35.8	36.2	127.1	3.4

Source: TEPCO 1999, 2010, KEPCO 2010, Korea Power Exchange's Statistics System

Note 1: Tokyo Power's TOU prices are based on "Special High Voltage B (140kV) Customer Group" while that of KEPCO is based on "Industrial High Voltage B-Selection II Group(154kV)" during the summer season.

Note 2: The KEPCO's figures in 1999, including prices of nuclear power generation and TOU, are substituted by figures in 2001 due to unavailability of official nuclear generation price in 1999.

At a glance, the aggressive TOU pricing practice in Korea seems to work for more CCGT power generation during the off-peak hours at nights. However, the large gap between the off-peak price – even cheaper than the nuclear power generation unit price – and the actual fuel mix cost, including the massive operation of 'expensive' CCGTs, paved the way for new nuclear power projects in the 2000s. The induced demand from electricity-intensive industries, such as EAF steel, and subsequent huge revenue losses during the off-peak hours justified the logic for new nuclear power projects, such as

“Baseload power generators are in absolute shortage” in government’s electric supply plans for the past two decades (Lee 2012; Lee et al. 2013).¹³⁹

Amongst the various industry customers, EAF steel has been the biggest beneficiary of the ‘wrong’ TOU price for the past three decades, in that it relies entirely on electricity for its production energy sources, and can easily control electric furnace load, including start and stop during a day. EAF steel is one of a few industries that could exploit the cheaper off-peak electricity late at night, and promptly reduce their load, or even shut down their facilities during peak hours when the electricity price more than triples, which most other industries cannot do. Even BOF or “integrated mill” steelmakers cannot control their production load once it starts its blast furnace.¹⁴⁰

Impact of Contrasting Regulations on Natural Gas Fuel Contract

Japanese ESI firms have led the development of overseas natural gas fields since the 1970s and enjoyed high degree of freedom in international trade of natural gas while Korean counterpart has been shackled by a compulsory supply contract with a state-owned monopoly natural gas supplier, namely Korea Gas Corporation (KOGAS), for cross-subsidy to the city gas sector. Moreover, public concerns on environmental issues have encouraged the Japanese ESI to actively develop and import LNG from abroad. By contrast, Korea’s compulsory LNG contract with KOGAS resulted from the cross-subsidy policy to reduce the cost burden of city gas customers (Table 6.2).

Subsequently, Japanese ESI enjoyed a much cheaper LNG price than the other two domestic customers, including industry and household did, while Korean ESI had to pay an additional price for the cross-subsidy to the city gas sector. In turn, the relative price

¹³⁹ Government’s electricity supply plans such as “The Basic Plan on Electricity Demand & Supply” or its previous version “The Plan on Long-Term Electricity Demand & Supply”, are made every other year in Korea.

¹⁴⁰ Instead, it can use its own self-power generator, mostly gas turbine, using by-product gas from the blast furnace.

difference of LNG resulted in major differences in the economic performance of the CCGTs, in terms of new construction projects and power generation in the two countries from the 1980s.

Table 6.2 Two Countries' Initial Natural Gas Import Contract with Indonesia

	First Contract	Contractors	Second Contract	Contractors
Japan	1977	Kansai Power, Chubu Power, Tokyo Gas, Nippon Steel	1981	Tohoku Power, Tokyo Power
Korea	1983	Korea Electric Power Company (transferred to KOGAS in 1984)	1991	KOGAS

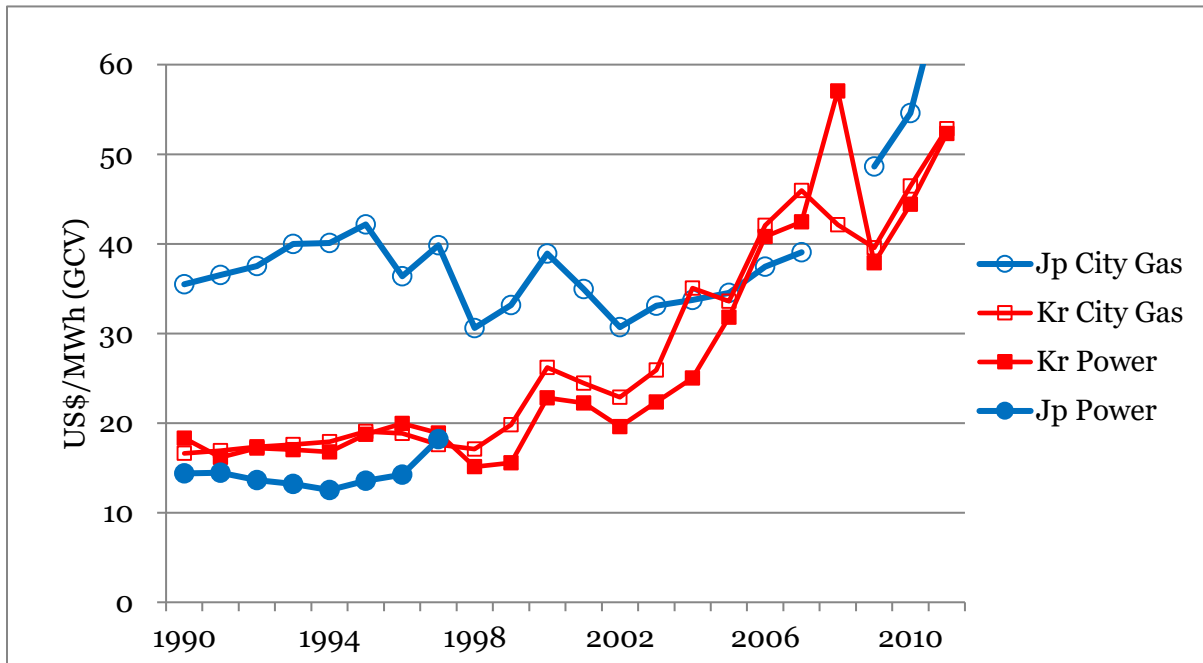
Source: Mehden and Lewis 2006 and Seo 2001

Note: All the contracts are made with a state-owned Indonesian gas supplier, Pertamina

The contrasting business regulations on natural gas for power generation shaped the relative price of gas turbine power generation in a contrasting way in the two countries. In addition, the Korean government often exercises additional price interventions, such as increasing gas price for power generation above the city gas price, when there are gas price hikes. Figure 6.2 illustrates that gas prices for power generation were higher than city gas prices in Korea in 1990, 1996, 1997, and 2008. Even in other years, the average price gap between power generation and city gas are negligible, whereas in Japan the difference in price is always more than double – the high household city gas price notwithstanding.

In effect, there has been a seven-fold price differential between household city gas and gas for power generation in Japan. In liberalised energy markets, such as the UK and the US, there is a two- or three-fold price differential between gas for power generation and household city gas. Considering the pressure differential of gas distribution pipelines and seasonal demand fluctuations between the two customer groups, such a price gap is inevitable in competitive energy markets. Consequently, the fact that gas prices for these two consumer groups in Korea are similar indicates that there is strong cross-subsidisation from the power generation sector to the household sector (Figure 6.2).

Figure 6.2 Gas Prices for Power Generation & City Gas in Japan and Korea



Source: Author's elaboration from KOGAS 2011, KEPCO 2012 and IEA 1999, 2013

Note 1: Japan has not reported gas prices for power generation to IEA and has not publicly disclosed in Japan since 1998 when the country opened its wholesale electricity market.

Note 2: GCV stands for Gross Calorific Value. It takes into account the latent heat of vaporisation of water in the combustion products.

6.2.2. Direct Effects of Environmental Regulations

ESI environmental regulations display the same pattern. Japan's stringent emission standards and practices introduced in the 1970s – the strictest in the world at the time – induced the Japanese HEI to develop low-NO_x combustor for gas boilers, initially. The technology for boilers became a foundation for MHI's world-first commercial low-NO_x combustor for CCGT in the early 1980s. It was a crucial component technology in catching-up with global frontier gas turbine OEMs as the US and Europe increasingly strengthened NO_x emission regulation. MHI's low-NO_x combustor technologies – developed on the basis of its gas boiler experience, in compliance with the strict regulations introduced in the early 1970s – enabled the latecomer to outperform GE. In addition, the regulations enabled gas power to compete against coal power from the mid-1970s.

Again, the Korean case displays an opposite trend with regard to environmental regulations and their impact on the performance of the two technologies. Lax emission standards and practices allowed coal power to dominate the Korean fossil power plant market at the expense of gas turbines. Lax safety regulations and practices relating to nuclear power resulted in the world's highest capacity factor, and a rapid construction lead time for the Korean nuclear fleet. The operational and construction performances paved the way for Korea's first nuclear export (*World Nuclear Association*, 2011).¹⁴¹

Impact of Safety Regulation on Nuclear Power Performance

Japan and Korea display contrasting regulatory guidelines and practices on nuclear safety issues. Japanese regulatory criteria and practices are the strictest in the world, while their Korean counterparts are relatively lax, as can be seen in the case chapters. The steam generator tube integrity issue, in particular, reveals the high degree of contrast that exists.

The degree of strictness regarding the steam generator tube issue is measured by four regulatory requirements, including flaw acceptance criteria, coolant leakage limit, inspection scope, and intervals between inspections. While Japan's guidelines can be summed up as the "no flaw, no leakage principle" – 100% tube inspection and inspection every year, in principle – their Korean counterparts allow flaws of up to 40%, varied rates of leakage, a 20% sample inspection, and inspection intervals dependent on the fuel replacement cycle. The contrasting figures are summarised in Table 6.3 and 6.4.

¹⁴¹ KEPCO claimed that its best track record in terms of highest capacity factor, lowest construction cost and the shortest construction lead time among the bidders from France, Japan and the US was the main factor of the award in the inter international competition for the UAE's nuclear project after the export contract in 2009.

Table 6.3 Regulatory Guidelines and Practices on Steam Generator Safety

	Korea	Japan
Flaw Acceptance Criteria	Flaws less than 40% of wall thickness are allowed	No detectable flaws are allowed (Detectable flaws are above 20%)
Coolant Leakage Limit	Varied by reactor (1,635 to 2,275 ℓ/day) ¹⁴²	Leak operation is not allowed. If a leak is detected, it must be shut down
Interval bet. Inspections	Depends on refuelling cycle, mostly 18 months	Less than 13 months (If no leak & no defect previously detected, every other year)
Scope of Inspection	20% sampling of tubes	All Tubes & Full-Length (If no leak & no flaw previously detected, 30% sampling)
Response to Tube Rupture Events	Re-operation was allowed in less than two months (from April to May 2002)	Shutdown for 3.5 years for analysis, preventive measures & steam generator replacement (Feb. 1991 to Aug. 1994)

Source: KEPCO Plant Service & Engineering (KPS) 2002 and Yashima 1995

Table 6.4 Intervals between Periodic Inspections on Nuclear Reactors (months)

	2000	2005	2006	2007	2008
US	17.9	18.9	18	18.6	18.4
France	-	14.6	14.7	14.6	15.4
Japan	13.0	13.0	13.0	13.0	13.0
Korea	17.5	17.3	17.6	17.6	17.6

Source: Japan Atomic Industrial Forum, "World Nuclear Power Plants 2010"

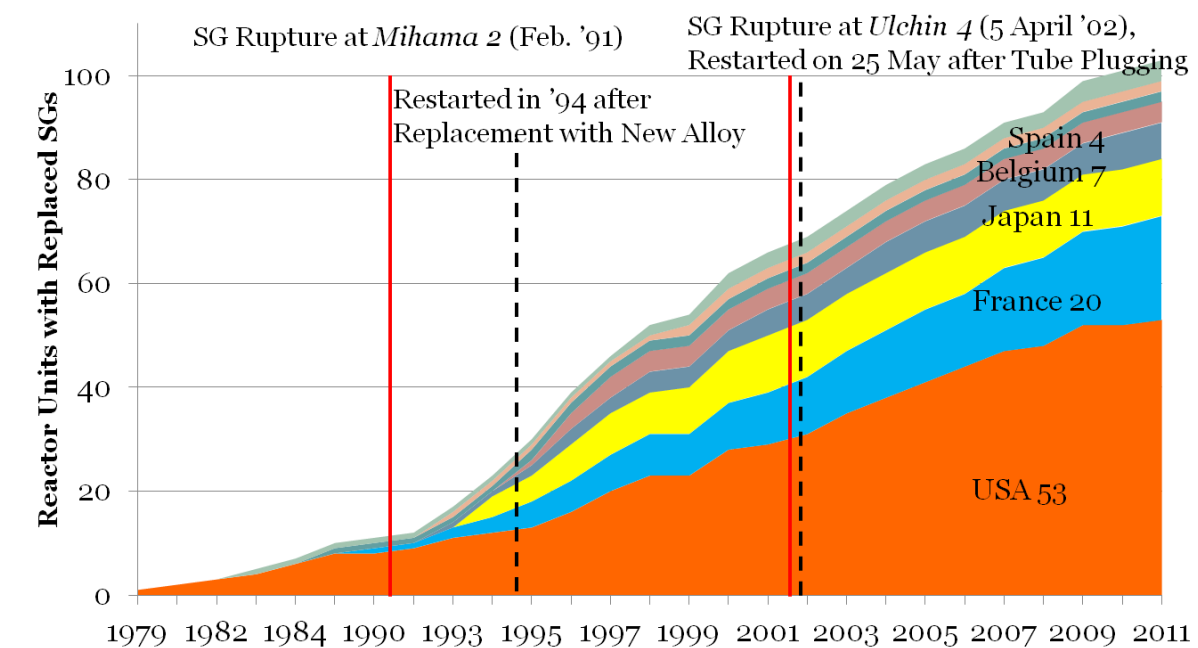
Moreover, actual practices in relation to steam generator tube rupture (SGTR) accidents in the two countries reveal a further contrast. In the case of Japan, when a steam generator tube ruptured at Mihama 2 nuclear reactor in 1991, the utility had to shut down the reactor for three and a half years. Until the restart, the utility was subjected to an in-depth analysis of preventive measure on similar design reactors, including the replacement of the existing steam generators by new ones made of a more corrosion-

¹⁴² The limits are applied to *Yonggwang* 3&4 and *Ulchin* 3&4, respectively (KPS, 2002).

resistant alloy tube material, namely Alloy 690. After the accident, Japanese utilities started to replace the steam generators at 11 reactors (Figure 6.3).

In the case of Korea, the safety regulator allowed the utility to restart operation of the reactor after a simple repair, including plugging of the ruptured tube, just seven weeks after the rupture event at *Ulchin* nuclear reactor 4 in 2002. This represented the quickest restart of a nuclear reactor after an SGTR accident in the world and surprised experts in other countries (see Section 4.2.5 on page 116). In addition, hardly any concern was raised about the steam generator alloy materials after the accident, and the steam generators made of corrosion-prone alloys were not replaced (Figure 6.3).^{143,144}

Figure 6.3 Cumulative Steam Generator Replacement Cases in the World



Source: Author's elaboration from IAEA 2011

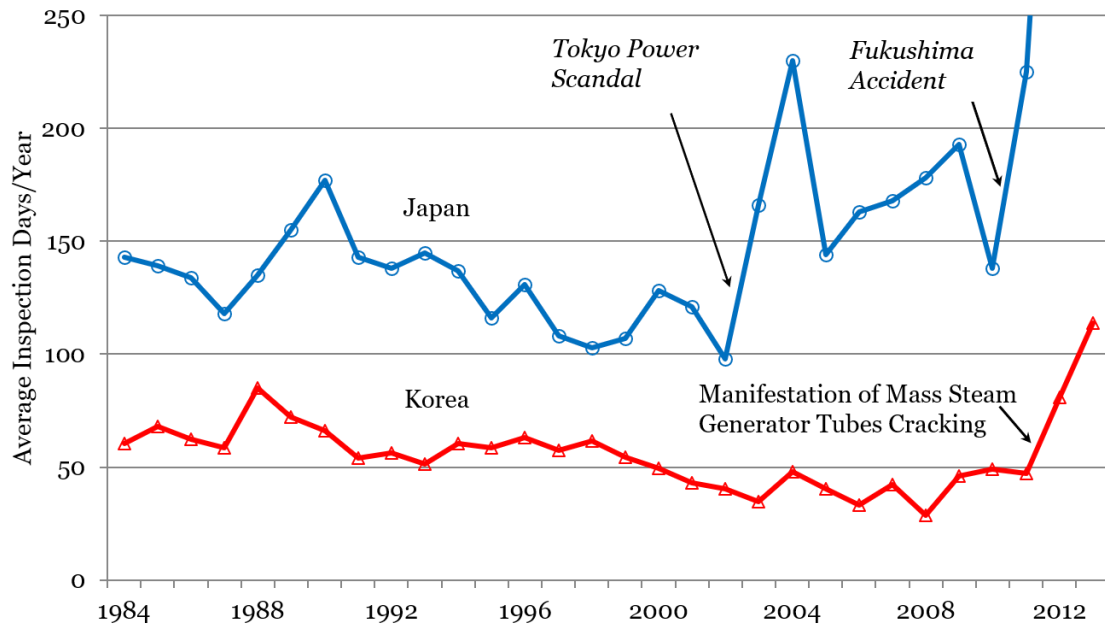
¹⁴³ It was revealed by Korean regulator's in-depth report in 2012 that the apparent manifestation of massive tube cracking was in effect the result of overlooked accumulation of stress corrosion cracking during the previous periodic inspections for the past decade.

¹⁴⁴ The utility had to pay for its hasty action a decade later with a sudden manifestation of massive tube cracking in 2011, replacement of steam generators and two years' shutdown

Although such contrasting practices are not codified by regulations, they are consistent with the contrasting regulatory guidelines referred to above. The contrasting regulatory guidelines and practices effectively influenced the contrasting operational performance of nuclear power in the two countries. Between 1984 and 2010, Japanese utilities had to spend an average of 142.8 days annually on periodic inspections. In principle, spending such a long time on periodic inspections every year does not allow utilities to achieve an annual capacity factor higher than 80%. In terms of Japanese regulations, the only way to achieve the desired level is to obtain an exemption from a periodic inspection by demonstrating “no flaw” and “no leakage” records during the previous operational cycle and inspection. In effect, the Japanese nuclear fleet achieved an average capacity factor higher than 80% in only seven years during the past four decades.

By comparison, the Korean utility, which enjoyed relatively lax regulatory guidelines and practices, spent only 53.5 days annually on periodic inspections during the same period. For the past two decades, Korea has achieved the world’s highest operational performance regarding nuclear power. Once it achieved an 80% capacity factor in 1991, it did not fall below that level until 2012. In fact, it maintained the world’s highest recorded capacity factor of higher than 90% between 2000 and 2011, the year in which it was faced with the manifestation of massive steam generator tube cracking in its first standardised reactors alongside enhanced safety checks as a preventive measure of the Fukushima accident (Figure 6.4).

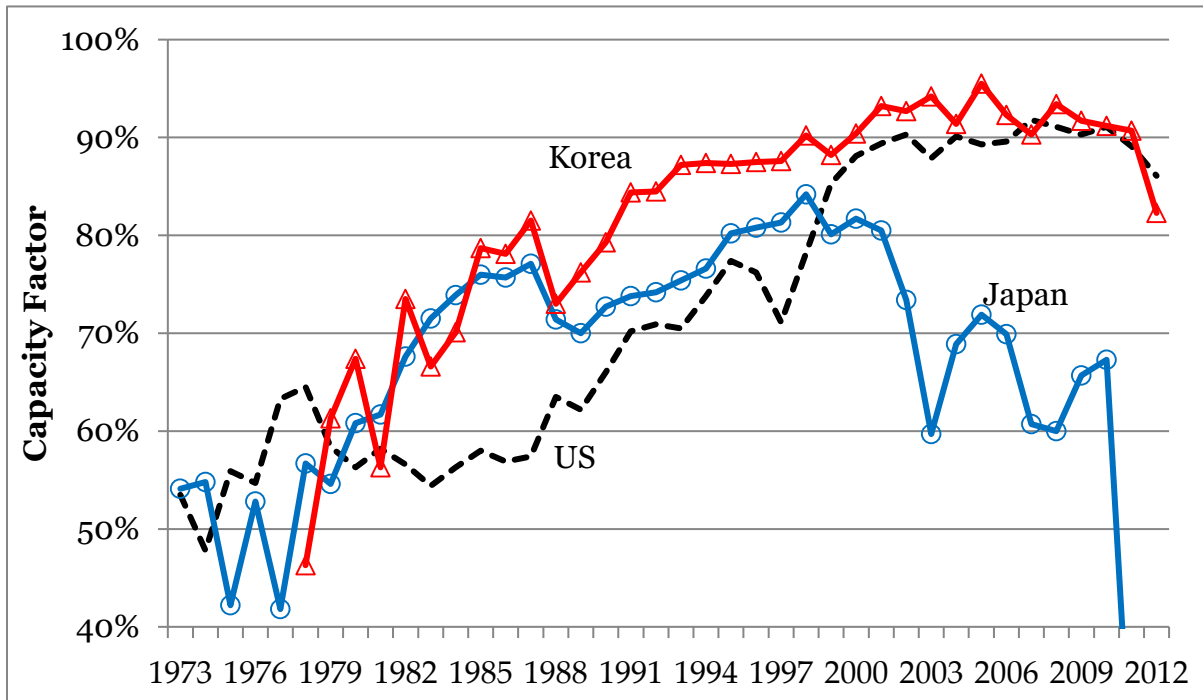
Figure 6.4 Average Annual Inspection Days in Japan and Korea



Source: Author's elaboration from Korea Electric Power Co. 1990-2014 and Japan Nuclear Energy Safety Organization 2000-2014

Figure 6.5 compares contrasting operational performances of nuclear power between Japan and Korea with those of the US as a reference case. Capacity factor refers to the operational performance of the reactors in terms of the ratio of the net electricity generated, compared to the energy that could have been generated continuously at full capacity over the same period. The Japanese nuclear fleet struggled to exceed 50% after it experienced its first steam generator tube leak incident in the 1970s. It then improved gradually until the late 1980s but remained below 80% for most of the time. Although the performance of Japanese PWRs was slightly better than BWRs – with a capacity factor above 80% for nine years – their overall performance was not much different from that of BWRs in terms the average performance during the four decades under consideration.

Figure 6.5 Operational Performances of Korean and Japanese Nuclear Power



Source: Author's elaboration from Korea Electric Power Co. 2014, Japan Nuclear Energy Safety Organization 2014 and US Energy Information Agency 2013

Note: Korean case includes PWR reactors and four small units of CANDU reactors, while Japanese and the US figures show an average capacity factor of BWR and PWR reactors. The dramatic drops after 2010 are results of the shutdown of 53 reactors after Fukushima accident in 2011 in Japan

As a result, the contrasting track records of operational performance influenced each country's export performance. Although Japanese HEI localised both PWR and BWR as early as the mid-1970s, its low capacity factor of below 70% until the 1980s gave it a 'bad name' in the global nuclear export market (Kitschelt, 1991). Even after that, it never achieved a 90% capacity factor. By contrast, Korea's record capacity factor throughout the 2000s, in addition to its rapid construction performance, impressed the global market and helped it win the international competitive bid for the UAE's first nuclear power project in 2009.

Impact of Emission Regulations on Gas Turbine Performance

As we have seen from safety regulations on nuclear power plants, the Japanese government and local authorities established the world's strictest emission level

standards on fossil power plants from the mid-1970s, whereas the Korean government set lax standards, even until the 2000s. In fact, Japanese local governments not only set much stricter emission limits than those of the central government – thus reflecting public discontents about the serious environmental incidents in the 1960s and 1970s – but had such authority at their disposal that they could cause utilities to withdraw from power plant construction processes if such utilities could not meet the local standards. The Korean government, by comparison, neither set such strict emission standards nor allowed local governments meaningful authority. As a result, the Japanese local standards for NO_x emission of all fossil power plants in 1975, were much stricter than their Korean counterparts in the 2000s (Table 6.5).

Table 6.5 NO_x Emission Standards on New Fossil Power Plants (ppm)

Fuels	Korean National Standards			Japanese Standards in 1975	
	1978~'86	1987~'04	2005-'09	Central Government	Local Governments
Gas	-	400	50	60	10
Oil	250	250	70	130	25
Coal	500	350	150	400	170

Source: Author's elaboration from Korea's Ministry of Environment 2005, 2014, "Permissible Air Pollutant Emission Standards" and Ando, 1983, "NO_x Regulation on Stationary Sources in Japan"

Note: The standards were applied to new power plants in both countries

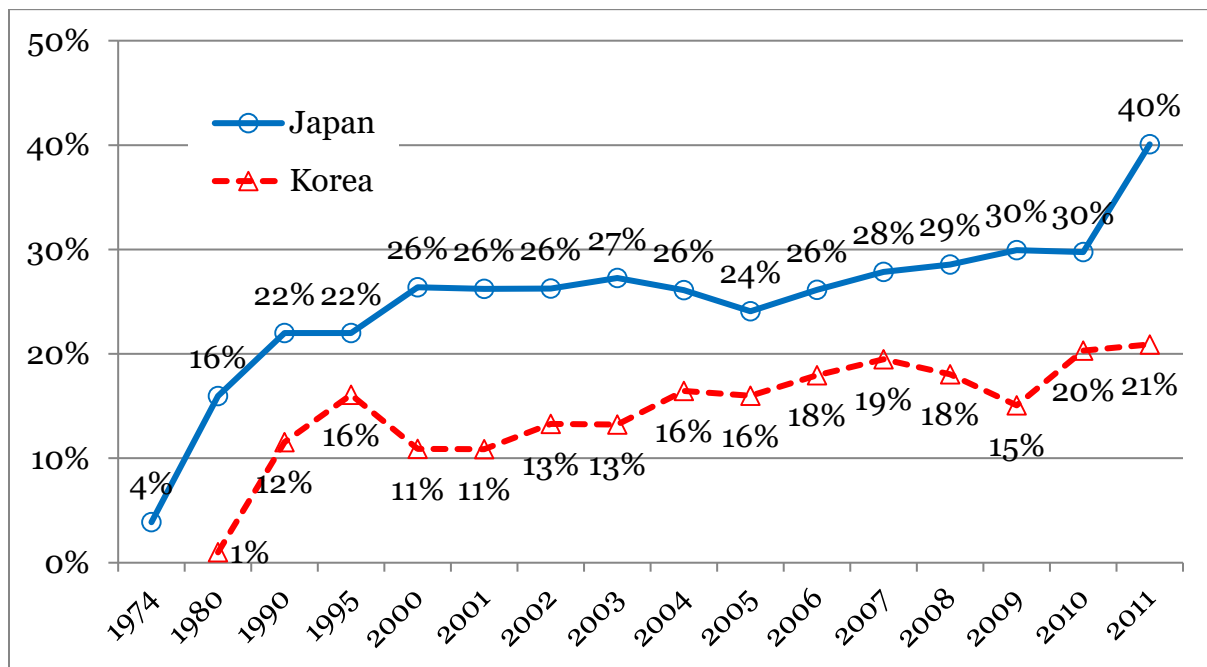
Such strict emission standards not only forced Japanese ESI to switch from 'dirtier' fuels, such as heavy fuel oil and coal, to environmentally benign fuel, such as natural gas, but also encouraged the ESI and their contractors, HEI firms, to develop low-NO_x burner technologies from the early 1970s. This gave a clear advantage to Japanese HEI firms in the 1980s when it came to catching up, in economic terms, with American standardised gas turbines, which did not comply with such strict standards. The Japanese HEI firm, MHI, could surpass GE, which supplied CCGT to Tokyo Power, by delivering Tohoku Power CCGT with low-NO_x burner technology, which complied with such strict standards, at a much lower cost than that of GE. It gave MHI a strong track record and

paved the way for its flourishing catch-up performance in the Japanese CCGT market, where even advanced foreign firms could not comply with the emission standards.

By comparison, Korea's much more lax emission standards gave a signal to Korean ESI, KEPCO, to continue using much 'dirtier' but cheaper fuels. In particular, coal power technology has been the sole beneficiary of the lax emission standards since the 1980s, when the Korean government removed oil power plants from its long-term electricity supply plan, as a countermeasure to the 'second oil shock'. Under such lax emission standards and the additional cost burden of cross-subsidy to the city gas sector, CCGT had to give way to coal power and has had to play only a limited role, such as providing peak-load power in the Korean market, for the past three decades.

Due to the contrasting regulatory combinations relating to gas import contracts and emission control issues – excluding the question of electricity price – the role of gas power has been quite different in the two countries. Autonomous gas field development and import contracts, as well as the world's strictest emission control in the Japanese ESI, paved the way for gas power, including CCGTs. Tight government control of the gas import contract and lax emission control of the Korean ESI limited the role of CCGT in the Korean electricity market. The share of gas power in terms of total generation by Japanese utilities has been mostly above 25%, while that of the Korean ESI has been approximately 15% since 1990 (Figure 6.6). Table 6.6 highlights the contrasting institutional characteristics of ESI between the two countries.

Figure 6.6 Share of Gas Power Generation in Each Electricity Supply Market



Source: Author's elaboration from IEA Electricity Information 2001, 2004, 2006, 2008 and 2013

Note: Gas boilers dominated gas power generation until the early 1980s in both countries before CCGTs emerged as a dominant gas power technology in the global market.

Table 6.6 Contrasting Institutions of ESI across the Two Countries

Japan		Korea
Business Regulations	Autonomous Management by Private Regional Monopolies	Tight and Micro Interventions on the State-owned Monopoly
Electric Price	World Highest Electricity Price (Arm's Length Relation with BMIs)	Lowest Electricity Price in OECD (Tightly Coupled with BMIs)
Gas for Power	Utilities-led Gas Field Development & Contract	Enforced Cross-Subsidy from Gas Power to City Gas
Environmental Regulations	World Strictest Regulations from the 1970s	Lax Regulatory Standards & Practices
Fossil Power	World Strictest National & Local Emission Standards	Lax Emission Standard, often Exemptions on Coal Power Sites
Nuclear Power	World Strictest Safety Criteria and Practices	Lax Regulatory Practices

Diversity of Electricity Frequency System

Although electric frequency systems are rather physical and technological conditions given by the ESI, they constrain or incentivise, as other institutions do, HEI's catching-up performance in terms of technological adaptation and global export market potential. In the post-war era, Japan's dual electric frequency system – which consists of the 60Hz system of the western region and the 50Hz system of the eastern region – made it possible for Japanese HEI firms to modify their technological capability from conventional steam turbine technologies. This provided another aspect for MHI to exploit in its efficient catching-up with regard to the 50Hz gas turbine, based on its licensor's 60Hz gas turbine designs. Since the 50Hz system dominates most of the global electricity market, the dual system offered MHI a technology 'ladder' to the global gas turbine market.

By comparison, Korean HEI did not have such a technological opportunity to modify designs under the 60Hz electrical system. For example, even the famously resilient *Chaebol* firm, *HHI*, did not have any incentive to enter the gas turbine business when the Korean government briefly lifted the entry regulation of the domestic HEI market in the 1990s, due to the mismatch between the domestic 60Hz gas turbine market and the global market, in which the 50Hz system largely prevails.¹⁴⁵ In other words, the firm strategically considered that the export market potential would not be large enough, even when it could have developed 60Hz gas turbine technologies for the domestic market.

¹⁴⁵ While most of regions in the World use 50Hz electrical systems, only North America, some parts of Latin America, Saudi Arabia, the Philippines, South Korea and Kansai Region of Japan use 60Hz electrical systems. Thus, in the sense of export market potential, development of 60Hz gas turbine may have less incentive than that of 50Hz technologies has.

6.2.3. Sectoral Institutions of the ESI and Demand Conditions

Although both Japanese and Korean governments have been supportive of the two electricity-intensive BMIs, namely aluminium smelters and EAF steelmakers, direct policy efforts to support the BMIs, it was business regulations of ESI that decided the opposite growth patterns of the BMIs between the two countries. Despite MITI's policy efforts to delay restructuring of the commodity BMI, virtually all of the Japanese aluminium smelters moved abroad in the face of an electricity price increase at the end of the 1970s. MITI's role was irrelevant again when another electricity-intensive BMI, namely EAF steelmakers, voluntarily reduced production capacity in the 1990s.¹⁴⁶ It was the world's highest electricity prices that caused the commodity BMI to voluntarily exit the domestic market, and reduce its production capacity.

By comparison, the Korean BMIs performed consistent growth under the government's electricity price control through the national ESI, namely KEPCO. Although the aluminium smelter eventually exited the Korean market in the late 1980s due to the absolute price gap between Korean and Canada, it persisted in the domestic market a decade longer than its Japanese counterpart. After the market exit of the aluminium smelter, EAF steel industry became the largest beneficiary of KEPCO's pricing practice in Korea. KEPCO maintained the cheapest electricity for industry amongst the OECD countries, and this shaped the persistent growth of the EAF steelmakers.

Regardless of other supportive policy efforts for the BMIs, it was the electricity price that decided the trajectory of the industry – either towards restructuring or expansion. Korean EAF steel firms maximised their exploitation of the persisting TOU electricity rate and expanded their share in domestic crude steel production to above 40%, which was close to the world's highest level throughout the 2000s. The strong bond

¹⁴⁶ As a few independent EAF steel firms such as Tokyo Steel expanded production capacity against *Keiretsu*-led Japanese Steel Association's consensus of production control in the 1980s, actual reduction of Japanese EAF steel production capacity was delayed to the early 1990s.

between EAF steel and cheap electricity prices has been crucial to the survival and expansion of the industry, despite the country's poor self-sufficiency in scrap steel, which is the major input material of EAF steel, other than electricity.

Table 6.7 Institutions and Policies on Commodity BMI: Aluminium and EAF

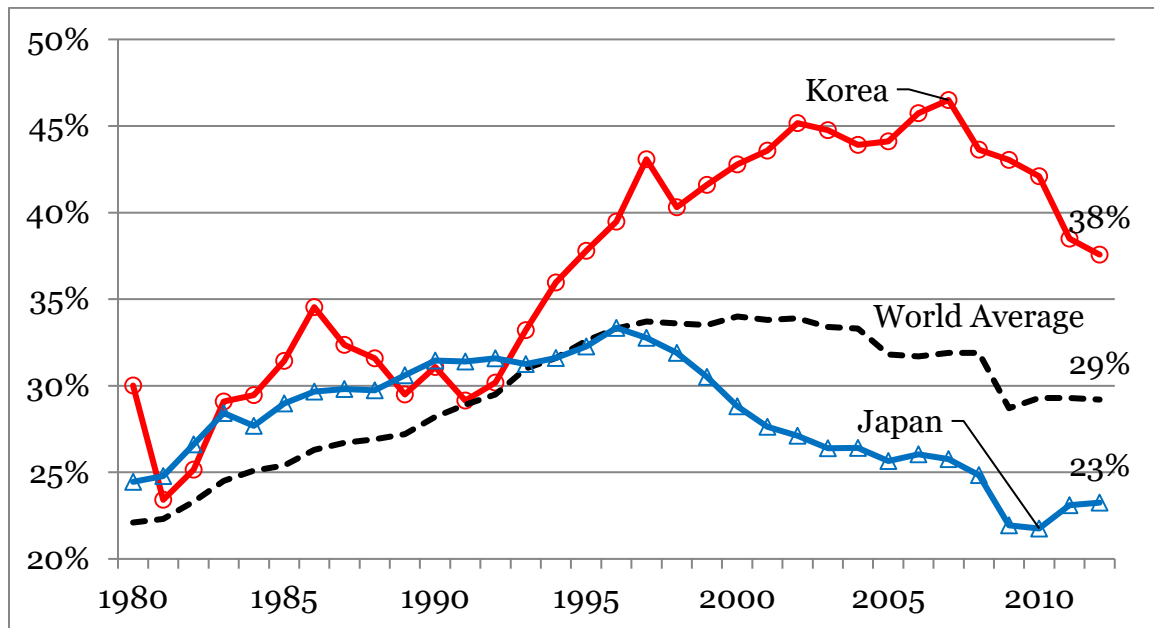
	Japan	Korea
Industry Policies	"Cartelization" and Delay in Restructuring facing Recessions	Scrap Steel Market Price Stabilisation Effort
Electricity Pricing Practices	World's Highest Electricity Prices without Special Arrangement	Special Discount for Aluminium, Excessive TOU Pricing Practice
Industries' Response	<i>Keiretsu</i> Firms' Voluntary Exit from Aluminium in the early '80s, Reduction of EAF from the '90s despite Government Support	EAF Firms' Exploitation of Excessive TOU Pricing and Over-Investment in the 2000s

Figure 6.7 illustrates contrasting trends of EAF steel share in national crude steel production in Korea and Japan for the past three decades. While Japanese EAF steel dropped to well below the world average from the mid-1990s, their Korean counterpart started to increase from the early 1990s and remained above 40% throughout the 2000s, which was much higher than the world average. It should be noted that the world average is biased by a single large steel-making country, namely the US, which maintained a share of nearly 80% for most of the period. The US EAF steelmakers enjoy abundant high-quality scrap steel from scrap automobiles, as well as cheap electricity, while most of the BOF steelmakers collapsed thanks to imported cheap steel. If the US is excluded, the world average would be much lower, and the share of Korean EAF steel will be the highest in the world.

In turn, the persistent growth of Korean EAF steel production since the 1990s has elevated base-load electricity demand and has ultimately paved the way for new nuclear power and coal power projects since then. Iron and steel are not only the largest electricity

consumer but also the most stable base-load electricity user amongst all the industry sectors in both Japan and Korea.¹⁴⁷

Figure 6.7 Share of EAF Steel in National Crude Steel Production



Source: Author's elaboration from World Steel Association 1982, 1990, 2000 & 2014

Although coal power is also a base-load power source, it has a load-following function and can change its output somehow in response to fluctuating electricity load demand. As a result, growth of new base-load demand is much less of a prerequisite for new coal power plant projects than for nuclear power. Table 6.8 illustrates the overall status of nuclear power and BMI in electricity supply and demand in Japan and Korea. The Korean case clearly reveals a higher share of nuclear power and BMI in electricity supply and demand, respectively, than Japan does.

¹⁴⁷ Although 'Machinery' is the biggest sector in electricity consumption among the industry sectors, the category is in effect sum of various sectors including automobile, semi-conductor, mobile phones and LCD panels.

Table 6.8 Status of Nuclear Power & BMI in Electric Supply & Demand (TWh)

Electricity Supply in 2010			Electricity Demand in 2010		
	Japan	Korea		Japan	Korea
% of Nuclear	25.5%	29.5%	% of BMI	6.6%	11.0%
Total Production	1,075	480	Total Final Consumption	999.7	449.3

Source: Author's elaboration from IEA *Electricity Information 2013*

Note: In total electricity production, power transmission & distribution loss is deducted while the industry's own self-power generation is added.

On the contrary, the world's highest average electricity price, and a hardly differentiated off-peak price, reduced base-load power demand in Japan. Consequently, most BMIs became the worst victims, and voluntarily exited the domestic market, or restructured their production capacity. Moreover, the remaining commodity BMIs invested in the large capacity of auto-power generators, often with gas turbines. In turn, the stagnated growth of base-load demand did not provide adequate conditions for new nuclear power projects.

6.2.4. Compatibility with a Global Window of Opportunity

The User-Institution framework can only partially explain successful technology catching-up cases, including Japanese gas turbines and Korean nuclear power, without technology transfer from advanced foreign firms. The MHI reaped the benefits of Westinghouse gas turbine division's move into Japan as a result of the asymmetric regulations on natural gas between Japan and Western economies, including the US and EC, in the mid-1970s. In a similar vein, resilient financial mobilisation of the Korean state-owned ESI was crucial to exploit the global nuclear market collapse in the early 1980s. Regarding matching-up between domestic institutional sets and a global window of opportunity in the form of advanced foreign firms' crises, subsequent public R&D programmes played an only supplementary role (Table 6.9).

In the Korean nuclear case, matching-up was a result of the global market contingency in the 1980s and the domestic institutional set, rather than deliberate governmental R&D programmes. The ‘package transfer deal’ between the financially troubled American reactor vendor and the Korean latecomer included nearly full-scope of reactor technologies from the blueprints of a reactor, main equipment designs, know-how, and training at the cost of less than one commercial reactor. It was possible mainly because of the exceptional opportunity provided by the collapse of the global market and subsequent ‘buyer’s market’ conditions, in which buyers could exert their asymmetric power on sellers. By comparison, Korean public R&D expenditure was minuscule both in its first and second reactor standardisation programmes. The relative importance of the two major R&D programmes is overshadowed by the effect of technology transfer from the foreign OEM. In this sense, learning by doing through repetitive construction of the reactors would be more important for indigenising the transferred technology.

Table 6.9 Compatibility between Institutional Sets and Global Opportunities

Windows of Opportunity		Distinctive Domestic Institutions		Results
Nuclear	Collapse of Global Nuclear Plant Market (1980s~90s)	Japan	High Electric Price and Strict Safety Regulations	Mismatch Constrained Domestic and Export Performances
		Korea	Low Electric Price and Lax Safety Regulations	Fit Drove Efficient Tech. Transfer: Exploiting Foreign Firm’s Knowledge and Skipping Development Stages
Gas Turbine	Closure of US and European Gas Turbine Market due to Gas Fuel Regulation (1974~’87)	Japan	Autonomous Gas Fuel Trade and Strict Emission Controls	Fit Drove Efficient Tech. Transfer: Exploiting Foreign Firm’s Knowledge and Commercialising Low-NOx Combustor
		Korea	Cross-subsidy to City Gas and Lax Emission Controls	Mismatch Constrained Domestic Market and User-Producer Interactions

'Earlier vs. Later Latecomers' in Global Market Contexts

It is important to consider the timing of catching-up efforts when discussing the compatibility between domestic institutional sets and global opportunities for technology catching-up. Essentially, the different timing of catching-up efforts *per se*, whether 'earlier' or 'later' latecomers, does not explain the two countries' dichotomous catching-up performances in the two technologies.

There have been contrasting effects of the catching-up timing regarding the two technologies. While the early indigenisation of commercial reactors was disadvantageous to the Japanese HEI in terms of its costly path-following safety upgrades from its 1st to 3rd generations, the late indigenisation of PWRs by the Korean HEI was a cost-saving and efficient catching-up exercise by skipping the early and smaller reactor commercialisation stages. By contrast, the earlier gas turbine catching-up efforts not only provided the Japanese HEI with an opportunity to exploit knowledge from a troubled foreign firm but also paved the way for its flourishing export performances following the lifting of gas fuel regulations in the US and European Commission in the 1980s.

In the case of Japanese HEI, the earlier latecomer, even when the industry had almost completed PWR indigenisation in the 1980s, must have had strong technological inertia, because it promptly diversified to the emerging CCGT market in the 1980s. The Japanese HEI export performance of CCGT continuously improved, and it became the third-largest global supplier of CCGT in the 2000s. Although Japanese HEI also exported nuclear power equipment, such as steam turbines and steam generators, it never produced a complete nuclear reactor export project beyond its domestic reactor projects.

In the case of Korean HEI, although the 'later latecomer' caught up with PWR technology two decades later than its Japanese counterpart, it skipped the upgrade stage from 1st to 2nd generation reactors by acquiring 2nd and 3rd generation reactor blueprints and training courses at a much cheaper price than a single nuclear reactor. In contrast, the

‘earlier latecomer’, Japanese HEI, took advantage of catching-up with gas turbine technology, while Korean HEI missed the window of opportunity for gas turbine catching-up, and so could not repeat its nuclear success.

Table 6.10 Advantages and Disadvantages of ‘Earlier’ and ‘Later’ Latecomers

	‘Earlier’ Latecomer (Japan)	‘Later’ Latecomer (Korea)
Nuclear Power	Followed All the Costly Upgrade Stages of Reactors from the 1970s to ‘80s (Disadvantage)	Efficient Technology Transfer of Modern Reactors Exploiting Global Market Collapse in the 1980s (Advantage)
Gas Turbine	The Discrepancy between Domestic and Global Natural Gas Regulations Offered Window of Opportunity for Technology Transfer (Advantage)	Missed Window of Opportunity for Gas Turbine Catch-up in the late 1970s and early ‘80s (Disadvantage)

Overall, although the core sectoral institutions of ESI do not directly influence domestic HEI firms’ technological capabilities, they govern the method of transactions of the two sectors and subsequently enabled the HEI for respective technology transfers from advanced foreign firms in a favourable market. The favourable domestic market invites advanced foreign firms when there is adverse institutional or economic change in the global market. As a result of the asymmetric institutional contexts between the domestic and global markets, the advanced firms suffering from financial problems or demand shortage sought the latecomer countries as a ‘shelter’, such as the gas turbine division of Westinghouse in the 1970s and the nuclear division of CE in the 1980s.

6.3. Comparisons with Rival Approaches

6.3.1. Firm Capability Approach

Inconsistency Between Capabilities and Catching-up Performances

Although the Japanese HEI firm, MHI, exhibits superior technological capabilities in terms of technology scope and depth compared to its Korean counterpart, its relative catching-up performances have been inconsistent with its technological capabilities. Even though MHI, together with the other two HEI firms, indigenised commercial reactor technologies in the 1970s, it never succeeded in nuclear export. By comparison, even though *Doosan*, including its predecessor, could not develop architecture & engineering (A&E) capabilities, its tight alliance with KEPCO led successful catching-up, including the nuclear export case in 2009 (Table 6.11).

It was the governance structure of the ESI that decided the export success and failure in the end. While the state-owned monopoly ESI supported the Korean nuclear export to the UAE in every aspect, the Japanese ESI as private investors, such as Tokyo Power, autonomously decided to withdraw from the Wylfa project in the UK, independent of the Japanese government's intent. The inconsistency between the firm capability and catching-up performance is also pronounced in upstream supplier's cases.

Table 6.11 Inconsistency between Firm Capabilities and Catch-Up Performances

	Nuclear Power	Gas Turbine
Japan	MHI: Early indigenisation of overall reactor technologies (1975)	MHI: Commercialisation of CCGT (1984)
Korea	<i>Doosan</i> : indigenisation of NSSS (1995), deficient in A&E capability, <i>Doosan-KEPCO</i> alliance's nuclear export (2009)	<i>Doosan</i> : Developed 5MW small gas turbine (2009)

Disproportionate Performances of Supporting Industries

Relative technological capabilities of specialized metal industries for the development of components of the two technologies exhibit unexpected but similar stories. Although Sumitomo Metal Tube Works successfully commercialised uniquely sophisticated steam generator tubes with advanced alloy and performed well in the global market, it did not help MHI to improve overall post-catching-up performances in the global nuclear market. By contrast, MHI Precision Casting Co. and its predecessor has been lagging behind the rest of the global OEMs in blades precision casting technologies despite MHI's successful catching-up performance in the global gas turbine market. The precision caster has always applied lower grade superalloy and casting technology for gas turbine blades than the global OEMs since its first CCGT in 1984 (see Section 5.3.4).

By comparison, Korea's specialised metal industries show dichotomous stories compared to their Japanese counterparts. Although Korean specialty metal firms from Sami to its successor, POSCO Specialty Steel, never could indigenise even outmoded Alloy 600 steam generator tubes for nuclear power, the inferior capabilities hardly hindered Korean nuclear catching-up success. The Korean precision caster, namely KRW, exhibited relatively better catching-up performance in the gas turbine blade and vanes segments among the specialty metal firms, on the contrary. It not only localised outmoded blade technologies such as CC blades but also developed DS blades through public and in-house R&Ds and exports its own DS blades to a couple of customers in the Middle East. Nevertheless, its relatively advanced capabilities compared to its HEI partner hardly improved Korea's gas turbine catching-up performances. Without involvement in commercial gas turbine projects in the Korean electricity market, the precision caster's capabilities have remained as only unproven potential (see Section 4.3.5).

Although the cross-nation and cross-technology dichotomy of the specialised metal industries are not clear as much as that of their HEI counterparts, the pattern offers unique insights from the 'producer – upstream supplier relationship' perspective,

recommended by the firm capability approach in the empirical literature. The inversely proportionate performances of the specialised metal industries compared to the performances of their HEI partners can be better explained by the effectiveness of the specific institutional set of ESI in this case study. Regardless of their relative strength and weakness compared to their HEI partners, the institutional sets of ESI effectively either constrained or incentivised HEI's catching-up performances in both countries (Table 6.12).¹⁴⁸

Table 6.12 Inversely Proportionate Performances of Specialised Suppliers

	Specialty Metal Maker of Steam Generator Tubes	Precision Caster of Gas Turbine Blades
Japan	Sumitomo Metal Tube Works: takes a large global market share with sophisticated tube technologies	MHI Precision Casting Co.: Lagged behind the global trends (DS blades vs SC blades)
Korea	POSCO Specialty Steel: Failed at indigenisation of even outmoded tubes	Korea Lost Wax: Produces own DS blades & exports to the Middle East market

6.3.2. Sectoral System of Innovation Approach to the Results

As discussed in the literature review (Section 2.4.2), the SSI framework's 'real boundary' of sectors encompasses numerous heterogeneous elements, such as universities, public laboratories, financial organisations, governments, upstream suppliers, producers, users, and 'sources of demand'. In addition, the SSI approach argues that sectoral systems could

¹⁴⁸ Regarding the relatively superior aircraft engine capabilities of the other precision casters in the Japanese case, Appendix Chapter B analyses the potential and the limits of the capabilities in the country's CCGT catching-up performance.

be reduced to technological systems based on the technology's interdependency and complementarity between upstream suppliers, producers, users, and 'source of demand' (Malerba 1999, 2006). Initially, categorising the four actors outlined above as a part of the nuclear- and gas turbine technology systems may appear convincing, given that most of the actors closely interact through the supply chain and user-supplier relationships. The framework is helpful in categorising the nuclear power and gas turbine 'industries' in terms of typological analysis.

However, even with the perspective of the technological subsystem, the overall contrasting catching-up performances of each technology subsystem between Japanese and Korean cases cannot be accounted for without analysing ESI's crucial role and institutions. As analysed in the firm-capability perspective above, the well-developed nuclear technology subsystem of the upstream supplier and the HEI firm in the Japanese case does not square with its unsuccessful performances in terms of operation, construction and export. Thereby, the technology subsystem view does not match with the case results.

Furthermore, if the SSI equates a sectoral system with a technological system, it cannot capture the overall effects of the sectoral institutions of ESI across different technologies. Although units of regulatory criteria and methods are different by technology, the SSI approach could miss the homogeneous pattern of the salient institutions of ESI and its effects on nuclear power and gas turbines. It would be more problematic when nuclear power and gas turbines are considered in a competing relationship in electricity markets.

6.3.3. Effects of HEI Research and Development Efforts

Research and Development Efforts on Nuclear Power Catching-Up

Although both governments have explicitly pursued catching-up policies through public R&D programmes in both technologies, these programmes cannot account for

success and failure of each technology catching-up in isolation. The Japanese government spent US\$5.7 billion on public R&D programmes for the standardisation of commercial reactors, over and above the notorious 'new reactor' R&D programmes that exhausted US\$74.5 billion without producing any commercial results over the past four decades. Although the Japanese commercial nuclear technology indigenisation was achieved much earlier than its Korean counterpart through its standardization and safety upgrade R&D programmes with gradual technology transfer from foreign licensors, the disappointing operating performance of the Japanese nuclear fleets was not significantly improved other than a few years in the 2000s. With weak performance in operation and new construction, the upgraded reactor, namely APWR, was never constructed in Japan despite a substantial R&D expenditure.

The R&D programmes played only a supplementary role even in successful technology catching-up cases. Korea spent only US\$820 million and US\$274 million for the first (OPR1000) and second (APR1400) indigenisation programmes, respectively, – less than the cost of a single commercial reactor – on a package technology transfer of modern large reactors. Furthermore, the operating performance of Korean nuclear fleets has been the world record level in the 1990s and 2000s. Although some nuclear engineering literature argues that this was a Korean success in terms of R&D efficiency, or an effective catching-up strategy(Choi et al. 2009), the minuscule expenditure exhibits that the 'efficiency' resulted from the exploitation of the global nuclear market recession rather than R&D *per se*.

In terms of policy efforts view, there was no such 'leapfrogging' or 'stage-skipping' strategy in Korea prior to the unexpected global nuclear market collapse in the 1980s. The Korean HEI skipped unnecessary catching-up stages, such as early-generation small reactors, whereas its Japanese counterpart followed the path of American partners including all the upgrade stages from the first-generation to third-generation technologies. Rather than intentional policy efforts, the fitness of the institutional sets of

ESI to the global market contingency appeals in the successful catching-up of nuclear power. In particular, the role of the state-owned monopoly ESI in rapid mobilising of finance for the technology transfer and training in the global market change was pronounced.

Research and Development Efforts and Gas Turbine Catching-Up

Gas turbine catching-up cases demonstrate the same pattern. Catching-up policies include public R&D programmes and energy supply plans. Public R&D programmes played only a supplementary role, even in the successful Japanese gas turbine case. Although the famous Moonlight Project shorten processes for MHI to master its component technology for the precision casting of blades and vanes, MHI was already on its own catching-up trajectory of commercial CCGTs in the late 1970s and early 80s. The actual effect of the programme is pronounced in reducing the large gap between MHI and follower firms, instead.

Considering the scale of the major public efforts, the Japanese government spent only US\$490 million – in 2013 prices – on the ‘High-Efficiency Gas Turbine’ development of the Moonlight Project, which represents less than 1% of public expenditure on new reactor development programmes and less than 10% of that on the Light Water Reactor indigenisation and upgrades programmes in Japan. The catching-up success achieved in the Japanese gas turbine and Korean nuclear power cases can be better accounted for by such as local institutional contexts and the global market changes.

By comparison, the Korean government repeated R&D programmes for small scale gas turbines at a similar level of public expenditure as Japan. Nevertheless, Korea’s public R&D programmes on small gas turbines did not generate meaningful technological improvements as well as commercial results. With the development of relatively obsolete component technologies, the development programmes without technological assistance from major foreign OEMs ended without reducing the big gap between such technology

and modern commercial gas turbine technologies. The Korean HEI firm is now involved in the country's first large gas turbine public R&D programme without a major global OEM partner, but few expect this programme to fill the technology gap between the Korean HEI and the global OEMs (Table 6.13).

Table 6.13 Major Public Expenditure for Indigenisation (US\$ million in 2013 price)

Japan		Korea	
		<u>1,407 in total</u>	
Nuclear Power	5,700 (1973-'10) for Reactor Upgrades from 1 st to 3 rd Stages	○	820 (1985-'95) for Transfer of CE Reactor(System80) into OPR1000
		○	274 for development of APR1400
		○	313 for miscellaneous nuclear R&D programmes (1984-'99)
		<u>460 in total (1991-'20)</u>	
Gas Turbine	490 (1978-'88) for 120MW	○	120 (1991-'98) for 1.2 MW
		○	80 (2005-'11) for 5 MW
		○	260 (2013-'20) for 100 MW

Source: IEA Energy R&D Statistics, Kimura & Kajiki, 2008, Science & Technology Agency of Republic of Korea 1997, Ahn 2014, and an interview with *Sooyong Kim*, op. cit.: p.144

6.4. Chapter Conclusion

This Chapter explained dichotomous cross-nation and cross-technology variations of the catching-up performances in HEI through the salient institutional set of ESI. It also showed the relative technological capabilities of HEI and upstream supplier firms, the sectoral system approach and R&D programmes do not explain the dichotomy. Although one country case could be a random phenomenon, a comparison of the two countries reduces such randomness to be unlikely.

The comparison between the country cases shows that the institutional set of ESI constrained the catching-up performances of nuclear power and gas turbine technologies, moving them toward opposite directions in the two countries' cases. First, the unintended

institutional set of ESI systematically, rather than randomly, incentivised the catching-up performances of one technology, while constraining the other. Although it is possible that a specific country could have more policy efforts in developing or exporting a specific technology over the other, the analysis shows the environmental (or safety) and economic institutions have been often beyond the boundary of specific technology policies. The patterns of the institutions and the extent of influence on the catching-up performances were explicitly manifested in both countries. Second, the unique patterns of the institutional set of ESI across the two countries induced the user-supplier interactions towards incentivising either gas turbine or nuclear power catching-up performances.

Chapter 7. Conclusion

7.1. Research Findings and Policy Implications

7.1.1. Major Findings

Motivated by Korea's first nuclear export in 2009, which defeated the Japanese counterpart in the international bidding competition, the case study investigated the cause of the nuclear export success and the overall ramifications to the catching-up performance of the two countries in the HEI sector. In order to evaluate the nuclear export success in a comparative fashion, the case study employed an axiomatic assumption that both nations are intent of developing and exporting every variety of technology in the HEI sector. The case study supported the assumption by demonstrating similar level efforts for catching-up and export of CCGTs as well as nuclear power in both countries.

Based on the basic assumption, the case study demonstrated that a historically evolved set of core regulations on the ESI sector engendered the contrasting catching-up results of nuclear and CCGTs regardless of public R&D efforts and firm capabilities. The finding reveals the fallacy of existing empirical literature attributing the Korean nuclear catching-up performance to a linear evolution from R&D efforts to the technology localisation to the export. The finding is supported by the reference case. The Japanese case demonstrated that its contrasting catching-up performances across nuclear power and CCGTs, compared to the Korean counterpart, are attributable to a combined effect of autonomous economic regulations and tight environmental regulations, regardless of firm capabilities and public R&D efforts.

The contrasting results of the replication across the two country cases, but for anticipated reasons, add up to important ramifications to catching-up studies as well as catching-up policies in the HEI sector. The finding revealed that both CCGT catching-up efforts in Korea and the efforts of nuclear expansion and export in Japan failed due to the

mismatch between the technology policies and the historically evolved regulatory structure of the ESI. Although neither the market nor government's hierarchical control give panacea to the failures, the findings urge the two countries to change either the technology policies or the regulatory structures in order to address the mismatch.

Further theoretical and empirical contributions to knowledge, rival propositions, and limitations of the study are addressed in the following sections. In order to address potential causes of the catching-up performances out of the rival propositions, Appendix Chapters are added. Appendix A analyses the relative technological capability of the two latecomers compared to the forerunners in the global nuclear and CCGTs markets. Appendix B analyses the Japanese aircraft engine capability in order to address the potential spill-over effects from the aircraft engine to the Japanese CCGT catching-up performance.

7.1.2. Theoretical Implications and Contribution

Contribution to the National Innovation System Framework

The case study built on and contributed to the broad version of the National Innovation System (NIS) literature (Lundvall et al., 2002) by employing and deepening its main analytical concepts. To researchers, it may be cost-effective to leave the intractable and complex institutional structure and focus on micro-level policy choices which are allowed within the structure, particularly in advanced economies where institutional structures are relatively well established. However, often idiosyncratic institutional arrangements with a rationale of resource allocation are deeply entrenched and seriously affect the overall catching-up performances in catching-up economy contexts, such as the cross-subsidy between the power generation and city gas sectors in Korea. Following the recipe of firm capability or NIS theories without addressing the institutional structure would not work in the catching-up contexts. In this sense, the case study built on the broad version of NIS.

Although the broad version NIS provides abstract concepts encompassing economic, social and political institutions influencing innovation activities beyond narrow science and technology development activities, more concise theoretical perspectives are rarely articulated. The case study supplemented the main concepts by integrating more specific perspectives, including institutional analysis, firm capability in the catching-up context and Porter's Hypothesis as specific analytical tools of the broad NIS framework as elaborated in Section 2.4.4. and Section 2.5.

Through the theoretical arrangement, the case study captured the effects of core economic and social regulations influencing the catching-up directions and rates of the two technologies in the two latecomer countries. In particular, it demonstrated a mutually exclusive pattern between the combination of catching-up performances and the combination of core regulations on the ESI(see page 181-186 and page 271-275), as compared to firm capabilities (page 305-307) and government's efforts through development programmes (page 309-311). Although the additional analytic perspectives do not explain the overarching story individually, they play a crucial role as parts of the integrated framework of the broad version NIS. In this way, it contributes to the generalisability of the broad version NIS beyond idiosyncratic catching-up cases. Through the integrated framework, the study provides additional contributions to the individual analytic perspectives.

Contribution to the Literature of Environmental Regulation and Innovation

This study exposed the gap in Porter's Hypothesis (Porter & van der Linde, 1995) of environmental regulation and innovation and the following literature. As environmental regulations do not exist in isolation, ignoring other regulations which influence the ESI could lead to false causality or ambivalent results at best. For instance, Porter's Hypothesis, *per se*, cannot explain Korea's remarkable nuclear catching-up

performance despite its lax safety regulations and Japan's weak nuclear catching-up performance despite the stringent safety regulations unless combined effects of environmental and economic regulations are considered. Although Porter's Hypothesis plays a role in explaining micro-level innovations, such as Japan's stringent safety regulation and Sumitomo Metal's 'low-noise' steam generator tubes and Korea's lax safety regulation and repeated failures of steam generator tube localisation efforts (see page 306-307), it cannot explain the overall catching-up performance.

Alternatively, the study showed the strong economic regulations on the Korean ESI not only secured continuous nuclear construction projects but also provided efficient mobilisation of resources and leveraging capability during the technology transfer process and the nuclear export deal. The efficient mobilisation of resources based on the strong economic regulation more than offset the potential micro-level innovation effect of the lax safety regulations. This pattern is replicated in both technologies across the two countries in opposite directions as anticipated. Autonomous economic regulations of the Japanese ESI did not secure the rapid growth of baseload demand for new nuclear construction projects despite the micro-level innovations, such as the low-noise steam generator tubes.

The tranquilising effect of economic regulations on Porter's Hypothesis appears to originate from a difference between the regulatory purposes as reviewed in Section 2.4.4 (see page 66). Economic regulations, in general, are motivated by resource allocation purposes, such as support of specific industries and economic welfare through energy subsidies, while environmental regulations require compliance and induce firms' innovations for compliance. The case study urges the following researches of Porter's Hypothesis to pay attention to the intrinsic tension between economic regulations and environmental regulations and its combined effects on the overall innovation (or catching-up) performances.

Contribution to Firm Capability Literature in the Catching-up Context

The case study demonstrated leveraging capability and combinative capability through catching-up firms' technology transfer process and modification processes. In particular, swift mobilisation of resources by the state-owned ESI during the technology transfer process of the American reactors played a crucial role in leveraging the whole package of reactor technologies from the blueprints to On-The-Job training in the Korean case. The leveraging capability enabled the Korean nuclear consortium to rapidly acquire modern reactor technologies within one and a half-decade skipping the intermediate stages that the Japanese counterparts followed through from the first generation small reactors to the modern reactors.

In this way, the finding suggests the possibility of conceptual expansion of "institutional resources" of the firm capability literature in the catching-up context. While the concept is used as a rather narrow term, such as public institutes for technology transfer facilitation, the case study shows the regulatory framework of the ESI, *per se*, could be the "institutional resources" in inducing attractive demand for foreign firms to the domestic market and leveraging technology transfer options.

Contributions to Institutional Analysis

The study findings contribute to the institutional analysis literature (Williamson, 2000) by analysing the evolution of governance structures from the historic events as the cause of focal regulations of the ESI in both country cases. In particular, the cases showed that SCAP's Occupation of Japan during the post-war period and the military Coup by *Park Chung-hee* in the 1960s' Korea shaped the contrasting governance structures of the Japanese and Korean electricity markets. Within the contrasting governance structures, energy ministries' degree of freedom in regulating the ESI has been polarised between the two countries. The study demonstrated that the contrasting governance structures

affected the ESI operation, including energy pricing, electricity supply planning, execution of reactor construction projects, and resource mobilisation for technology transfer and nuclear export projects, toward opposite ways across the two countries.

In addition to the economic issue, it also demonstrated the process from historic environmental events, such as *Yokkaichi Asthma* in Japan and mass carbon monoxide poisonings in Korea, to the establishment of stringent environmental regulations and gasification of the electricity supply market in Japan and cross-subsidy for rapid gasification of households in Korea, respectively. Ironically, the two historic environmental events shaped contrasting market conditions of CCGTs between the two countries. While Williamson(2000)'s institutional analysis and governance structure are focused on the variation of regulatory instruments between market incentive and administrative control, the case study demonstrated a necessity to pay attention to the combined effect of economic and social regulations within a specific sector, such as the ESI.

Given that a specific regulation does not play in isolation, the assumption of the combined effects of heterogeneous regulations is more realistic and intuitive. Nevertheless, the combined effect of multiple regulations is not yet well established in the literature. In this context, the case study captured a detailed process from a few historic events to the establishment of corresponding regulations to the combined effects on the catching-up performances in the two countries. In particular, the contrasting regulatory combination and following combined effects in the cases suggest that it is possible to capture generalisable patterns of evolutions in the governance structure of the ESI for international comparison.

This case study supplements such a perspective depending on a single regulatory factor and its effect by demonstrating a combined effect of the two core regulations, including environmental and economic regulations of the user sector. The framework in Chapter 3 anticipates that there are contrasting sets of institutions of ESI between Japan and Korea,

in accounting for the dichotomy of cross-technology and cross-nation catching-up performances. The case study results confirm the contrast of institutions between the two countries as anticipated by the proposition. Accordingly, research questions are addressed below.

Research Question 1: Why did Japanese and Korean HEIs show dichotomously contrasting catching-up performances between nuclear power and gas turbines in the past three decades?

The case study shows that the contrasting institutional set of ESI between the two countries effectively incentivises one technology while effectively constrain the other technology. It also shows the specific institutional sets are not randomly emerged but historically ingrained elements of the ESIs in both countries. By comparison, other potential factors, including public R&D efforts, and technological capabilities of HEI firms and upstream suppliers in both countries, do not match with the performance results in the case study.

Research Question 2: What are the specific weaknesses of user-supplier linkages of the Korean HEI that might explain contrasting catching-up performance between nuclear and gas turbines, compared to their Japanese counterpart?

The case study shows ambivalent results. ‘The lack of user-supplier relationship’ or ‘the lack of producer-specialized supplier relationship’ are commonly raised as a major obstacle for other Korean manufacturing industries to shift from their past technology catching-up success to emerging technology areas in the empirical literature. Regarding the ‘user-supplier’ relationship, the interviewees in the Korean case consistently point out the lack of demand for CCGTs in the Korean electricity market as the main obstacle for catching-up. The uncertain future demand for CCGTs also discourages private and public actors’ investment in human resources and in-house R&Ds.

Regarding the ‘producer-specialized supplier’ relationship, Korean a precision caster has exhibited relatively advanced performances than its HEI partner regarding gas turbine technology catching-up. Nevertheless, deficient demand for gas turbines has effectively constrained the precision caster from further user-producer interactions. The repeated public R&Ds without involvement in commercial gas turbine projects have not given a chance for the precision caster to get access to advanced technologies. Even a niche market such as the gas turbine repair service is blocked by foreign OEMs’ new strategy. It does not square with contexts and capabilities of other Korean specialised suppliers in other manufacturing sectors such as machine tool sector. Instead, the case study results point to the current Korean electricity market, which is locking-out gas turbines as discussed above.

Research Question 3: To what extent, can a specific set of user sector’s institutions explain the contrasting catching-up performances of the Korean HEI, as compared to the experiences of the Japanese?

Although the case study results show constraining effects of ESI’s institutions on gas turbine catching-up performances of Korean HEI, there is still uncertainty in addressing the degree of constraining effect. The large technology gap between the Korean latecomer and the global gas turbine OEMs leave such uncertainties. Nevertheless, it is clear that the current institutional set of Korean ESI blocks the chance of technology transfer from advanced foreign firms. Considering both of the successful Japanese CCGTs and Korean nuclear cases have benefitted from a match between domestic institutions of ESI and global market change, the current institutional set of Korean ESI is not prepared for a future window of opportunity.

7.1.3. Policy Implications

The case study demonstrated the unsatisfactory catching-up performances compared to the governments’ efforts, mostly focused on public R&D programmes. The

study results imply that the unsatisfactory catching-up performance of the Korean CCGT case would repeat unless the existing economic and environmental regulations of the ESI are reformed. It pointed out that the economic regulations continue despite the rationales of resource allocation already exhausted by showing the cross-subsidy between power generation and household city gas sectors despite the world record level of gasification rate of Korean households and continued electricity price subsidy scheme for specific steel industries despite the saturated demand for those steel products.

The sectoral-level level juxtaposition of institutions and policies shows what governments should consider before they plan a specific energy technology catching-up policy. Although NSI literature addresses the mismatch issue between national institutions and technology development policies (Freeman 1997), the thesis reveals that some specific technology catching-up policies, such as CCGT, may need a thorough and comprehensive evaluation of the policies in terms of fitness with the existing institutions across relevant sectors, user sector's institutions. In other words, policymakers who pursue energy technology catching-up policies may need cohesive evaluations and subsequent reforms of the existing institutional set of ESI before the start of a specific policy programme.

In particular, the set of cross-subsidies that once functioned well for rapid socio-economic development in the 1980s and 90s, are now hampering Korean NSI for 'catching-up shift' of the HEI while continuing to support already strong NSI for nuclear technology development. The Korean case shows how the cross-subsidies for the city gas sector weakened not only the price competitiveness of CCGTs but also the demand and incentives of stakeholders for investment on human resources and technology of CCGTs in Korea. In this context, repetition of undifferentiated technology catching-up policies, such as public R&D programmes, may result in unsatisfactory catching-up performances.

On the other hand, this case study raises a necessity of overall reform of the major institutions surrounding the Korean HEI and ESI to recover resilience of the catching-up

policy in question. Although unorthodox institutional arrangements for rapid catching-up, often addressed as “getting relative price wrong”, in the 1970s and 80s’ Korea worked well, the Korean case demonstrated that socio-economic factors have dramatically changed for the past three decades. It raises a question about the efficacy of such cross-subsidies in energy pricing practices in terms of social welfare as well as catching-up policies. The city gas penetration rate already reached to the world highest level while the price of city gas is even cheaper than that of some natural gas exporting countries due to the continued cross-subsidy. In a similar vein, the saturation of demand for specific steel industry questions about the efficacy of the intense TOU electricity pricing, which cross-subsidise EAF steel, at the expense of other manufacturing industries.

The Korean cross-subsidy issue is comparable to the US and European restriction on natural gas use for power generation in the 1970s. Although the restriction was legislated based on misinformation about natural gas reserves and political concern on city gas consumers, once the misinformation was corrected the governments abolished the restriction in the next decade. The withdrawal was resilient enough, though not much prompt, for the American CCGT OEMs to rapidly recover their innovative activities.

In addition, the Korean case highlights that the loose environmental and safety regulations and practices in the ESI need to be strengthened and sophisticated. It is not only for more efficient catching-up but also to address public discontent regarding safety and environmental concerns in the country. The Japanese case shows that stringent but gradual environmental regulations offered the Japanese CCGT firms a runaway into the global CCGT market. Sophisticated environmental and economic regulations could let the Korean HEI prepare future shocks, whether internal or external and exploit the window of opportunity.

The case study also has some implications for the Japanese nuclear policy that enthusiastically sought export cases even after the Fukushima accident. The export success of the Korean nuclear power seems hardly replicable in the Japanese case. The

Korean export case mainly comes from the efficient mobilisation of financing, vertically integrated supply chain from A&E to construction sub-contractors, and the subsequent cost performance based on the state-owned monopoly ESI, namely KEPCO.

However, the Japanese HEI has an entirely different catching-up path and institutional background from its Korean counterpart. The strong autonomy of private ESI firms in the decision-making of new investments, extensive and stringent safety inspection, as well as exhaustive reactor retrofitting works in Japan after the Fukushima accident make an export case virtually impossible to achieve. The withdrawals of Hitachi, Toshiba and Mitsubishi from the nuclear export market in the late 2010s give the evidence.

7.2. Comparing the Findings with Rival Explanations

As discussed in the Methods Chapter, there could be three rival explanations for the research results. These alternative explanations derive from the firm-level capability approach and the SSI approach are addressed, below.

Rival Proposition 1: The cross-technology and cross-nation contrast in catching-up performance is a result of different firm capabilities, including supporting industries' capabilities.

Rival Proposition 2: The cross-technology and cross-nation contrast in catching-up performance is a mere coincidence, given that the two technologies are different, and each has its own independent sector.

Rival Proposition 3: The cross-technology and cross-nation contrast in catching-up performance is a result of different R&D efforts, including the size of public expenditure and frequency of R&D projects.

Rival Proposition 1 (Firm Capability Approach)

The firm-level capability approach can only partially explain the contrasting shapes and performances across the two countries, given that the major characteristics and performances of HEI firms are co-evolved with sectoral and inter-sectoral institutions. Considering the technological gap between Japanese and Korean HEI firms, in terms of scope and depth, the firm-level capability approach has a limit in explaining the less successful catch-up performance of the Japanese nuclear power, and the pronounced success of the Korean nuclear power.

The limit of the firm capability approach is more evident if supporting industry firms' capabilities are compared. The case study highlighted that the Japanese HEI has been unsuccessful in nuclear power catching-up despite specialty metal firm's highly sophisticated component technology capability, such as steam generator tube, whereas its Korean counterpart has been successful in nuclear power catching-up despite specialty firm's incompetence in the same component technology.

Rival Proposition 2 (Sectoral System of Innovation Approach)

The SSI approach assumes that different technologies within the same sector might have different subsystems. From this assumption, mutually irrelevant co-existence of the two technologies within the HEI sector could be deduced.

However, the case study highlighted that catching-up performances of the two technologies are substantially influenced by the homogeneous set of institutions in the user sector in terms of operation, construction, indigenisation and export. In particular, the case study showed that the same set of the ESI's institutions incentives one technology while effectively constrains the other. Thus, the two technologies are highly relevant elements of the same sector.

Rival Proposition 3 (Public Research Efforts Claim)

The case study exhibits all the major public R&D programmes without consideration of cohesive institutional context have failed, while even in successful cases, such as the Japanese gas turbine and the Korean nuclear, the R&D programmes played an only supplementary role. Furthermore, the stark contrast between the large public expenditure for the R&D programmes in the failed cases such as the Japanese nuclear case, and the minuscule public expenditure in the successful cases reject this kind of claim. Duration and frequency of such R&D programmes do not square with the results, as well.

In order to clarify possible causes of the contrasting catching-up performances out the research framework and the rival propositions, Appendix Chapter. Analyses the two latecomer countries' performance during the advanced nuclear and CCGT development programmes in the US. Appendix Chapter B analyses the Japanese aircraft engine capabilities and the potential ramifications to the country's CCGT performance.

7.3. Limitations and Suggestions

The comparative case study of the cross-technology and cross-nation catching-up performances inevitably limits in-depth analysis of each technology and sector. By themselves, each sector and technology deserves in-depth single case studies in finding more detailed variables in explaining their catching-up performances from a different perspective. For instance, the analysis of the actors' network and knowledge base is limited by only focusing on institutional factors amongst the sectoral components. Amongst the two sectors of the Japanese case, this study lacks direct information sources on HEI and its upstream specialist suppliers. Thereby, the comparative case study results have a limit in claiming a definite causality. The Japanese HEI and specialised metal industries, in particular, need a further in-depth case study.

Regarding methodology, the qualitative comparative case study approach of the thesis was effective in highlighting the dichotomy of cross-nation and cross-technology catching-up performances. Focusing on the pattern of institutional sets as an explaining variable of the contrasting catching performances generated further insights. Although it is difficult to witness institutional change, and the subsequent results in catching-up performance, this thesis analysed institutional variation, and its subsequent effects, through contrasting institutional sets across the two case countries.

Appendix A. Advanced Energy Programmes and Ramifications to the Latecomers' Catching-up Performances

A1. Chapter Introduction

This Appendix Chapter describes a representing aspect of state-of-the-arts of commercial nuclear and CCGT technologies originated from two advanced energy technology programmes in the US and respective ramifications to the Japanese and Korean latecomers. The advanced nuclear and CCGT development programmes were public and private reactions to considerable changes in economic and environmental regulations in the 1980s and 90s (see Section 2.2.). In this perspective, the US Department of Energy (DOE) and the relevant industries launched two major public-private energy technology development programmes, namely Advanced Light Water Reactor (ALWR) (1985-1999) and Advanced Turbine System (ATS) (1993-2001) programmes.¹⁴⁹

In order to cope with the conflicting requirements of the environment (safety in case of nuclear power) and economics, a respective consensus among the US DOE, the ESI and the HEI emerged in each of nuclear and CCGT cases. The shared idea was that each technology would need a new technological approach in addition to incremental innovations of existing commercial technologies to overcome the conflicting requirements. The nuclear OEMs focused on the application of nuclear submarine technologies, which was previously impractical to apply due to scale-up issues, to nuclear power plants, while the CCGT OEMs focused on the application of non-jet engine technology to CCGTs beyond the technical boundary of their jet engine predecessors.

¹⁴⁹ Although there have been miscellaneous energy programmes in the US, the two were the largest public-private programmes among them in the past three decades and played a decisive role in shaping state-of-the-art innovations of nuclear and CCGT technologies in the global market.

Although the Japanese and Korean latecomers did not play any meaningful role in the new approach of the US energy programmes abovementioned, they actively took advantage of the innovations from the programmes through cooperative relationships with their American licensors. The Chapter shows their relative catching-up performances in exploiting the results of the energy programmes as well as their relative positions in the global nuclear and CCGT markets. In comparing relative catching-up performances and capabilities of the Japanese and Korean latecomers in both technologies, the Chapter shows to what extent the latecomers' capabilities are different in terms of their relative resilience in the relationship with their American technology licensors during and after the programmes.

A2. Advanced Light Water Reactor Programme in 1985-1999

Serious concerns about the future of the US nuclear industry brought by major nuclear accidents, including Three Mile Island (1979) and Chernobyl (1986), triggered Advanced Light Water Reactor (ALWR) Programme in the 1980s. The shared consensus that the industry could not afford another major accident weakened the nuclear industry's resistance to stricter safety regulations and standards. Furthermore, the industry leaders themselves urged that new nuclear designs should reduce the accident probability by two orders of magnitude lower than existing reactors to gain future public acceptance of nuclear power (MacKerron, 1992). The nuclear industry's accident probability is expressed as Core Damage Frequency (CDF) per reactor year, and the CDF of existing average PWRs is considered as 5×10^{-5} /RY, for instance (Gaio, 2010).

In addition to the safety concern, the US ESI and its advisory body, Electric Power Research Institute (EPRI), articulated safer and modularised reactor design requirements which standardise subsystems and components for reduction of the construction lead-

time and capital cost. Although EPRI's voluntary programme for 'the next generation light water reactor' was launched in the mid-1980s, details of the programme were embodied by "Advanced Light Water Reactor Utilities Requirements Documents" in 1990 which contain owner-operator guidelines to the US nuclear OEMs of the new reactors. The documents suggested mainly two versions of new reactor requirements, namely Mid-Sized Light Water Reactors (LWRs) with Passive Safety Features and Large Evolutionary LWRs (NRC, 1992; Cummins & Matzie, 2018). The former required simplified and passive safety systems beyond existing reactors while the latter required modified and scaled-up designs of existing reactors. The OEMs developed AP600 (Westinghouse) and SBWR (General Electric) in responding to the former and ABWR (GE), APWR-1300 (Westinghouse), and System 80+ (CE) in responding to the latter (Table A1).

Table A1. Nuclear Reactor Designs of the ALWR Programme and the Results

	Design (MW)	OEM	Results	
			US Market	Other Markets
Mid-Sized Reactors (Passive)	AP600 (615)	WE	Certified (1999); Scaled-up AP1000 reactors were constructed in China (2018) & US (2022, expected)	
	SBWR (600)	GE	Not Certified	-
Large Evolutionary Reactors	ABWR (1,350)	GE	Certified (1997), Expired (2002)	Four units constructed in Japan from 1996
	APWR (1,350)	WE	Not Certified	Certified in Japan (1987) but never constructed
	System80+ (1,300)	CE	Certified (1997), Expired (2002)	Modified & Constructed as APR1400 in Korea (2016) & UAE (2018)

Source: Author's elaboration from NRC 1992 and Cummins & Matzie 2018

Note: SBWR and AP600 stand for Simplified BWR and Advanced Passive 600, respectively.

The reason why the 'Mid-Size' was emphasised for the passive reactor was that much larger capacity than a reference size of 600 MW would be impractical or not cost-effective for the purpose. More extensive safety-related equipment, such as reactor vessel and cooling water tanks, would be inadequate for passive operation without electricity supply during emergency conditions, or it would be too expensive to make them operable.

Also, smaller reactor sizes would enable shorter construction lead time, more extensive modularisation of equipment, and more efficient learning by replication (Taylor et al., 1989).

However, the initial consideration of the passive reactor development was shifted to the economy of scale from the early 1990s when abundant and low-cost natural gas became available to CCGT power generation developers due to the regulatory change of natural gas and electricity supply markets in the US (see Section 2.2.1). The lift of the previous ban on natural gas use for power generation enabled the emergence of low-cost CCGT power generation while the liberalisation of the electricity market enabled CCGT's direct competition with nuclear power. The OEMs for the passive reactors, GE and Westinghouse, turned to larger reactor designs, such as Economic Simplified BWR (ESBWR) (1,500MW) and AP1000 (1,100MW), in order to lower capital costs in the middle of the ALWR programme (Ahearne et al., 2001; Davis et al., 2002).

Neither OEM realised how much cost they would pay for the abrupt scale-up. Although Westinghouse received the certification of the AP600 in 1999 and the initial certification of AP1000 from the US NRC in 2006 with a subsequent subsidy programme, namely "Nuclear Power 2010", it had to change the designs repeatedly for another decade. By comparison, GE not only withdrew from the development process of SBWR but also failed at completing the ESBWR design due to safety concerns on its components, such as steam dryer, and the eventual withdrawal of the designated user, Entergy, from the ESBWR construction project in 2015 (US DOE, 2012; Nuclear Engineering International, 2015).

Unlike the complicated scale-up and design change processes of the passive reactor group, the Large Evolutionary LWRs group made a straightforward completion of designs. ABWR and System 80+ received design certifications from the US NRC in 1997, respectively, but never commercialised in the US market. The American electric utilities were rather indifferent to the reactors and focused on the passive reactors, particularly

AP1000 (Cummins & Matzie, 2018). Instead, the certified Large Evolutionary LWRs's designs were transferred to the Japanese and Korean latecomers. The technology transfer process and results will be dealt with in Section A4.

A2.1. Canned Motor Pump: Flagship Technology of the ALWR

Significant differences in AP600 design and its scale-up version, AP1000, from previous and existing reactors are simplified and passive safety systems. It reduced miscellaneous valves, pipes, pumps and control cables extensively in order to reduce the overall construction cost as well as operational complexity. In terms of the passive safety system, it applies gravity, convection, and stored energy for natural circulation rather than active systems using pumps which need electricity supply during severe events, such as station blackout and Loss of Coolant Accident (LOCA).

Among various innovations of AP600/AP1000, replacement of existing 'sealed shaft' reactor coolant pumps (RCPs) with 'canned motor' RCPs represents the simplified and passive characteristics of the design. The sealed shaft RCPs are widely used in most of existing commercial PWRs in the world. Attached to the coolant pipes between the reactor and the steam generator, the sealed shaft RCPs drive circulation of reactor coolant from the steam generator to the reactor (Figure A1). The impeller section of the RCP is exposed to the high-pressure and high-temperature reactor coolant system, for instance, at about 15.5Mpa (155 bar) and 290°C in existing Westinghouse reactors, while its motor section is exposed to much lower pressure within the containment building. The enormous pressure differential between the impeller and the motor sections induces leaking up of the hot and contaminated reactor coolant into the motor section through the penetrating shaft. In order to minimise the leakage, the labyrinth seal package is located between the motor and impeller sections. Filtered seal injection water passes both down

to the reactor coolant system and upward to the seal cartridge to enhance the sealing function (US NRC Technical Training Center: 4-15, 4-21) (Figure A2).

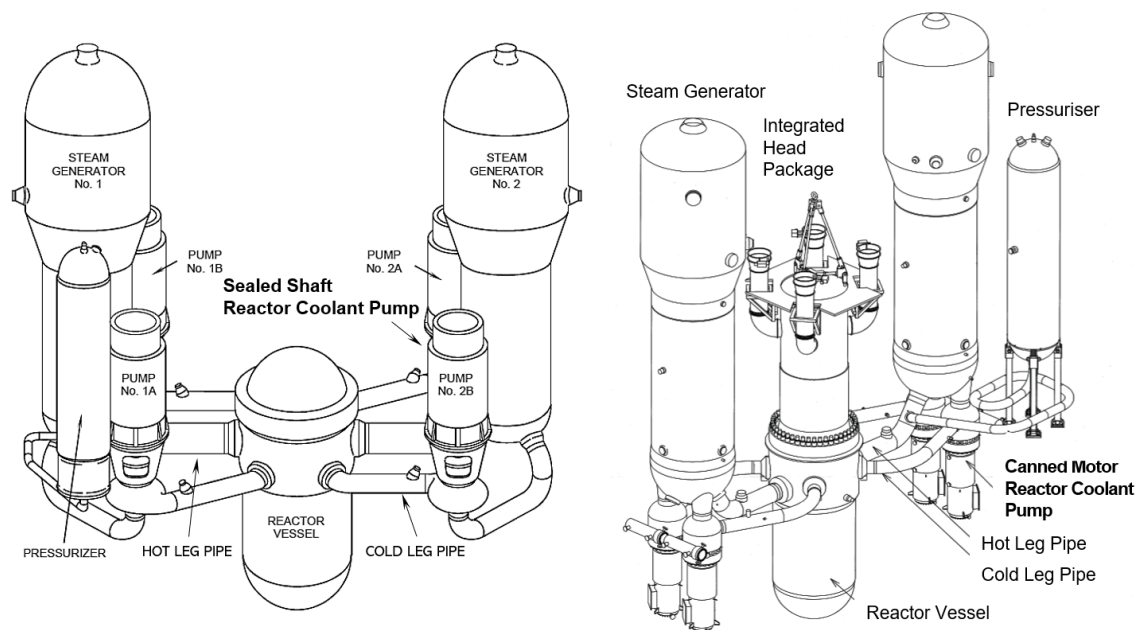
Despite the complex sealing package, it is inevitable for the RCP to leak the reactor coolant water due to the massive pressure differential. Thus, the nuclear safety regulation allows leaks of the reactor coolant to a certain amount, for instance, 20 gallons per minute in the Westinghouse models. Any coolant water that does leak up the shaft is collected and routed to the seal leak-off system for collection in various systems (US NRC Technical Training Center: 4-15, 4-21). The sealed shaft RCPs not only incur radiation exposure of workers during the maintenance but also can induce so-called small break LOCA which eventually could lead to uncovering of the reactor core (IAEA, 2004; Gaio, 2010) (Figure A1 and A2).

In order to eliminate the coolant water leaks and probability of the small break LOCA, Westinghouse applied the canned motor RCPs into the AP600/AP1000 designs. The term 'canned motor' originates from the configuration that each rotor and stator of the motor section is 'canned' with a thin non-magnet stainless sheet for protection from the reactor coolant. The pump eliminates pressure differential between the impeller and the motor sections and leakage of the contaminated coolant water into the atmosphere by locating the pumps within the so-called 'pressure boundary' of the reactor coolant system. Also, it uses cooled reactor coolant water through a heat exchanger, rather than electric fans and oils, for cooling and lubricating bearings (Figure A1 and A3).

In this context, the canned motor RCP has been the flagship technology of AP600/AP1000 since the start of the ALWR programme. The OEM summarises the advantages of the canned motor design over the conventional sealed shaft RCPs as below:

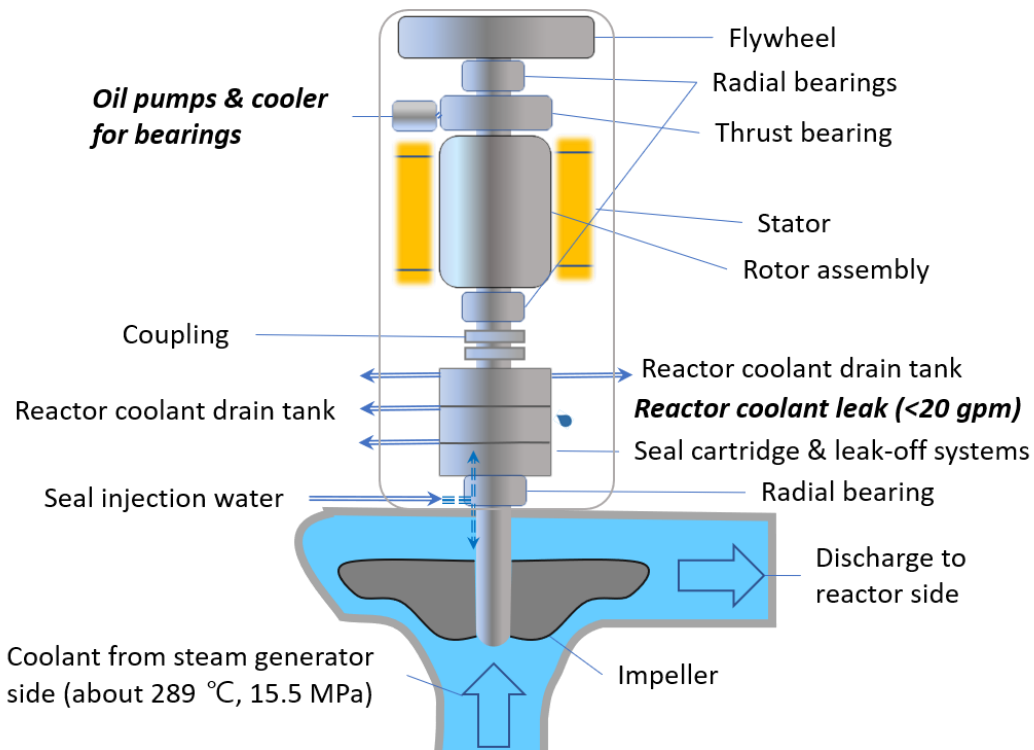
- Elimination of the shaft seal and the system needed to maintain seal injection
- By eliminating this seal and seal injection, a potential leakage path of primary coolant and a source of small break LOCA are also eliminated
- Canned motor pumps require very little or no maintenance and thereby also help lower worker dose (Gaio, 2010: 7)

Figure A1. Reactor Coolant Systems of Conventional PWRs and AP1000



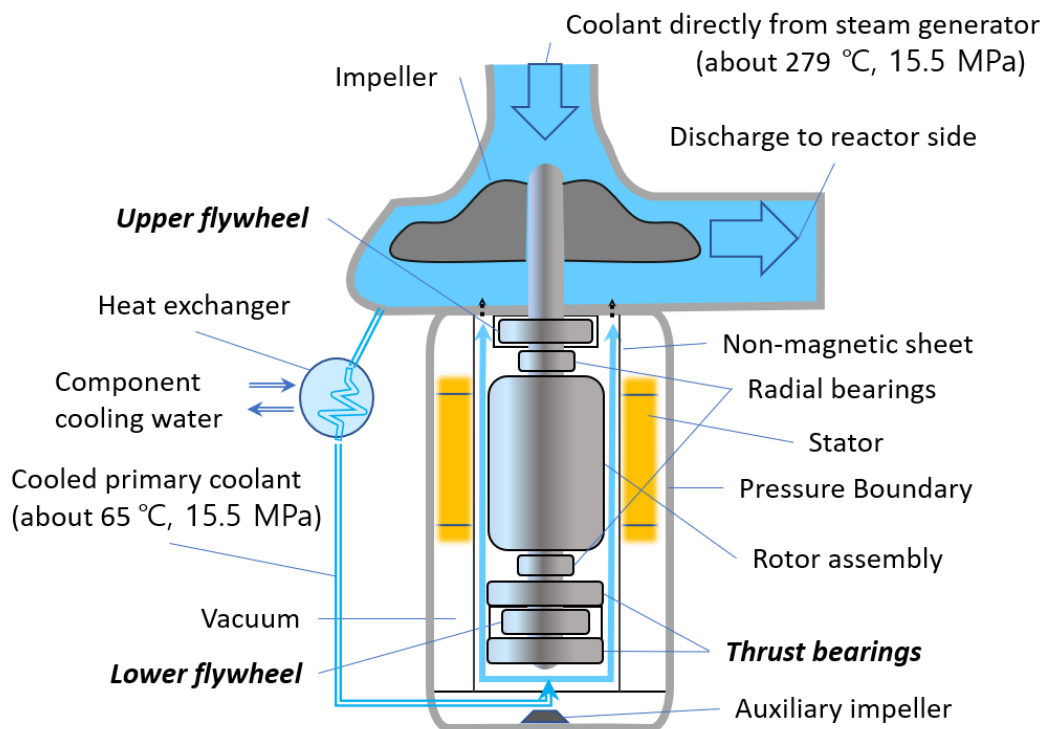
Source: Adapted from USNRC Technical Training Center and Westinghouse Electric Company LLC. 2011
 Note 1: System 80 reactor coolant system on the left is a typical two-loop PWR design among existing PWRs.
 Note 2: The copyright in this image is owned by Westinghouse Electric Company LLC. Reprinted with permission.

Figure A2. A Conceptual Diagram of the Sealed Shaft Type Reactor Coolant Pump



Source: Author's elaboration from US NRC Technical Training Center

Figure A3. A Conceptual Diagram of the Canned Motor Reactor Coolant Pump (AP1000)



Source: Author's elaboration from Westinghouse Electric Company LLC. 2011

Concerning the overall safety system, the canned motor RCPs would facilitate the natural circulation of AP1000 during severe events, such as station blackout, by attaching the pumps onto the bottom head of steam generators in an inverse position and removing interconnected coolant pipes (Figure A1). Although they have been widely used in the US Navy ships, such as submarines and aircraft carriers, since the *Nautilus* in 1955, it was unavailable to commercial reactors due to technical limits in scaling-up. Only a few small prototype reactors in the late 1950s, such as Shippingport, applied the canned motor RCPs. During the ALWR programme, however, Westinghouse considered the technology for Navy applications became mature enough to scale-up for commercial nuclear reactors, such as AP600 and even larger AP1000, and it would be minor modifications as below:

All major components of both AP600 and AP1000 have been proven in operating reactors under similar flow, temperature, and pressure conditions, except for the AP1000 reactor coolant pump. It is a modest extension of proven pump designs (Cummins et al., 2003: 3).

A2.2. The Reality of the Canned Motor Pump and Its Impact on AP1000

Contrary to the hopeful appraisals during the programme, the scale-up process of the canned motor RCPs for commercial reactors involved much more than a simple extension of dimensions of its predecessors for the naval propulsion. Thermal distortions of the enlarged components which could lead to failure of 'bearing film', protecting the bearings from the hot reactor coolant, brought re-design issues, for instance. Scaling up and subsequent optimisation of rotating parts, such as flywheels, bearings, and auxiliary impellers brought severe technical challenges too. They caused malfunctions due to defects in design and materials and repeatedly delayed the AP1000 projects, including *Sanmen* Unit 1&2 and *Haiyang* Unit 1&2 in China. Consequently, the issue delayed five years of project schedules and still causes problems, such as coolant leakage of the pumps

at *Sanmen* Unit 2 as of 2019. The coolant leakage is a serious issue given that all the components of motors are integrated into the “leak-proof” pumps and are designed to operate for the life cycle of reactors without maintenance in principle. The experiences make additional AP1000 projects unlikely in China (Freebairn, 2014, 2019; MacLachlan, 2010).

On the other hand, the earlier experience of the RCP problems in China does not seem much helpful for improvements in other AP1000 construction projects in the US, such as Vogtle in Georgia and Summer in South Carolina. Although the US Energy Information Administration admits that a technological optimism factor of a first-of-a-kind reactor, such as AP1000, tends to underestimate actual costs of such a new design, it assumes the problems would be addressed as experience is gained after building first four units (US EIA, 2017). Similar problems of the pumps in addition to quality control issues of the subcontractors caused delays of the projects for five years in the US even after the experience of four units in China, however. Thermal distortion of the bearings was one of the main problems of the pumps in the projects. Faced with repeated repairs, redesigns and delays with substantial cost increases, Westinghouse filed for bankruptcy while the Summer project was cancelled in 2017 (Freebairn, 2015; Hals & Flitter, 2017).

The repeated re-design, re-manufacturing and construction delays doubled the construction cost. Initially, the project was planned to be completed by 2017 with the total construction cost of about US\$14 billion when the electricity utility consortium applied the US federal government’s loan guarantee in 2008. However, the consortium announced in 2017 that the estimated project cost doubled to about US\$28 billion and the project schedule would be delayed to 2022. The US DOE subsidised the project about US\$12 billion in total to alleviate the cost overrun issue of the consortium as of 2019 (Patel, 2018; US DOE, 2019).

The only reason why the Vogtle project continues is that the cancellation cost is higher than the forecasted loss from the project completion, given that the project secured

a conditional subsidy including tax credit and direct subsidy upon completion of the construction from the US DOE. With this experience, the global nuclear market analysts, such as Chris Gadowski from BloombergNEF, evaluate that “the AP1000 is dead in China, and it may very well be dead all over the world (South China Morning Post, 2019)”. A joint inspection group of Chinese and American safety regulators, namely National Nuclear Safety Administration of China and the US NRC, on the RCP issue of AP1000, criticised overall problems from the design to quality control to manufacturing as below:

The observations from the RCP design and manufacturing inspection indicated that the previous quality incidents with the RCPs were caused by inadequacies in the design process, insufficient personnel qualification assessments, process control inadequacies, insufficient subcontractor oversight, inadequate control during manufacturing, and a poor operator’s awareness to quality (NEA, 2018: 8).

Despite the blame on the overall issues of the canned motor RCPs, it should be reminded that Westinghouse has been successful in designing and manufacturing of the canned motor RCPs for the US Navy ships since the 1950s (Hewlett & Duncan, 1974; MacLachlan, 2009). Westinghouse’s Electro-Mechanical Division has been an original manufacturer of the canned motor RCPs for the US Navy ships. Although it was acquired by Curtis-Wright in 2002, it still supplied the RCPs to all AP1000 projects in China and the US (MacLachlan, 2009, 2010).

The core problem of the RCPs for commercial reactors is the abrupt scale-up without addressing accompanied risks. In that the Seawolf-class nuclear submarines (220MWt) in 1997 and Shippingport prototype reactor (225MWt) in 1957 have been the largest reactors using the RCPs in the US nuclear history, AP1000 (3,400MWt) was an

abrupt scale-up.¹⁵⁰ Even the largest US Navy aircraft carriers, such as *Nimitz*-class, use two reactors of about 220MWt instead of one larger reactor. Although AP1000 is based on AP600 design (1,933MWt), AP600 was never constructed and could not provide a reliable base for the scale-up process. Westinghouse's huge leap of scale by a factor of nearly 15 without similar operational experience for the past half a century brought irretrievable costs, including doubling construction costs, its bankruptcy, cancellation of remaining projects, and despairing future of the design (Table A2).

Table A2. Abrupt Scale-Up Evolution of the Reactors Using 'Canned Motor RCPs'

	1955	1957	1997	2006	2018
Purpose	Submarine	Power Plant	Submarine	Design Only	Power Plant
Name	<i>Nautilus</i>	Shippingport	Seawolf	AP600	AP1000
Capacity (MWt)	70	225	220	1,933	3,400

Source: Author's elaboration from Cummins & Matzie 2018, Ragebh 2011, Hewlett and Duncan 1974

Thereby, the design and manufacturing problems of the canned motor RCPs that the regulators pointed out were the *effect* of the scale-up rather than the cause of the problems. It is worthwhile to remind the lesson of early scale-up trials by the US Navy and Westinghouse in order to figure out the core problem of the AP1000 issues. The first nuclear power plant using the canned motor RCPs was Shippingport (1957). Although the prototype reactor was the scale-up of the *Nautilus* submarine reactor by a factor of *only three*, the scale-up process was accompanied by severe burdens of design and engineering (Table A2). Even after the construction of Shippingport, Westinghouse and the US ESI scrapped the canned motor RCPs and switched to current 'sealed shaft' RCPs for larger nuclear power plants from the 1960s. A historical review of the US Atomic Energy Commission, predecessor of the US DOE and the US NRC, indicates that there had been

¹⁵⁰ Megawatt thermal (MWt) refers to thermal power capacity of nuclear reactors before the power is converted to electrical power, the capacity of which is measured as MWe or MW.

overwhelming burdens in designing and manufacturing during the scale-up process from the *Nautilus* to Shippingport as below:

Scale-up itself involved much more than just putting new dimensions on old blueprints. ... Fabricating a vessel of this size would push existing technology to its limits and generate new engineering problems. The same could be said for the huge canned motor pumps, hydraulic valves, and steam generators needed to control 225 megawatts of thermal energy. ... It shifted the heaviest load of responsibility from the already overburdened design forces to component fabricators (Hewlett & Duncan 1974: 243).

A3. Advanced Turbine System Programme in 1993-2001

As can be seen in the nuclear power case, the reforms of economic and environmental regulations in the late 1980s and early 90s in the US resulted in a dramatic change of the global CCGT market (See Section 2.2.1). Deregulation of the US electricity market and declining natural gas price made power plant developers wait and see until the market adjustment. The US DOE considered that the increased uncertainty might discourage the American OEMs' innovation efforts and the tightening emission standards would threaten their competitiveness. In this policy background, DOE launched a public-private gas turbine development programme, namely Advanced Turbine System (ATS), facilitating cooperative networks between the American CCGT OEMs, national research institutes, universities and precision casters in 1992 (Rycroft & Kash, 1999; Curtis, 2003).

The networks of internal and external resources which the CCGT OEMs exploited during the programme demonstrate that the advanced NIS of the US cannot be replicated in any other nations. While GE exploited knowledge stock of its internal resources,

including GE Aircraft Engines (GEAE) and GE Corporate Research & Development (GECRD), for improving aerodynamics and combustion systems, Westinghouse mostly depended on the networks of external resources, including US national laboratories, the US Air Force, precision casters, and universities to overcome its limited knowledge in materials, aerodynamics and combustion fields. In particular, Westinghouse took advantage of the advanced capabilities within the national laboratories, including the National Aeronautics and Space Administration (NASA)'s Glenn Research Center and the US Air Force's Institute of Technology. The network with the national research centres provided a rare chance to improve Westinghouse's limited capabilities in aircraft engine technologies, which became a base of its steam cooling technologies (Rycroft & Kash, 1999; Curtis, 2003) (Table A3).

Table A3. Networks of Internal & External Resources of CCGT OEMs in the ATS

	GEPS	Westinghouse (Siemens)
Closed-loop Steam Cooling	GEAE, GECRD	R-R, MHI, NASA, US Air Force
	Precision Casters (Howmet, PCC Airfoil)	
Single Crystal Alloy Casting		ORNL
	Precision Casters (Howmet, PCC Airfoil)	
Thermal Barrier Coating	GEAE, GECRD	ORNL, R-R
DLNC	GECRD, US Air Force	NETL, Universities (Clemson, Georgia Tech., Carnegie Mellon)

Source: Adapted from Rycroft & Kash 1999

Note: GEAE = GE Aircraft Engine, GECRD = GE Corporate Research & Development, R-R = Rolls-Royce, MHI = Mitsubishi Heavy Industries, NASA = National Aeronautics and Space Administration, ORNL = Oak Ridge National Laboratory, NETL = National Energy Technology Laboratory

The development programme aimed at higher energy efficiency above 60 per cent and lower NO_x emission less than ten parts per million (ppm) departing from those of existing F-class CCGTs, developed by GE and Westinghouse in the late 1980s and early 90s. Alongside the external pressure of the conflicting requirements, the intractable characteristics of the CCGT technology are that higher efficiency of the gas turbine cycle

is accompanied by higher temperature of combustion leading to an exponential increase of NO_x emission. In tackling the bottleneck, the ATS programme devised four main targets, including i) closed-loop steam cooling system against existing air-cooling system, ii) large SC blades and vanes against existing DS ones, iii) advanced DLNC, and iv) advanced thermal barrier coating for blades and vanes (Curtis, 2003; Jeff, 2008).

A3.1. Closed-loop Steam Cooling: Flagship Technology of the ATS

Major technology development of the CCGTs in the ATS programme was the closed-loop steam cooling. Previously, CCGTs entirely depended on extracted air from the compressor for cooling of the inner combustor wall as well as turbine blades and vanes.¹⁵¹ The air cooling, however, not only interrupts injections of air for combustion from the compressor to the combustor generating more NO_x emission but also reduces energy efficiency. Also, the discharged cooling air through miscellaneous fine holes of the first stage vanes drops the hot gas path temperature which is the driving force of the blades in the first and second stages, and thereby lower energy efficiency (Diakuenchak et al., 2002) (Figure A4).

In tackling the problem, the OEMs applied a non-jet engine technology concept, namely closed-loop steam cooling. This design utilises steam from the heat recovery steam generator (HRSG) of CCGTs for cooling vanes, and blades if possible, and returns the heated steam to the HRSG for driving steam turbines. It minimises parasitic air extraction from the compressor, thus provides stable and more air rich combustion reducing NO_x emission. At the same time, it sustains a higher hot gas path temperature between the first stage vanes and following blades by eliminating air discharge into the hot gas path. The

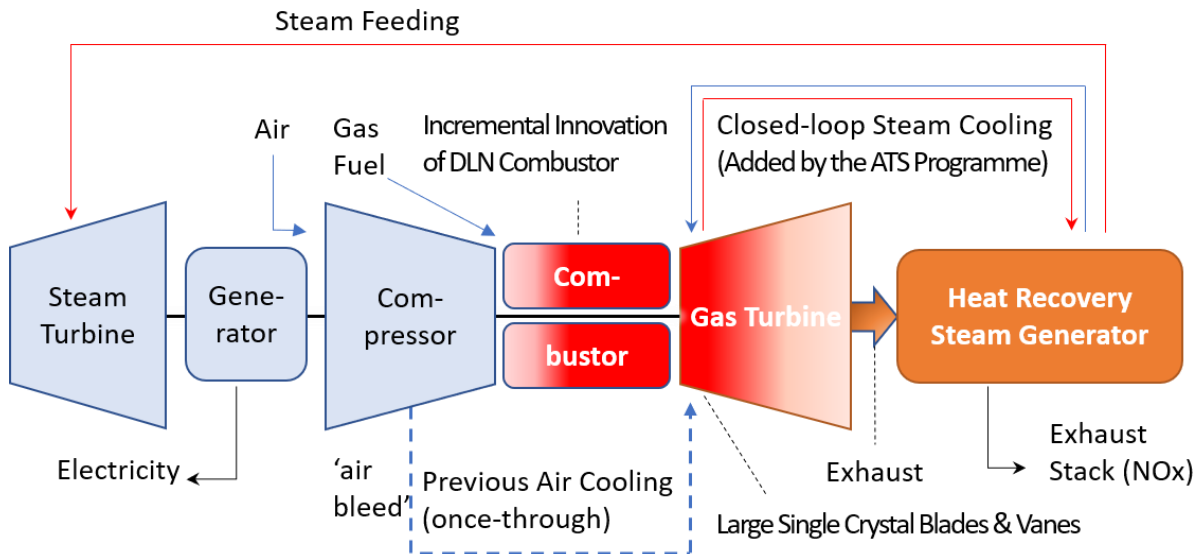
¹⁵¹ The OEMs call it 'air bleed' due to the parasitic nature of the air extraction from the compressor.

uninterrupted expansion of the hot gas transforms more thermal energy into kinetic energy of rotating blades and improves fuel efficiency (Figure A4 and A5).

General Electric led the innovation by applying the steam cooling to the vanes and blades of the first two stages in the four-stage gas turbine while Westinghouse's steam cooling concept was limited to the vanes of first two stages. The remaining third and fourth stages still use air cooling or are uncooled (Gülen, 2019; Matta et al., 2000; Siemens Westinghouse Power Corporation, 2004). The technology was transferred to MHI through a cooperative development between MHI and Westinghouse in the mid-1990s and to Siemens through its acquisition of Westinghouse in 1998 (Jeff, 2008; Soares, 2008).

At the end of the programme, the OEMs appeared successful in developing their next-generation CCGTs reaching 60 per cent of thermal efficiency and achieving single-digit NO_x emission, namely GE's H-system and Siemens/Westinghouse's G & H classes, in the late 1990s and early 2000s. The early observations of the programme appraised the achievements, including steam cooling, as a 'transitional' innovation departing from traditional incremental innovations (Rycroft & Kash, 1999; Curtis, 2003). Serious problems of the flagship technology, namely steam cooling, would be unveiled in the following years of field operation, however.

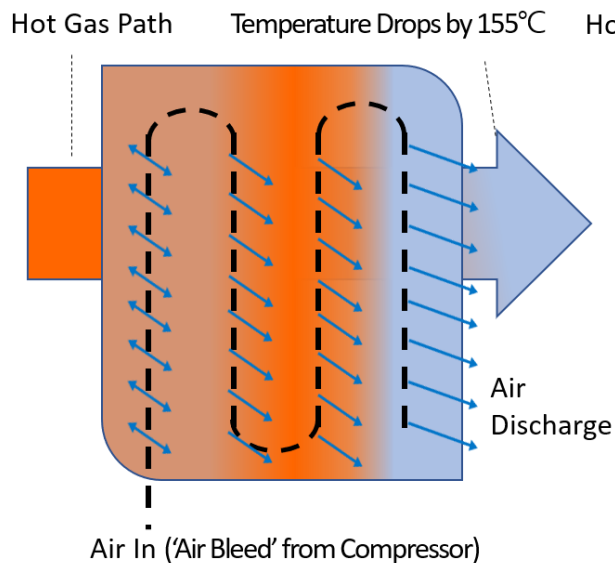
Figure A4. Conceptual Diagram of the Closed-Loop Steam Cooling CCGTs



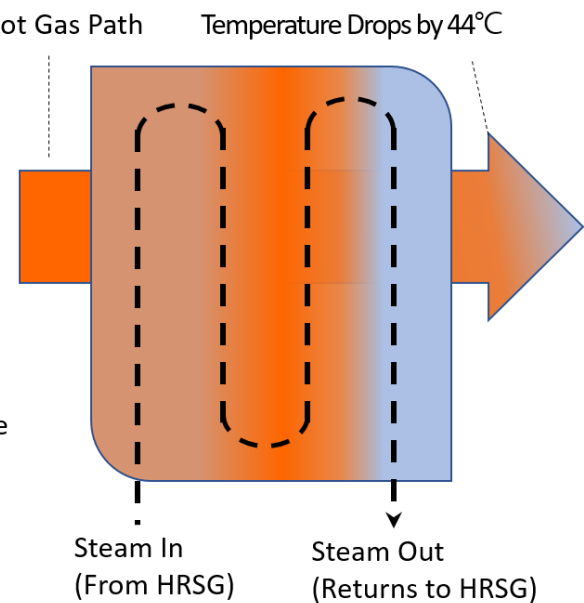
Source: Author's elaboration from Matta et al. 2000 and Diakuenchak et al. 2002

Figure A5. Conceptual Diagrams of 'Air Cooling' and 'Steam Cooling' Vanes

Air Cooling Vane (1st Stage)



Steam Cooling Vane (1st Stage)



Source: Ibid.

A3.2. The Reality of the ATS Programme

Contrary to the initial observation, the flagship technology of the ATS programme turned out to be commercially impractical during the several years' field operation after the programme. The closed-loop steam-cooling system not only increases the operational complexity but also weakens the flexibility, which is the core technological competitiveness of CCGTs. Miscellaneous redundant equipment, such as intermediate boilers, expensive alloy pipes and valves, should be added between the gas turbine, the HRSG and the steam turbine for harnessing the benefits of the system. The operational complexity due to the integration with the steam cycle weakens the flexibility of the CCGTs in responding to changing loads from start-up to full-load. For instance, start-up of the steam cooling CCGTs takes much longer than the air cooling ones given that the steam is unavailable from the HRSG when they start-up. It makes them use air cooling during the start-up phase and switch to steam cooling once the CCGT reaches a certain level of load, say above 15 per cent of the capacity, and steam from the HRSG is available. Otherwise, they need to install auxiliary boilers to provide cooling steams in order to start-up faster, which also complicate the operational process (Gülen, 2019; Jeff, 2008).

Having struggled with the operational complexity issue during up to a decade's disappointing experiences in the field, both GE and Siemens/Westinghouse completely abandoned the steam cooling design and returned to the air-cooling one. For instance, Siemens/Westinghouse started development of air-cooling in 2005 and commercialised SGT5-8000H in 2011 while GE replaced its steam-cooling H-system with the air-cooling HA-system in 2015. It makes MHI, which never participated in the ATS programme, the only steam cooling CCGT OEM, technically limited though (Jeff, 2008; Gülen, 2019).

Failure of the closed-loop steam cooling in the ATS programme reveals risks of energy technology development efforts without prior experience in reference sectors, such as aircraft jet engines. While the air cooling technologies have been proven with long years' development and operating experience by jet engine OEMs during the Cold War

era and well appreciated by CCGT OEMs, the closed-loop steam cooling design was alien to both sectors. The CCGT OEMs would need substantially more development efforts and time to reach successful commercialisation of the steam-cooling unless they find sources from other sectors to exploit relevant knowledge and experience.

Except for the steam cooling system, the OEMs were successful in relatively incremental innovations in other areas, such as improvement of DLNC, applications of SC alloy blades, and thermal barrier coating (TBC). Although the OEMs previously developed DLNC for the F-class CCGTs in the late 1980s and early 90s, the programme facilitated the OEMs' upgrade of the still immature DLNC technologies, for instance. They drove a commercial success of CCGTs in the last decade despite the failure of the steam cooling. Some of the incremental innovations of CCGTs based on jet engine technologies need brief explanation here.

Initially developed by jet engine OEMs, SC blades are made without grain boundaries by precision casting techniques. The traditional casting processes produce polycrystal alloys having grain boundaries which are vulnerable to oxidation, corrosion and cracking. Although the CCGT OEMs applied DS technology, also based on jet engine technologies, to mitigate the problems of polycrystal blades, it still contains grain boundaries. Only GE has been successful in the application of the SC blades to CCGTs mainly due to its advanced jet engine capabilities and advanced American precision casters. Although Siemens/Westinghouse also developed the large SC blades during the programme, it abandoned it due to increasing price of core material, namely rhenium, and returned to DS blades. GE maintained the technology by replacing the expensive rare metal with an alternative one.

Another application of jet engine technology into CCGTs during the ATS was active clearance control (ACC). The ACC improves fuel efficiency and lifecycle of gas turbines by adjusting gaps between the turbine blade tips and the turbine casing to the desired level according to operational conditions. The metal volume of the blades and

casing parts could expand or contract asymmetrically according to changing thermal loads of gas turbines and alter gaps between the two parts. The alternating clearance beyond the desired level either generates wasteful leakage of hot gas from the combustor allowing the hot gas to bypass the blades or induces harmful frictions between the two parts. GE Aircraft Engine developed the ACC using electronic sensors and cooling air control valves in the early 1980s. Its ACC for aircraft engine utilises compressor air and fan air to expand or contract the blade shroud according to operational conditions (Lattime & Steinetz, 2002; Lennard & Fasching, 1982).

Exploiting the prior innovation of its aircraft engine division, GE developed ACC for its CCGTs during the ATS programme. Unlike GE, Westinghouse and its successor, Siemens, with weak aircraft engine capabilities had to develop alternative ACC technologies for CCGTs. Westinghouse developed a conceptual design of the ACC using its limited steam cooling technology with the support from the national aircraft engine research centres at the end of the programme. Siemens abandoned the limited ACC design after the acquisition of Westinghouse, however. Instead, Siemens commercialised a simplified version of ACC, namely hydraulic clearance optimisation, in 2005. It moves the entire set of turbine blades toward the compressor side by pulling the rotor with a hydraulic piston to reduce the clearance between the blade tips and the conical shape of turbine casing when the gas turbine reaches a predetermined load, and the casing is thermally expanded to outward (Langston, 2013; Gülen, 2019).¹⁵²

¹⁵² Figure A4 provides tips about the concept using the conical shape of the turbine casing.

A4. Ramifications of the Advanced Programmes and the Results

A4.1. Ramifications to the Global Nuclear and CCGT Markets

First, the American CCGT and nuclear OEMs benefitted from the advanced American NIS which could not be replicated in other nations. The programmes demonstrated to what extent the OEMs could exploit the advanced infrastructure including the advanced national research centres, specialised suppliers and universities. It raises a question about the efficacy of a narrow version NIS literature, based on the specific context of the US, to other national cases.

Second, the programme results demonstrated that even the advanced nuclear and CCGT OEMs in the most advanced NIS could not escape from the technical boundary shaped by the prior experience in their respective traditional reference sectors. It shows that radical energy technology development without enough experience in the reference sectors is accompanied by substantial risks as warned in the literature (Cook & Surrey, 1989; Sahal, 1985). The empirical literature on the programmes either finds the OEMs' sourcing of complementary knowledge from relevant sectors as a success factor (Bergek et al., 2008) or concentrates on immediate technological achievements of the programmes (Cummins & Matzie, 2018; Cummins et al., 2003; Curtis, 2003). However, the literature pays little attention to the eventual failure of the flagship technologies and its ramifications to the industries. The results of the two programmes deserve special attention regarding lessons to future energy technology innovations.

Third, relative technological flexibility decided the winner and the loser in the current global electricity market despite the failure of flagship technologies in both programmes. The CCGT OEMs succeeded in compensating the failure of the steam cooling by incremental innovations in other technical areas, whereas the nuclear counterpart's failure in the canned motor RCPs influenced entire projects irreversibly. It seems that the modularised characteristics of gas and steam turbine parts allowed the

flexible adaptation of the CCGT OEMs upon the failure of the flagship design while the nuclear counterpart got stuck in the ambitious scale-up of the pump, an inseparable subsystem of the passive reactor coolant system. A substantial difference in capital cost and construction lead time widened the difference of flexibility between the two technologies. The difference enabled the CCGT OEMs to discard their failed design through the experience of full-scale field operations before further investment while restricted the nuclear OEM's verification process within quasi field-tests using other reactors, which were not sufficient to realise the extent of problems.

Table A4 highlights the initial performance targets and eventual achievements against the conflicting requirements of environment and economics in each programme. It also juxtaposes the major initial innovations, field experiences and commercial results of the two programmes. Both programmes appear to succeed in achieving their initial targets in safety and environmental requirements unless the canned motor RCP issue of AP1000 recurs. However, their economic performances polarise. In terms of overnight construction cost, which includes direct & indirect construction costs and owner's cost, AP1000 was estimated as much as about \$1,000/kW in 2002 (Davis et al., 2002). The cost, however, escalated to \$8,600/kW in 2017 when Georgia Power filed its construction cost estimate of the Vogtle project to the Public Utility Commission of Georgia State (MIT Energy Initiative, 2018).

A first-of-a-kind (FOAK) reactor, such as AP1000, may incur an extra cost in the beginning, and the cost may decrease as following reactors are constructed. Learning effects between the first four AP1000 units in China and the other four American units seem negligible, however. Also, the official cost of the Vogtle project has doubled from the utility consortium's initial cost estimation in 2008 which already covered the extra cost regarding the FOAK issue (Patel, 2018; MIT Energy Initiative, 2018). Compared to the nuclear counterpart, CCGT OEMs achieved the economic target in terms of overall efficiency despite the failure of the steam cooling technology (Table A4).

Table A4. Overall Results of the Advanced Energy Programmes in the US

Concern of Economics				Environmental & Safety Concern	
Nuclear (ALWR)		Overnight Construction Cost(\$/kW)		Core Damage Frequency (CDF) ³	
		Target: \$1,363 ¹	Result: \$8,600 ²	Target: 5 × 10 ⁻⁷ /RY	Result: 5 × 10 ⁻⁷ /RY
	Innovations	Simplified Passive Safety System, Canned Motor Coolant Pump (AP1000)			
	Field Experience	Repeated Design Changes, Construction Delay, Cost Overrun			
	Results	OEM's Bankruptcy, Several Projects Abandoned			
CCGT (ATS)		Thermal Efficiency (%) ⁴		NOx Emission (ppm) ⁴	
		Target > 60%	Result > 60%	Target < 10 ppm	Result < 10 ppm
	Innovations	Steam Cooling, SC Blades, DLNC Improvement, TBC, ACC			
	Field Experience	Operational Complexity of Steam Cooling			
	Results	Return to Air Cooling, Combustor Improvement			

Notes: 1. The figure is converted to 2017's US Dollar from Westinghouse's target (Davis et al., 2002)

2. The figure comes from Georgia Power's data in 2017 (MIT Energy Initiative, 2018)

3. Cummins & Matzie 2018,

4. Curtis 2003; Gülen 2019

A4.2 Performance of the Latecomers During and After The Two Programmes

A4.2.1 Performance of the Latecomers during and after the ALWR Programme

The Japanese and Korean latecomers' catching-up performances based on close cooperation with their American partners during and after the two programmes show their relative capabilities and limits. During the ALWR programme, the latecomers of both countries resiliently absorbed the 'Evolutionary Large Reactor' technologies, including ABWR, APWR and System 80+. In terms of localisation of the reactor designs, the Japanese latecomers show faster and more resilient capabilities than their Korean counterpart.

In particular, Hitachi, Toshiba and Mitsubishi were successful in cooperative development of ABWR and APWR designs with their respective licensors from the very

beginning phase of the programme. For instance, the three Japanese nuclear latecomers developed ABWR and APWR designs with the support from GE and Westinghouse, respectively, in the 1980s, when only early draft designs of the two reactors emerged in the US during the ALWR programme. It shows not only their remarkable absorptive capacity of the reactor technologies but also their resilient leveraging abilities in negotiating technology transfers from their licensors from such early stages.

However, their following performance limited to the construction of only four units of ABWR in Japan without any reactor export record. The four units of ABWR were not sufficient to overcome the unfavourable track record of the entire BWR fleet in the global market, including the higher radiation dose of maintenance workers and the negligible presence of BWRs out of the US and Japan, compared to the PWR counterpart (see Section 3.3.1 on page 64 and Section 5.3.2. on page 217-218 for details). It is unfortunate for MHI that it could never build APWRs and a subsequent track record for the past three decades considering the PWR-dominant global nuclear market context. The Japanese nuclear latecomers' unsatisfactory catching-up performance cannot be explained by a firm capability perspective, thereby. It is highly related to domestic institutions, such as strict safety regulations.

By comparison, the Korean latecomer is the biggest beneficiary of the ALWR programme in terms of its track record. It has constructed four units of APR1400 and has six more units of APR1400 under construction, including two in Korea and four in the UAE, despite its slower technology transfer of System 80+ design from GE in the 1990s (see Section 4.3.2 and Section 5.3.2 for details). Given that construction projects in the respective domestic market could make a big difference in terms of the track records and the maturation of the newly developed reactors, a combination of safety and economic regulations of the domestic electricity market has been a decisive factor to the catching-up performance in the two countries (see Section 6.2.1 and 6.2.2).

In particular, Korea's success in APR1400 was supported by the tight economic regulation on the electricity market from the rapid mobilisation of financial and human resources in the technology transfer process to securing the reactor construction projects through the national electricity supply plan. The resource mobilisation, the electricity supply plans and rapid execution of the construction projects were realised by the state-owned monopoly ESI, namely Korea Electric Power Co.(KEPCO), under the government's tight control. The monopoly status of the ESI played a role in protecting the reactor construction projects from safety regulations.

The absorptive capacity of the Korean nuclear consortium, including KHNP, KEPCO and *Doosan*, in learning CE design System 80+ was remarkable from the technology transfer of basic design features in 1992 to the design certification of APR1400 by the Korean safety regulator in 2002. It was based on the accumulated capabilities during the previous System 80 design from CE for developing the Korean Standard Nuclear Power (KSNP) reactor in the 1980s. Nevertheless, the extent of design modifications involving the combinative capability from System 80+ to APR1400 was marginal. In effect, the APR1400 design is virtually same to the System 80+ design, having the same core size and fuel lattice type (16 × 16 CE fuel type) (KEPCO/KHNP, 2018) (Table A5).

Table A5. Design Features of APR1400 and CE's System 80+

Design Features		APR1400	System 80+	KSNP(System80)
Capacity (Mwe)		1,400	1,300	1,000
Safety Goal (CDF/Ry)		$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-4}$
Containment		Cylindrical	Spherical	Cylindrical
ECS	No. of Trains (nozzle)	4	4	2
	Safety Injection	Direct Vessel Injection	Direct Vessel Injection	Cold Leg Injection
	RWST Location	Inside Containment	Inside Containment	Outside Containment
Seismic Design (g)		0.3	0.3	0.2

Source: Lee et al. 2010; KEPCO/KHNP 2018

Among basic components of nuclear power plant cost, including capital cost, operating and maintenance cost, and fuel cost, the capital cost is the largest component. Capital cost is composed of two parts. The first part is the overnight cost. The ‘overnight cost’ refers to the cost of building the plant, including equipment, construction materials, and labour, regardless of how long it takes to complete the construction. The term ‘overnight’ comes from the assumption that the reactor is constructed ‘overnight’. The second part is the cost of interest on financial arrangements to build the reactor, affected by the time required to construct the reactor and the composite interest rate of the funds used. The cost of interest on the funds makes it difficult to compare the economic performance of reactors in the global market due to the variety of financial arrangements according to nations, however. (MIT Energy Initiative, 2018).

Thereby, the overnight cost gives relatively straightforward figures in comparing the economic competitiveness of reactors without concerning distortions due to the financial arrangements or subsidies. In addition, the construction lead time also gives a criterion to figure out the relative performance of reactors in the international comparison given that the additional months induce an exponential increase of the overall capital cost. Although the two indicators are not enough to figure out the relative competitiveness of nuclear power compared to other energy technologies, they provide a straightforward yardstick to compare relative competitiveness among reactors.

Hitachi/Toshiba/GE alliance’s Kashiwazaki-Kariwa unit 6, completed in 1996, in Japan is the first commercialised case among the ALWR programme results. The ABWR projects in Japan have been the shortest in terms of construction lead time and one of the cheapest in terms of overnight cost among the ALWR-derivative reactors in the past three decades. Despite the remarkable performance, the strict domestic safety regulation preventing further ABWRs after the first four units in Japan and the dismal track record of the BWR fleet beyond Japan and the US in the global market constrained the Japanese latecomers’ catching-up performance as abovementioned (Table A6).

Table A6. Economic Performance of the Latecomers in the Global Nuclear Market

		Construction Lead Time	Overnight Cost	Construction Status	
		Months	\$/kW (2017's price)	Start	Completion
ABWR	Kashiwazaki-6 (Japan)	48 ^I	4,298 ^D	1992 ^I	1996 ^I
APR1400	Shin-Kori-3 (Korea)	98 ^I	2,090 ^N	2008 ^I	2016 ^I
	Barakah-1 (UAE) ^M	96 ^e	4,000	2012	2020
AP1000	Vogtle-3 (US) ^M	104	8,600	2013	2021
EPR	Olkiluoto-3 (Finland) ^M	174	8,000	2005	2019
	Flamanville-3 (France) ^M	126	7,400	2007	2019

Source: Du and Parsons 2009(D); MIT Energy Initiative 2018(M); NEA 2015(D); IAEA Power Reactor Information System(I); crude estimate based on the industry's expectation (e)

Note 1: ABWR=Advanced Boiling Water Reactor, APR1400=Advanced Power Reactor 1400, EPR=European Pressurised Reactor, AP1000=Advanced Passive 1000

By comparison, Korea's APR1400 reactor was constructed two decades after the first unit of Japan's ABWR and took nearly double construction lead time compared to the ABWR counterpart. The forgery scandal of the qualification certificate of some components in 2012 delayed the construction schedule as long as three years and delayed its export project in the UAE for the same duration. Even if the scandal and following delays of the schedule are excluded from the calculation, the APR1400 projects lag behind its ABWR counterpart. Instead, the Shin-Kori units' overnight cost has been the cheapest among the OECD countries.

Although the overnight cost of Shin-Kori units is not well accepted by the literature other than Nuclear Energy Agency of OECD due to the transparency issue of detail components, that of the Barakah units in the UAE is considered still the cheapest among the recent nuclear construction projects in the literature (MIT Energy Initiative, 2018)(Table A5). Together with the economic performance, the world highest operational performance of Korea's domestic PWR fleet in terms of capacity factor contributed to its reactor export to the UAE in 2009 outpacing its competitors in the global market (Table A5).

A4.2.2 Performance of the Latecomers during and after the ATS Programme

Regarding the ATS programme, the catching-up picture across the two latecomer countries is the opposite. While Japan's MHI was remarkable in modifying the new technologies from Westinghouse and commercialising them into its own J-series CCGTs, the Korean latecomer never could exploit the benefits of the programme due to its limited capability and arm's length relationship with GE, its licensor at that time. Heavy electrical divisions of MHI and Hitachi, except their nuclear divisions, merged to MHPS in 2014 (See Section 5.4.3). This Chapter uses MHI instead of MHPS in order to avoid confusion, however. Korea's *Samsung Aerospace* was struggling with a tiny emergency purpose gas turbine (1.2MW) without advanced foreign firms and designated users when MHI was busy with absorbing and modifying advanced technologies from Westinghouse with a close partnership with Tohoku Power during the ATS programme.

In particular, MHI demonstrated its combinative capability during and after the programme. While the programme provided Westinghouse advanced external knowledge networks in reducing a technology gap with GE, MHI efficiently exploited the benefits through its close relationship with Westinghouse. The combinative capability of MHI was pronounced when the ATS participants abandoned the failed technologies after the programme. Whereas Siemens abandoned Westinghouse's steam cooling and ACC designs, MHI kept the steam cooling application to reduced stationary parts, such as the combustor and the blade rings (inner parts of the turbine casing) like Westinghouse's design. The purpose of the limited steam cooling was for enhancing its already competitive DLNC and compensating its weak ACC capability rather than the overall efficiency. MHI's tweaking of the limited steam cooling technology for DLNC and ACC purposes has ramifications in three aspects.

First, the limited steam cooling deepened MHI's already competitive technology, namely DLNC, further. It already has been competitive in the combustor in the global CCGT market since its pioneering commercialisation of DLNC in 1984. The technical

bottleneck of the combustor innovation is that higher flame temperature for efficiency improvement induces an exponential increase of NO_x emission. In overcoming the bottleneck, MHI's steam cooled combustor transition piece, meaning the inner combustor wall for the hot gas path from the combustor to the turbine, eliminates extraction of 'air bleed' from the compressor for the cooling the inner wall and enables air-rich and fuel-lean combustion minimising NO_x emission. Besides, the elimination of the cooling air from the inner wall minimises thermal loss of the hot gas due to dilution with the cooling air. Thereby, the steam cooling enables MHI's DLNC to preserve more thermal energy of the hot gas and increase electrical output at the same flame temperature and NO_x emission of the previous combustors.

Secondly, MHI's limited steam cooling compensated its weak ACC capability. The steam secures clearance between the rings and blade tips by thermally expanding the rings outward while minimises the clearance by cooling the expanded rings at a predetermined load (Fukuizumi et al., 2004; Gülen, 2019). As explained in Section A3.1, the ACC technologies for CCGTs originated from the aircraft engine OEMs, such as GE Aircraft Engine. Westinghouse, MHI's CCGT partner at that time, did not have the aircraft engine capabilities while MHI's aircraft engine licensor, namely P&W, has been bounded by the US export control, however (see Section B1). It was the ATS programme that provided Westinghouse external networks with aircraft engine research centres reducing the gap of aerodynamics capability and enabled the OEM to develop conceptual ACC designs using the steam cooling. MHI exploited the benefits through its alliance with Westinghouse. It explains somehow why MHI strived to exploit even the failed steam cooling technology. Mitsubishi's weakness in aircraft engine and its implication to catching-up performance in CCGTs, other than the ACC issue, will be analysed further in Appendix Chapter B.

Thirdly, MHI's gradual approach, which limited the steam cooling application to the combustor and the blade rings, minimised the expensive transition cost between the

air-cooling and the steam-cooling designs. It is comparable to GE's expensive trial of the fully steam-cooling H-system which covers cooling of blades and vanes and the return to air-cooling HA-system after the complete abandonment of the steam-cooling design. It is also comparable to Westinghouse efforts to expand its steam cooling application to vanes of the first two stages through its W501ATS gas turbine design (Table A6).

The gradual transition of MHI, deepening accompanied peripheral technologies, repeated during the return process from the limited steam cooling to air cooling in the early 2010s. Given that even the limited steam cooling incurred operational complexity and the additional cost, including auxiliary boilers, high-pressure steam pipes and materials, it was inevitable for MHI to shift to the advanced air cooling CCGT, such as the production of J Air-Cooled (JAC) from 2016. Its return process to air cooling was not the same as its competitors abandoned the steam cooling altogether with surrounding technologies, however. It incorporates the essential technical features of the limited steam cooling into its combustor cooling and ACC. It applies external air coolers for supplying the combustor transition piece compressed cooling air and the bypass air valve to control blade tip clearance assimilating its steam-cooling design (Gülen, 2019; Turbomachinery International, 2016) (Table A7).

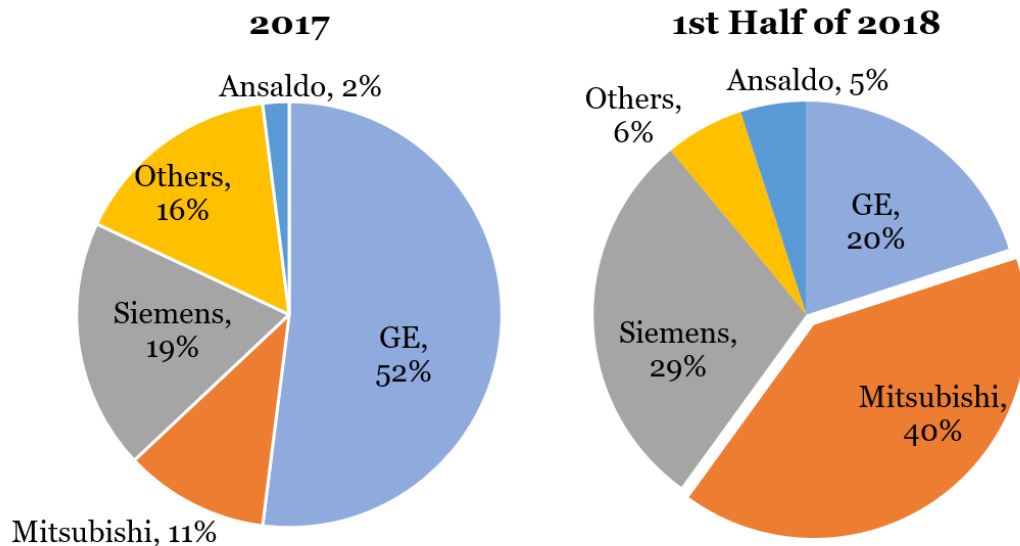
GE's hasty return process from the full-scale steam cooling to air cooling in order catch-up MHI and Siemens who initially applied the steam cooling to a quite limited area and replaced the steam cooling with air cooling one much earlier, respectively, incurred another transition cost. As briefly introduced in Section 5.3.3., GE's apparently hasty return process incurred the devastating blade failure of the HA-system CCGTs sold to four countries, including Japan, Taiwan, France and the US, from 2017. Although GE announced its plan to replace all blades of the HA CCGTs with alternatives in 2018, it had to hand over its leading position to MHI in the large CCGT market segment for the first time in its history (Scott, 2018, 2019; Gülen, 2019) (Figure A6).

Table A7. CCGT OEM's Transition between Steam Cooling and Air Cooling

Steam Cooling		Air Cooling
GE	H-System (1998~ the early 2010s): Full SC + ACC	HA-System (2015~): Air Cooling + Passive Clearance Control
S/W	W501G & W501ATS (1998~'05): Limited SC + Pilot ACC	SGT8000H (2011~): Air Cooling + Hydraulic Control
MHI	M501G & J-Series (1999~): More Limited SC + ACC	JAC-Series (2016~): Air Cooling + Enhanced ACC

Note: S/W = Siemens/Westinghouse, SC = Steam Cooling, ACC = Active Clearance Control

Figure A6. Global Gas Turbine Market Share by Capacity Ordered



Source: Author's elaboration from Scott 2018

A5. Chapter Conclusion

The Chapter analysed the two advanced energy technology programmes in the US with particular attention to their flagship technologies and relatively marginal

technologies in each programme in order to understand the technological sources and limits of the Japanese and Korean latecomers in nuclear and CCGT technologies from the global market perspective. It finds that neither the technological capability nor the NIS brought the advanced OEMs failures of the flagship technologies after the two programmes. It was the ignorance of a rule of thumb of energy technology development that brought the OEMs the failures. Their radical approaches, including the abrupt scale-up of military pumps for commercial nuclear reactors and the non-traditional integration of steam and gas turbine cycles, in the absence of sufficient experience of their traditional reference sectors, exposed them to the tremendous risks. Despite the failure of flagship technologies of both programmes, technological flexibility made a difference in the adaptation of the OEMs across nuclear power and CCGTs.

It also finds that changes in economic and environmental regulation on the US energy markets in the 1980s not only induced the two energy technology programmes but also influenced their relationship during the programmes. The regulatory reforms of electricity and natural gas markets induced the abrupt scale-up of the AP600 design concerning the prospective competition with CCGTs having access to cheap natural gas. Thereby, the institutional changes not only linked the two irrelevantly co-existed technologies into a direct competition but also changed the direction of the advanced nuclear programme, which eventually exacerbated the development process.

While the American OEMs paid substantial transition cost and time for their unqualified flagship technologies after the programmes, the Japanese and Korean latecomers caught-up with their American partners through either rapid deployment of the second-best reactor or limited applications of the unqualified design from the programmes. It could be considered as a typical benefit of latecomers that catch-up with forerunners from a distance assimilating only proven technologies while avoiding the development risks the forerunners should take. In this case, absorptive capacity and firm capability of latecomers are frequently emphasised as the source of catching-up

performance in the literature. Indeed, the Japanese CCGT latecomer's combinative capability and its nuclear counterparts' absorptive capacity have been remarkable in individual catching-up perspectives.

However, neither firm capability nor absorptive capacity explains the mutually-exclusive catching-up performances of the two latecomers across nuclear and CCGTs despite the Japanese latecomers' superior capabilities in both technologies, compared to the Korean counterpart. The failure of the Japanese nuclear latecomers in accumulating enough track records of ABWR and APWR in the country despite their decades earlier technology localisation of the ALWR-derivative reactors compared to the Korean counterpart was the result of domestic regulations rather than firm capabilities. Korea's nuclear export case in addition to continued construction projects in the country despite its much slower localisation of another ALWR-derivative reactor also urges to pay attention to institutional factors rather than firm capabilities.

Table A7. Latecomers' Catching-up Performance after the Two Programmes

American OEMs' Results			Latecomers' Catching-up	
ALWR (Nuclear)	AP1000 (W)	Failed with irretrievable cost due to abrupt scale-up of RCP	-	-
	System 80+ (CE)	Transferred to Korea	APR1400 (KHNP/DHIC)	Overcame the limited capability with rapid mobilisation of resources
	ABWR(GE)	Transferred to Hitachi & Toshiba	ABWR	Constrained by safety regulations despite superior absorptive capacity
	APWR(W)	Transferred to MHI	APWR	
ATS (CCGT)	HA-System (GE)	Return to Air Cooling with substantial transition cost, Incremental innovations in TBC & DLNC enabled the OEMs to thrive	J/JAC (MHI)	Limited Steam Cooling for enhancing already robust DLNC and compensating weak ACC,
	SGT5-8000H(SW)			Return to Air Cooling minimising transition cost & took a leading position

Appendix B. Japan's Jet Engine Capability and Limits

B1. Spill-over Effect of Jet Engine Technology to CCGTs

In order to clarify the possible spill-over effects of the Japanese jet engine capability to their CCGT catching-up performance, this Appendix Chapter analyses the potential and limits. As described in the case of Ishikawajima Precision Casting Co. (see Section 5.3.4), Japan's more extensive coverage in jet engine programmes and stronger performances in commercial aircraft engines compared to its Korean counterpart raises a question whether its CCGT success originates from its jet engine capability. For instance, IHI's licensed production share was about 60 per cent in both F-15J and F-2 (Japanese version of F-16) programmes in dollar value while *Samsung Techwin's* share during Korea's F-16 and F-15 fighter programmes were 41 per cent and 29 per cent, respectively (Chen, 2014; NRC, 1994).

Before the analysis of the potential of the Japanese version spill-over, it is necessary to look at a typical case of spill-over between aircraft engine and CCGT technologies. General Electric has efficiently exploited its advanced jet engine technologies in developing high-pressure turbine(HPT) components, thermal barrier coatings and DLNC for CCGTs. In improving the temperature of CCGTs, the material, casting process, and cooling design of the HPT blades and vanes of the jet engine were the key technological factors. General Electric's development of the F-class gas turbines in 1990 typifies the characteristics of the spill-over effect. It applied the same material (GTD111 superalloy), precision casting process (DS), and cooling air passage concept (serpentine) of its CF6 jet engine blades, developed in the late 1960s, to the F-class gas turbine blades (Peterson, 1989; Soares, 2008; Watson, 1997).

Regarding the DLNC technology of the F-class, GE developed the capability based on the North Atlantic Treaty Organisation (NATO)'s jet fighter programme for reducing NO_x emission which was a signature of radar detection during the Cold War era (Watson, 1997). In parallel with the military development, NASA also conducted a low NO_x combustor technology research programme from 1976 to prepare prospective requirements of the Clean Air Act (CAA) which would require all types of aircraft engines to reduce NO_x emission. Under NASA's support, GE and P&W participated the joint 'Experimental Clean Combustor Program' and researched a few combustor concepts, including premixed lean burn (Anderson, 1976; Munt, 1981). Although the programme did not result in immediate commercial success, it should have offered a substantial knowledge base to the DLNC of F-class gas turbine too.

However, the successful Japanese CCGT catching-up case did not depend on such a spill-over, at least in core parts. Among the three major Japanese jet engine makers, namely Ishikawajima-Harima Heavy Industries (IHI), Kawasaki Heavy Industries (KHI) and MHI, IHI has been the primary producer of military jet engine parts under GE and P&W licences in Japan while MHI has been more active in commercial jet engines under the P&W licence (NRC, 1994). Whether it is military or commercial, the Japanese engine makers have not had access to core parts of jet engines due to technology strategies of the global jet engine OEMs and the US government's export control.

In principle, the US government under the Arms Export Control Act of 1976 does not allow the transfer of core technologies both in the military and commercial jet engines, such as the 'hot section' of engines, to foreign partners.¹⁵³ More specifically, "exports of the most sensitive hot section technology have not been permitted, even to close allies" under the US Department of State's authority (GAO, 1997a: 18). Although it does not define what "the most sensitive hot section" indicates, technologies of the HPT blades and

¹⁵³ The hot section of the jet engine includes a combustor and a turbine while a cold section includes a turbofan and low-pressure and high-pressure compressors.

vanes which should endure high temperature and high-pressure have not been transferred from the global OEMs to the Japanese aircraft engine latecomers. Although licensed productions of some hot section parts have been allowed under government-to-government agreements, they were limited in technically non-core parts, such as a low-pressure turbine (LPT), in the Japanese air fighter programmes (GAO, 1997a, 1997b; NRC, 1994).

B2. Division of Labour Between Jet Engine OEMs and Parts Suppliers

There is a considerable difference between the HPT and the LPT in terms of severity which they should withstand and their contribution to the overall efficiency of engines. The compressed air stream, from a compressor, is mixed with fuel in a combustor and reaches a very high temperature. As the hot gas mass enters the HPT, its volume expands, and the energy is transformed into the kinetic energy of the HPT blades, the pressure and temperature of the hot gas shrink dramatically. In GE's GE90 series engines for commercial aircraft, for instance, the temperature of the air reaches about 1,500°C in the entrance of the HPT and drops to around 1,000°C before it enters the LPT (EASA, 2017; Lukachko & Waitz 1997).

Thereby, the aircraft engine OEMs' innovations concentrate on the HPT blades and vanes applying high-grade superalloy, complex air-cooling designs, TBC and ACC while leaving the LPT blades with low-grade or outmoded superalloys and often uncooled designs. The logic is the same as the CCGT counterpart's innovations concentrate on the first two stages of the modern four-stage gas turbines (see Section A3.1.). Instead, the global OEMs' primary concern on the LPT is reducing the count of blades and vanes to reduce the overall weight of jet engines and maintenance cost (Donachie & Donachie, 2002; Gier, 2008). It leads to the outsourcing of the LPT parts to licensed producers for cost reduction rather than technological issues.

The specific concern of weights in the aircraft engine industry makes the jet engine LPT technology even less relevant to CCGT OEMs that do not concern about the weight of power plants. Unlike the aircraft engine OEMs, the CCGT counterparts focus on the overall thermal efficiency of the gas turbines with increasingly larger and heavier LPT blades and vanes. Although relatively smaller CCGTs in the early 1990s, such as GE's 7001F case, improved efficiency using jet engine technology spun off the US Department of Defense (DOD) programmes, there has been a diverging trend between modern CCGT and DOD spill-over technologies in that required energy efficiency and the extent of NO_x control of CCGTs are far beyond those of the jet engines (NRC, 2001).

Therefore, there has been a clear division of labour between the global OEMs and parts suppliers in the global jet engine market. While the three OEMs, notably GE, P&W and Rolls Royce (R-R), cover the main engine control, overall system integration and high-pressure parts, including the HPT and high-pressure compressor, they outsource specific components for low-pressure parts, including the LPT & low-pressure compressor (LPC) and a low-pressure shaft, combustion chamber, and some accessory parts to respective licensed producers. For instance, they outsource LPT supply to Snecma (France), Avio (Italy), *Motoren Turbinen Union* (MTU) (Germany), Guest, Keen & Nettlefolds (GKN)/Volvo (UK), *Industria de Turbo Propulsores* (ITP) (Spain), IHI and KHI (Japan), while outsource combustor supply to another group including Avio, MHI (Japan), *Samsung Techwin* (Korea), GKN Volvo, Danville Metal Stamping and Turbo Combustor Technology (US).¹⁵⁴ The OEMs often invite those licensed producers as Risk and Revenue Sharing Partners for joint international aircraft engine programmes, such as V2500, to reduce development cost burden, but the division of labour is similar (EC, 2013).

Table B1. Shows the global LPT market share for large commercial aircraft (installed base) in 2013, dominated by numerous parts suppliers. Snecma's large market

¹⁵⁴ *Samsung Techwin* was taken by a Korean conglomerate and became *Hanwha Techwin* in 2015.

share comes from its special arrangement of production and marketing with GE in the EU region rather than its technological capability. MTU also has been actively involved in the production of LPT modules through the long-term alliance with P&W since the 1980s. The jet engine OEMs' own production of LPT is quite limited while they depend on outsourcing to the parts suppliers to reduce production cost. Often, the OEMs support the parts suppliers in manufacturing or even sponsor new entrants into the LPT market. R-R's support of a new entrant of ITP in 1992 shows the case (EC, 2013, 2017).

Despite the active involvement of the parts suppliers in the LPT market, the high-pressure parts are so critical that the deficiency of proprietary technological knowledge in the area acts as a substantial barrier for potential new entrants into the jet engine market. The parts suppliers do not have other choice but become subcontractors or joint venture partners of the jet engine OEMs (EC, 2001, 2013). It is not surprising that the LPT parts suppliers do not have an independent capability to develop CCGTs other than licensed manufacturing of parts of small aero-derivative gas turbines, such as IHI's production of GE's LM-series gas turbines.

Table B1. World Low-Pressure Turbine Market Share for Commercial Aircraft (2013)

	Narrow-body (100-200 seats)	Wide-body (200-400 seats)	Total
Snecma (France)	70-80%	5-10%	50-60%
MTU (Germany)	10-20%	10-20%	10-20%
GKN/Volvo (UK/Sweden)	0-5%	30-40%	10-20%
P&W (US)	5-10%	0-5%	5-10%
Avio (Italy)	5-10%	5-10%	5-10%
GE (US)	0-5%	0-5%	0-5%
KHI (Japan)	0-5%	0-5%	0-5%
IHI (Japan)	0-5%	10-20%	0-5%
ITP (Spain)	0-5%	10-20%	0-5%

Source: European Commission 2013: 21

Note: Avio and ITP were merged by GE and R-R in 2013 and 2017, respectively.

B3. Reversed Positions of the Japanese Jet Engine and CCGT Capabilities

Together with the clear division of labour in the global market, the US export control regime has effectively constrained Japanese aircraft engine capabilities. Japanese air fighter programmes have been a major source for the manufacturers' access to modern jet engine technologies. Ishikawajima-Harima has been the primary licensed-producer of jet engine parts among the Japanese engine makers during the Japanese air fighter programmes including P&W's F100 engines for F-15J in the 1980s and GE's F110 engines for F-2 in the 1990s and 2000s. In both programmes, IHI produced about 60 per cent of the engines in dollar value covering the LPT parts including LPT blades and vanes and low-pressure shafts. Nevertheless, the US export control regime prohibited licensed production of core engine technologies, such as HPT parts (Drohan, 2015; GAO, 1997b; NRC, 1994).

As such, the role of MHI's aero-engine division in the commercial engine programmes also has been limited in combustors and the non-HPT parts. While MHI took a part of the development of fuselages and avionics systems rather than jet engines in both Japanese fighter programmes, it has been active in the production of commercial jet engine parts based on other international programmes. It started licensed production of LPT blades and LPC disks of jet engines under P&W licence from the 1970s. It, nevertheless, has not been involved in the production of HPT blades and vanes other than combustors in its joint international jet engine programmes, such as V2500, PW4000 and Trent 1000 (MHIAEL, 2014; NRC, 1994).

Only recently, MHI began to produce HPT disks in addition to combustors of P&W's PW1200G engines for its indigenous commercial aircraft, namely Mitsubishi

Regional Jet, in 2018 (MHIAEL, 2014; Waldron, 2018).¹⁵⁵ It would be the first case that MHI has produced HPT parts in its history of commercial jet engines, but the disks do not contain such technological ramifications as the HPT blades and vanes in terms of design, material and casting process. Given that its technological implication is rather marginal, it seems a somewhat symbolic attempt of MHI gradually stepping over the threshold of the US export control on core engine parts. Also, it could be explained as the latecomer's 'linking and leveraging strategy' expanding its coverage of production gradually from relatively simple to more complex parts in the relationship with the foreign partner.

Whether symbolic or strategic, the relevance of the HPT disk production to MHI's CCGT catching-up performance is questionable considering that it already achieved major progress in its CCGT catching-up trajectory in the 1980s and 90s, such as the world-first DLNC and its proprietary DS turbine blades. By comparison, Japanese aircraft engine industries never could manufacture their own original aircraft engines other than licensed production of the LPT parts.¹⁵⁶ Occasional productions of marginal HPT parts, such as disks, would contribute an only fringe portion to its already flourishing CCGT capability at best.

On the contrary, MHI's consistent involvement in combustor production for collaborative jet engine programmes with foreign OEMs is more pronounced in a potential relationship between its jet engine and CCGT business. Contrasting to the GE's spill-over case, its DLNC of CCGTs contributed to its specialisation of combustors for those collaborative jet engine programmes from V2500, commercialised in 1993. The speciality of MHI in combustors for jet engines repeatedly played a role in the following

¹⁵⁵ MHI stopped receiving orders for the MRJ aircraft after a few dozens of cancellation cases occurred. It reportedly shifted its main product line from the initial 90-seat MRJ to 70 plane-seat M100 in 2019.

¹⁵⁶ Although Japan produced indigenous 60 seat YS-11 aircraft from the 1960s to 70s, it had to depend on R-R's propeller engine. Even the second indigenous aircraft, namely 70 seat M100, depends on P&W's jet engine as of 2019.

jet engine co-development programmes, such as PW4000 and PW6000 with P&W, and Trent 1000 with R-R (MHIAEL, 2014). It should be noted that MHI already specialised its capability in the DLNC system from its M701D CCGT in 1984 (see Section 5.3.3).

Appendix C.

List of Interviewees

Interviewees in the Korean Case

Interviewees Regarding Nuclear Power Issues

Taejung Park, Principal Engineer, Steam Generator Design Team, *Doosan Heavy Industries & Construction, Changwon*, on 14 March 2011

Chaeyoung Lim, Director of R&D Coordination Division, Korea Atomic Energy Research Institute (KAERI), *Daejon*, on 18 March 2011

Manki Lee, Senior Researcher of Nuclear Economics, Korea Atomic Energy Research Institute (KAERI), *Daejon*, on 18 March 2011

Byungoo Kim, a former senior researcher of Korea Atomic Energy Research Institute, Professor of Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science & Technology (KAIST), *Daejon*, on 23 March 2011

Unghan Lee, former deputy director of Quality Control division at *Yonggwang Nuclear Power unit 5 & 6*, on 14 July 2012 (Email Interview)

Taehyun Choi, Director General for Materials and Components Industries, Ministry of Trade, Industry & Energy, *Sejong*, on 16 January 2015

Seonkyo Jung, former Director of Technology Development Department, KEPCO Nuclear Fuel, *Daejon*, on 23 January 2015

Jongbae Park, Professor, Department of Electricity and Electronics Engineering, *Konkuk University, Seoul*, on 14 May 2015

Anonymous, General Manager of Pricing Office, Korea Electric Power Co. (KEPCO), *Naju*, on 19 May 2015

Younghwan Chun, Professor, Department of Electrical Engineering, *Hongik University, Seoul*, on 12 July 2017

Interviewees Regarding Gas Turbine Issues

Hyunkyū Kim, former Senior Researcher of Korea Electricity Power Engineering Co. (KOPEC), Seoul, on 21 February 2011

Byungmoon Chang, Executive Director, Korea Lost Wax Technology Research Center, Sihwa Industrial Complex, on 7-8 March 2011 and 8 September 2017

Bumsoo Kim, a senior researcher of Korea Electric Power Research Institute, Daejeon, on 10 March 2011

Chunrok Kang, Chief Engineer, Gas & Hydro Turbine Engineering Team, Doosan Heavy Industries & Construction, Changwon, on 14 March 2011

Daeseok Jung, Assistant Manager, Gas & Hydro Turbine Engineering Team, Doosan Heavy Industries & Construction, Changwon, on 14 March 2011

Haechan Kim, former senior engineer of Hyundai Heavy Industries, a deputy director of Hyundai Electric, Changwon, on 15 March 2011

Sooyong Kim, Management Director of Gas Turbine Development, Doosan Heavy Industries & Construction, Daejeon, on 16 March 2011

Sungho Lee, Senior Researcher of Green Energy Laboratory, Korea Electric Power Research Institute, Daejeon, on 16 January 2013

Jungchel Chang, Senior Researcher of System Reliability Group, Korea Electric Power Research Institute, Daejeon, on 16 January 2013

Byungwook Kong, Senior Researcher of Central Research Center, Doosan Heavy Industries & Construction on 15 January 2015 (Email interview)

Anonymous, Team Leader of Marketing, Independent Power Producer, Seoul, on 15 May 2015

Anonymous, Officer of Climate and Air Quality Policy Division, Ministry of Environment, Sejong, on 8 June 2015

Participatory Observations

Heebong Chae, Director General for Energy Saving and Efficiency, Ministry of Trade, Industry and Energy (MOTIE), Public comments during a conference meeting for the 2nd Energy Demand and Supply Basic Plan, *Gwacheon*, on 14 June 2013

Suengjin Kang, Professor of Graduate School of Energy, Korea Polytechnic University, Public comments during a conference meeting for the 2nd Energy Demand and Supply Basic Plan, *Seoul*, on 21 June 2013

Kyungsik Kim, Director of External Cooperation Department, *Hyundai Steel*, Public comments during a conference meeting for the 2nd Energy Demand and Supply Basic Plan hosted by the Federation of Korean Industries, *Seoul*, on 2 October 2013

Yunki Ahn, Director of Management Research Centre, POSCO Research Institute, Public comments during a Public-Private Joint Workshop on Greenhouse Gas Forecasting hosted by Greenhouse Gas Inventory & Research Centre of Korea, *Seoul*, on 27-29 March 2015

Interviewees in the Japanese Case

Interviewees Regarding Nuclear Power Issues

Yuji Takahashi, Chief Operating Officer, International Nuclear Energy Development of Japan Co., LTD. (JINED), Tokyo, 1 February 2011

Yoshihiro Tomioka, General Manager of Nuclear Power Department, The Federation of Electric Power Corporations, Tokyo, on 1 February 2011

Takuya Hattori, President, Japan Atomic Industrial Forum, Inc., and former CEO of Tokyo Electricity Power Company, Tokyo, on 5 February 2011

Jiro Kida, Deputy Director of Nuclear Energy Policy Division, Ministry of Economy, Trade and Industry, Tokyo, on 5 February 2011

Shin Horiguchi, Officer of Nuclear Energy Policy Division, Ministry of Economy, Trade and Industry, Tokyo, on 5 February 2011

Tatsujiro Suzuki, Vice Chair of Japan Atomic Energy Commission, Tokyo, on 16 February 2011

Tetsunari Iida, Former Senior Researcher, Socioeconomic Research Center, Central Research Institute of Electric Power Industry on 5 July 2012 (Email interview)

Interviewees as Secondary Information Sources from Korea

Sunkyo Jeong, former Executive Chief of KEPCO Nuclear Fuel on 23 January 2015

Interviewees Regarding Gas Turbine Issues

Osamu Kimura, Research Economist, Socioeconomic Research Center, Central Research Institute of Electric Power Industry, Tokyo, on 2 and 15 February 2011, and a separate Email interview on 8 April 2015

Shinya Kajiki, Research Economist, Socioeconomic Research Center, Central Research Institute of Electric Power Industry, Tokyo, on 2 February 2012

Interviewees as Secondary Information Sources from Korea

Youngsoo Yu, Senior Researcher, High Temperature Material Department, Korea Institute of Material Science, on 13 January 2015 (Email interview)

Byungwook Kong, Senior Researcher of Central Research Center, *Doosan* Heavy Industries & Construction, on 15 January 2015 (Email interview)

Jungwoo Lee, Deputy Director, Gas & Hydro Turbine Engineering Team *Doosan* Heavy Industries & Construction on 23 January 2015 (Email interview)

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