Global Nuclear Power Supply Chains and the Rise of China's Nuclear Industry

by

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Abstract

China has embarked on a massive expansion of nuclear power that may fundamentally change the global nuclear industry, for better or for worse. Some industry observers argue that the incumbent nuclear power companies are already losing their position of leadership to emergent Chinese actors. Others argue that the growing Chinese nuclear power industry creates more opportunities for all. In this thesis, I discuss Chinese nuclear power development in relation to the global nuclear power industry. I argue that understanding three aspects of the development of China's nuclear industry help understand the opportunities and threats that come with it: (1) common practices of the global nuclear industry in regard to technology transfer and localization (2) different global trends towards deverticalization and integration and (3) idiosyncrasies of the Chinese manufacturing ecosystem that affect global nuclear power supply chains. I argue that Chinese and foreign companies, and policy makers, need to comprehend these principles well as they inform corporate and national strategies, affecting the present and future competitiveness of nuclear power industry actors globally.

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1 Introduction

1.1 Thesis

With 15 operating nuclear power reactors and 11.3 GW of installed capacity in China, the Chinese National Development and Reform Commission has called for a large scale expansion of its nuclear power program, targeting more than 70 GW by 2020 and 200 GW by 2030. Currently, more than 25 nuclear reactors are under construction in China, accounting for almost half of the global nuclear new builds (WNA China, 2012).

In addition to the installation of the targeted capacity, China has declared technological self-sufficiency and the buildup of a globally competitive nuclear industry as its explicit goal (Xu, 2010). This development has caught the interest of many observers in industry, politics and academia. How should the emerging Chinese nuclear industry be viewed? Are we witnessing an unprecedented expansion that will change the global nuclear industry fundamentally? Or does the growth of the Chinese nuclear industry follow established precedents and familiar trajectories pioneered by other nations with nuclear industries?

Today, in the United States in particular, the rise of China's nuclear industry is widely viewed with suspicion, if not anxiety. Politicians, industry representatives and members of the public fear that China, through the sheer momentum of its massive expansion, could come to dominate an industry that the US had led for decades.

The nuclear power industry originated in the US with the first civilian nuclear reactor at Shippingport. More than 100 commercial nuclear power plants then followed. The CEO of a major US nuclear reactor company once claimed that his organization "invented the nuclear industry" (Interview 10142011). It is from that perspective that one has to interpret efforts like those of Senator Jim Webb (D., VA) to pass legislation in order to prevent American nuclear companies from "giving away technologies to China." Webb claims that "the transfer of publicly supported proprietary technologies by American firms to China – and potentially other countries – clearly and unequivocally places the competitive advantage of the American economy at risk" (Webb, 2011).

Senator Webb most explicitly criticizes technology transfer agreements between the US-based nuclear reactor vendor Westinghouse and its Chinese client, the State Nuclear Power Technology

Corporation (SNPTC). These agreements involve the transfer of 75,000 documents, as reported by the Financial Times (Hook, 2010). Pundits such as University of California, Irvine professor and author of "Death by China," Peter Navarro, speak of "Westinghouse's naïveté" in "surrendering those 75,000 documents." (Navarro and Autry, 2011) Some US industry representatives refer to Westinghouse's involvement in China as "selling its soul" (Interview 11182011).

Little has been said, however, on what exactly such technology transfer agreements mean. What is the value of those 75,000 documents, and what does a company like Westinghouse receive in return? And more generally: How do partnerships between foreign and Chinese companies in the nuclear industry affect both parties' prospects? What are the roles of today's foreign and Chinese companies in nuclear power plant projects and what may be their roles in the future?

In this thesis, I suggest answers to such questions as I discuss characteristics of global nuclear equipment and technology value chains and nuclear power plant construction projects and how they affect, and are affected by, China's own rising nuclear industry.

Much has been written on China's nuclear policy and on individual organizations in the Chinese nuclear industry. Xu (2010) wrote the book "The Politics of Nuclear Energy in China" which contains a comprehensive history of the Chinese nuclear industry and a rich characterization of different actors. Zhou (2010) and Zhou et al. (2011) have repeatedly analyzed the prospects of the Chinese nuclear industry. Moreover, the World Nuclear Association provides several detailed fact pages on the Chinese nuclear industry, describing reactor types and individual actors (WNA China, 2012).

I do not intend to add more on individual Chinese firms or on Chinese nuclear policy-making since much has been said on these topics. Rather, I focus on specific aspects of the Chinese nuclear industry which I have not seen covered in sufficient detail: technology transfer and localization, organization and product architectures, and idiosyncrasies of the Chinese economy as a whole which shape the development of its nuclear industry.

These topics make up the three main parts of this thesis.

In Part I, I investigate the nature of technology transfer and localization in the global nuclear industry from its beginnings to today. The purpose of this part is to better understand common practices of the global nuclear industry and its historical path.

Part II begins with a broad analysis of the nuclear value chain, discussing how value in nuclear power plant construction projects is spread across various tasks and organizations. Next, I discuss different organization architectures and product architectures that have emerged in the nuclear industry and their impact on supply chain organization and innovation strategies. The purpose of this chapter is to better understand the current global environment for nuclear power industries, the backdrop to China's growing nuclear industry.

In Part III, I present idiosyncrasies of China's economic development which shape its nuclear industry. Chapters in this part aim to present the peculiar local environment from which the Chinese nuclear industry emerged.

Finally, I close with conclusions drawn on each of the three topic areas.

1.2 Data

This thesis will draw on literature from the academic fields of nuclear engineering, political economy, management, and international relations as well as on industry reports, conferences and exhibitions. In addition, I carried out more than 50 interviews with representatives of companies across the nuclear supply chain from 2010-2011. This includes companies from China, the US, France, Germany, Austria, and Japan. Table 1 describes the different fields the respective companies are involved in.

Field	**No. of firms interviewed**
Reactor vendor	4
Architect/Engineer	1
EPC	2
Nuclear construction	1

Key equipment	7
Non-key equipment	10
Commodity equipment and materials	7
Fuel cycle	2
Consulting	2
Research institutes	2
Inspection services	2

Table 1: Interviewed firms by field

PART I - TECHNOLOGY TRANSFER AND LOCALIZATION

In order to understand the nuclear industry in its present state, and the development of China's nuclear industry in particular, it is helpful to look at the global industry's origins and emergent common practices as well as at the development of nuclear industries in other countries.

In this part, I discuss the role of technology transfer in the global nuclear industry both historically and today. I illustrate how technology transfer led to other forms of collaboration and often to long term cooperation that took on different forms, from research partnerships to future supplier or client relationships. I describe the case of South Korea's nuclear industry and its partnership with Westinghouse in more detail to demonstrate that point.

2 Technology transfer and localization in the nuclear industry

2.1 Overview

The practice of transferring advanced technology along with the sale of products emerged with large projects and competing bidders which equipped the ordering party with significant bargaining power and became common industry practice. In addition to the products purchased, technology transfer would provide knowledge on how to independently use, maintain, or produce technical artifacts. In the course of the 20th century, technology transfer agreements had become common place in many advanced sectors, as noted by Michael Lemaire of Alsthom-France (1985): “It is well known that large export contracts are increasingly subject to technology transfer requirements, particularly where advanced technologies are involved.” Lemaire specified: “The objective is generally to oversee the transmittal of engineering and manufacturing documents, to train the client’s personnel, and to provide on-the-spot technical assistance.” The nuclear power industry, from its inception, was particularly affected by this practice.

The first nuclear power plants to produce electricity commercially through nuclear fission were built by the United States and the Soviet Union, both of which had a considerable head start on other nations due to their research efforts during and immediately following World War II. While both nations were restrictive in sharing knowledge on nuclear fission during the immediate postwar years, President Eisenhower’s Atoms of Peace program of 1953 caused a major change in the US position. For reasons of Cold War strategy, worldwide cooperation to help other countries build nuclear power industries was suddenly encouraged (Katz and Marwah, 1982). The importance of the Atoms for Peace program can hardly be overstated and James Donnelly of AECL-Canada described its effects as follows (1985): “Never in history has the world engaged in such an open display of technological generosity as that which has characterized the peace time application of nuclear technology started under the Eisenhower ‘Atoms for Peace’ initiative. The first Geneva conference (1955) opened the book on nuclear technology for all the world to read.”

American companies such as Westinghouse, General Electric (GE) and Combustion Engineering (CE) have since built nuclear power plants and transferred nuclear power technology to Iran, Pakistan, Belgium, India, Japan, South Korea, Mexico, Slovenia, South Africa, Spain, Sweden, Switzerland, Taiwan, Germany, and France. Among these, France, Germany, South Korea, and Japan later developed their own internationally competitive nuclear vendor companies. Apart from the United States and the latter countries, only Canada, Russia and China have built nuclear reactors in other nations.

While the Soviet Union transferred nuclear technology to its satellite states, Germany transferred nuclear technology to Argentina, Brazil, Iran, Spain, Switzerland and the Netherlands. France transferred nuclear technology to Belgium, South Africa, South Korea and China. Canada transferred nuclear technology to India, Pakistan, Argentina, China, South Korea, Romania, and China transferred nuclear technology to Pakistan.

This section showed that technology transfer has a long tradition in the nuclear industry and has been practiced many times, often with multiple "generations" of transfers where former recipients turned into later transferees.

2.2 International conferences on nuclear technology transfer

The prevalence of nuclear power projects involving technology transfer led to the organization of a number of international conferences on technology transfer in the nuclear industry, of which two of the largest were "Transfer of Nuclear Technology" in Iran 1977 and "Nuclear Technology Transfer" in Spain 1985. Both conferences were supported by leading nuclear reactor vendors including Westinghouse, GE, the French Framatome and the German Siemens/KWU (the latter two of which later merged to become today's Areva).

Comments like those of Chong K. Lewe and Donald L. Couchman of NUS Corporation, a leading consultancy for nuclear projects, illustrate clearly how widespread the practice of technology transfer had become by 1977: "A developing country planning its first nuclear power plant will have two principal goals – to get the plant constructed and to acquire practical know-how on design and engineering as well as all aspects of project management in order to reduce to a minimum its dependence on foreign contractors for later plants. " The following sections will provide concrete examples to back up that claim by describing a number of prominent cases.

2.2.1 Siemens/KWU

During the 1985 Madrid conference, German reactor vendor Siemens/KWU stressed that it routinely offers "complete engineering technology transfer that could also be adapted to include complete manufacturing technology transfer to meet the demands and capabilities of the recipient country." This would include "manufacturing of all components" and a "full range upgrading of national industry." Eventually, this could lead to "complete proficiency in the new technology" and "independence in all fields of nuclear technology as quickly as possible." (Hüttl, 1985). Siemens/KWU specified that technology transfer is carried out through: "1. Transfer of documents 2. Man-to-man transfer (hence the foundations are laid for future technology independence) 3. Management know-how and assurance that there are no gaps in the transfer process." Siemens/KWU's largest nuclear power plant projects outside of Germany include the nuclear power plants Angra II in Brazil, Atucha in Argentina, Gösgen in Switzerland, and Bushehr in Iran.

2.2.2 GE

As summarized by Neil L. Felmus of GE (1985), GE helped "to establish broad-based nuclear engineering capabilities throughout the world" following the Atoms for Peace program. In the 1960s, GE provided extensive assistance to German and Japanese companies, among others. When the original license agreements expired in the 1970s, new technology exchange agreements, so called Technical Cooperation Agreements, were struck with companies from both countries. Under such agreements, GE "continued exchanging technical information and operating experience" and "expanded the relationship to include joint research activities in areas that are of mutual interest." This led to the Japanese-American joint development of the advanced boiling water reactor (ABWR), a nuclear reactor that "incorporates not only the best technological features developed in Japan and the United States, but also incorporates technology that originated with other BWR technical associates in Germany, Italy and Sweden." The ABWR was later ordered by Japan, the United States and Taiwan. For GE, technology transfer was clearly not a one-way street. Rather, over time, the company came to benefit from its relationships with its clients and partners around the world and secured new business opportunities based on joint development initiatives such as the ABWR project. Other benefits GE was able to reap as a consequence of its technology transfer agreements were opportunities in servicing facilities, including through maintenance and upgrades: "Our efforts in transferring engineering technology in recent years has expanded beyond the major suppliers of nuclear plants and fuels. The growing demand throughout the world for technical services for operating plants and the updating of those facilities to meet new regulatory and operating requirements have accelerated our efforts in these areas." Through ample deployment of nuclear reactors and transfer of technology, GE also built a global reputation as a competent and experienced nuclear technology service company. The sourcing and installation of new computer based control systems is but one example of nuclear technology related services offered by GE to former technology transfer recipients.

2.2.3 Westinghouse

Westinghouse's C. K. Paulson emphasized during the 1985 Madrid conference that his company benefitted in three major ways from technology development cooperation programs with partners to whom nuclear technology had previously been transferred. As benefits he identified (1) more opportunities to test, deploy and spread state-of-the-art technologies, (2) a more efficient use of R&D resources, and (3) "well-known synergistic effects due to the cross-fertilization of technical expertise." He concludes: "The enhanced relationship has a value far greater than anything measurable in monetary terms. The understanding that is gained of the technical expertise and working methods of the other organization leads to a better working relationship in all areas."

2.2.4 Framatome, CEGB, ENSA

It was not uncommon for former recipients of technology transfer to later transfer technology themselves. Framatome, for instance, had received knowhow from Westinghouse on equipment manufacturing in the 1970s and a few years later delivered reactor pressure vessels to the UK, as a partner of Westinghouse. The UK in turn benefited from "the greatest possible opportunity to participate [...] so that PWR technology and manufacturing knowhow is transferred to the fullest possible extent." as expressed by a representative of the Central Electricity Generating Board (CEGB) (George, 1985). Along the same lines, the Spanish nuclear primary cycle equipment manufacturer Equipos Nucleares-Spain (ENSA) "accumulated experience first at the receiving end, benefitting from technology transfer from others, and later, at the transmitting end, instructed different groups with little or no previous experience in engineering, quality assurance, metallurgy, etc." (Espallardo, 1985)

This section introduced some of the basic mechanisms as well as the reciprocity of technology transfer in previous cases by providing concise examples across a spectrum of companies and countries that were engaged in technology transfer on both the transferring and receiving end. The next section will go into more depth, discussing in greater detail a case of technology transfer that led to later forms of partnership and collaboration: the case of South Korea's KEPCO and Westinghouse.

2.3 Case: Technology transfer in South Korea

2.3.1 General history

Among the countries that had been recipients of nuclear technology transfer, France, Germany, Japan, Canada, and South Korea have emerged as major nuclear reactor vendors in international markets. In this section, I discuss the development of the nuclear industry in South Korea as one of the five countries that have brought forth internationally respected vendors of nuclear power plants based on previous technology transfer.

South Korea had received various forms of support from the Atoms for Peace program beginning in the 1950s, including research and other assistance for creating political institutions required for a national nuclear power program. It was not until 1978, however, that South Korea began operating its first nuclear reactor. Today, 34 years later, South Korea has built 23 reactors with 20.7 GWe of installed capacity, generating one-third of that country's total electricity (WNA South Korea, 2012). By 2030, Korea aims to build more than 15 new reactors domestically while exporting 80 reactors. The World Nuclear Association expects South Korea to be on its way to become the world's fourth largest vendor of nuclear reactors behind the USA (Westinghouse and GE), France (Areva) and Russia (Rosatom) with a 20% global market share. In 2011, South Korean firms celebrated their first international bidding success on winning a $20 billion contract to build four nuclear reactors in the United Arab Emirates, outcompeting French, US and Japanese firms. The South Korean Ministry of Knowledge Economy declared that "nuclear power-related business will be the most profitable market after automobiles, semiconductors and shipbuilding" and "we will promote the industry as a major export business" (WNA South Korea, 2012). The foundation for this development was laid through extensive technology transfer from the US, France and Canada over the last four decades.

Park (1992) differentiates between three major phases in South Korea's early development of commercial nuclear power. The first commercial phase involved the ordering of three turnkey reactors from the US and Canada which were commissioned between 1978 and 1983. Very few Korean firms were involved in these early nuclear power plant construction projects and the few that were involved focused on conventional tasks such as the construction of non-safety related buildings. During the second phase, six nuclear reactors were built and commissioned between 1985 and 1989 by US and French companies with the increasing participation of Korean industry.

During the third phase, Korean companies had taken over the projects' overall management responsibility with US companies being hired as subcontractors. In this phase, two reactors were built and commissioned in 1995 and 1996. The Korean nuclear industry selected the design of those two reactors, originally the "System 80" design from CE which is now a part of Westinghouse, for standardization and scale up and it has since commissioned nine more reactors of similar design, known as OPR-1000. In 1999, work was completed on the APR-1400 design, an evolutionary improvement and 40% power uprate from the OPR-1000. Reactors currently under construction and offered to export markets are APR-1400 reactors. Westinghouse still owns different kinds of intellectual property for this reactor design. The Koreans decided, however, to become completely self-sufficient by 2012. Whether they will be able to follow through on that goal is doubted by some industry observers (Berthelémy and Leveque, 2011).

2.3.2 Equipment manufacturer Doosan

A key player in the Korean nuclear industry is Doosan Heavy Industries & Construction which was founded in 1962 under the name Korea Heavy Industries and Construction (KHIC). After the three turnkey reactors of stage 1, and two reactors with relatively low local participation of stage 2, KHIC was designated to become a major supplier of nuclear power plant equipment in Korea in 19xy. In 2001, KHIC rebranded to Doosan Heavy Industries and Construction. By then, the company had developed capabilities for manufacturing key equipment of nuclear power plants, including nuclear island equipment such as reactor pressure vessels and steam generators as well as turbine island equipment such as turbines and generators.

KHIC's development of manufacturing capabilities began in the 1976 when it invested $50 million into a large integrated manufacturing complex. The purchase of modern manufacturing equipment was accompanied by technical license agreements with foreign partners. KHIC did not have much freedom in choosing its partners. Instead they depended on the choice of the Korean government, exercised through the state-owned utility KEPCO, for nuclear reactor and turbine island vendors. In 1976, a technical license agreement and a technology transfer contract were made with GE for turbine island components and in 1977 with CE for nuclear island components. Priority was given to fabrication technology and design software. In 1981, KHIC became a subcontractor to Westinghouse and entered more technology transfer agreements focusing on steam generators and non-rotating turbine generator components. 83 engineers were dispatched to CE, GE and Westinghouse as trainees during this period and KHIC was able to obtain a series of nuclear certificates from the American Society of Mechanical Engineers (ASME), also known as N-stamps.

In the early 1980s, the Korean government decided to order two more nuclear reactors. This time the Koreans picked French vendor Framatome as there had been concerns over fuel supply security with relying on the US as a sole provider of plants and fuel. As a consequence of working with French companies, technology transfer agreements with American companies did not get extended. New agreements with French companies Framatome and Alsthom were made in 1981 and 1982 respectively. While Framatome focused on nuclear island components, Alsthom specialized in conventional islands as well as electrical and control systems. Only a few years earlier, the French nuclear industry itself had benefitted from extensive technology transfer from US companies. At this point, however, a Framatome representative described the French nuclear industry as "totally independent and the sole owner of its technologies, which can be freely transferred to any country." (Lemaire, 1985) Subsequently, 23 Korean engineers were dispatched to be trained at French companies to gain experience with manufacturing steam generators and reactor pressure vessels. They stayed for several months and focused on material procurement, production, inspection and maintenance. At the same time, more than 1000 welders were trained in South Korea in compliance with American ASME and French RCC standards (Kwon, 1985). French professionals organized other training programs in domains such as scheduling and metallurgy. Programs were designed to be the same as training programs for new employees at the companies' home bases in France (Commeau, 1985).

Framatome and Alsthom also sent French experts to Korea who stayed for several years and assisted in virtually every step along the manufacturing process, including tool procurement and preparation, layout and sequencing of manufacturing operations, procurement of consumables, assistance during various manufacturing stages, demonstration of welding and machining, inspections, and assistance on documentation. This was complemented by an effort to adapt French designs to the available quality of domestic materials, products, and machine tools and to local industry standards as far as they applied. Michael Lemaire of Alsthom emphasized (1985) the hands-on nature of the technology transfer process and the commitment to their partner's success: "during the manufacturing period, we did not merely send know-how, but added a 'do-how' dimension to ensure quick success." The training of personnel was complemented by the delivery of "complete and up-to-date technical information, identical to that used in our factories, for several components and localized parts that were to be manufactured in Korea, as specified in the agreement." This included large amounts of technical documents. Alsthom alone prepared 15,000 drawings with five revisions of each. The final issues of the transferred technical documents packages "consisted of 75,000 drawings and about 100,000 letters, notes, memos, etc." (Lemaire, 1985) Alain Commeau of Framatome (1985) summarized the technology transfer process as an effort "to allow our partner to achieve independence based on our own experience."

By the 1990s, KHIC was able to manufacture most components of both nuclear island and conventional island equipment and became a lead supplier for Westinghouse (Interview 09142011). Today, KHIC's successor Doosan is one of the largest power equipment companies globally, along with GE, Siemens, Alstom and ABB. In 1999, Doosan received orders from Westinghouse for replacement steam generators in the US and the Korean company has since made inroads into foreign nuclear power plant markets (Doosan, 2008). Doosan received more orders from the US subsequently. In 2007, Doosan received orders from Westinghouse for supplying major nuclear island equipment such as pressure vessels and steam generators for its four AP1000 reactors in China (WNN, 2008). Additionally, it received orders worth more than $4 billion from KEPCO for four nuclear power plants in the United Arab Emirates (UAE) (Doosan, 2010). Doosan's involvement in AP1000 reactor projects in China requires the Korean company to provide assistance to China First Heavy Industries from whom it was required to obtain forgings for the reactor pressure vessels it manufactured (WNN, 2011). In 2011, Doosan signed agreements with a Westinghouse joint venture in the UK, indicating future collaboration with Westinghouse in the UK (Power Engineering, 2011).

Doosan has thus evolved from being a recipient of nuclear technology transfer in the 1970s and 1980s to becoming a leading global power equipment supplier and an important partner of Westinghouse, one of the companies that helped it gain its manufacturing and management expertise in the first place. Like Framatome and Alsthom before, Doosan cannot change the rules of international technology transfer: after having received knowhow in the past, it now finds itself contractually bound to assist newly emerging actors such as Chinese power equipment companies CFHI and others.

2.3.3 Westinghouse, KEPCO and the UAE

The Korean case further illustrates how new supplier relationships emerge from former technology transfer agreements. But it does more than that. Korea's closest partner Westinghouse benefits from its close connections with Korea in other ways too.

Westinghouse's role in the $20 billion Korean-led UAE project illustrates the point. In fact Westinghouse played a central role in the Korean-led consortium that won the tender. According to Korean officials, Westinghouse received a $1.3 billion share of the UAE tender for technical assistance and royalties (Berthelémy and Leveque, 2011). This seems a relatively small portion compared to the total project volume of $20 billion, the large majority of which is assigned to Korean contractors. However, as has been pointed out by Berthelémy and Leveque, the Korean bid was so aggressive that margins for Korean companies must be assumed to be extremely low or even below breakeven. Westinghouse will likely be the contractor with the highest margins among all contractors – while not carrying any of the risk typically associated with such large projects. In other words, South Korea's KEPCO turned out to be an excellent vehicle for Westinghouse for its low-risk/high-return participation in a major international nuclear power project.

Although the UAE deal is likely to lead to very low, if not negative, returns for Korea, the country nevertheless celebrated it as a great success. South Korea had demonstrated that it was now part of the small and exclusive group of international nuclear reactor vendors. However, despite its progress in localization and technology development, a number of factors speak for the continued involvement of Westinghouse both in South Korea domestically and abroad:

- Officially, South Korea strives for complete independence from foreign intellectual property by 2012, but it is not clear how many license and cooperation agreements still exist with foreign companies (WNA South Korea, 2012). Industry experts believe that there are still a substantial number of them. Particularly in areas like nuclear design code, Korea is believed to still have deficits (Berthelémy and Leveque, 2011) and in regard to fuel design and manufacturing Korea relies on a joint venture with majority ownership of Westinghouse, KW Nuclear Components (WNA South Korea, 2012).

- Westinghouse is a mature nuclear technology company with global experience and a large knowledge base. Due to the deverticalization of Westinghouse in recent decades the company was forced to virtually reinvent itself and focus on key strengths such as engineering services and automation. South Korean companies can benefit from Westinghouse's knowledge base and increasing specialization in those domains.
- Westinghouse brings a globally respected brand name and credibility to the table due to dozens of reference projects, valuable assets for Korea to enter foreign markets. The importance of this aspect in the UAE deal is illustrated by a comment by a UAE official who said: "ultimately much of the [Korean] technology has a US thumbprint on it" (McLain, 2010). South Korea benefits greatly from the credibility that comes with having Westinghouse on board.
- Berthelémy and Leveque point out many indicators that show that the US provided valuable diplomatic support to the Korean bid due to the involvement of US-based Westinghouse. To compete with diplomatic heavyweights like Russia and France and their state-backed reactor vendors Rosatom and Areva, South Korea may be well advised to maintain its US connections and benefit from American diplomatic support.
- In addition to design and technical assistance, Westinghouse is involved in Korea's nuclear fuel supply. According to the US-Korea nuclear cooperation agreement of 1974, Korea is not permitted to enrich or reprocess its own nuclear fuel and therefore, has to buy fuel through companies like Korea Nuclear Fuel (Manyin et al., 2012). Westinghouse has a joint venture with Korea Nuclear Fuel where it holds majority shares for the fabrication of Control Element Assemblies (CEA), i.e. fuel elements (Westinghouse, 2009).

These are reasons that speak in favor of South Korea continuing its close relationship with Westinghouse. At the same time, the partnership with South Korea offers unique and crucial opportunities for Westinghouse. They are as follows:

- Westinghouse competes for nuclear reactor projects globally with large state-owned companies like Areva of France and Rosatom of Russia. Although, as seen in the previous section, the US has historically supported Westinghouse in the realm of diplomacy, even after it had been acquired by Toshiba[1], it cannot live up to the level of direct state support that Areva and Rosatom enjoy. In nuclear power industry circles companies like Areva and Rosatom are sometimes dubbed "France Inc." and "Russia Inc." for that reason (Interview 10142011). State support is multilayered: governments can coordinate between different actors of their nuclear industries such as utilities, reactor vendors and equipment manufacturers. Often, governments provide subsidies to nuclear equipment companies for building and maintaining capital intensive capacity. They can facilitate financing of international projects by providing export credit and they can influence bidding processes by tying large international orders to political issues. Rosatom explicitly highlights these aspects in its promotional materials by stating that as "a state corporation Rosatom is taking advantage of unique industry access to privilege resources" (Samoshin, 2012). The absence of various forms of state support commonplace in other countries has manifested itself in the US in various ways: US nuclear reactor vendors suffer from the lack of coordination among the large number of different utilities in the US. Large forging capacity necessary for the manufacturing of major nuclear power equipment did not remain competitive in the hands of private companies as new builds were stalled. In turn, its close relationship with South Korea's KEPCO helps Westinghouse to benefit from the type of state support it would otherwise be lacking, state support that has become crucial in competing with state-owned competitors Areva and Rosatom. The Korean government coordinates between different actors of its nuclear industry, promotes the industry's overall development and supports Korean bids for nuclear power projects abroad. The Korean Export Import Bank (KEXIM), for instance, will provide up to $10 billion to the UAE to finance the nuclear plant order (Daya, 2010).

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[1] In the absence of new nuclear plant orders through much of the 1980s and 1990s, Westinghouse underwent a series of reorganizations. In 1999, the originally American company was bought by British Nuclear Fuels Limited (BNFL) and renamed to Westinghouse Electric Company (WEC). Soon after, the ABB Group's nuclear power sector was merged into Westinghouse. In 2006, BNFL sold Westinghouse to Toshiba and WEC has since been a part of the Japanese conglomerate. Nevertheless, WEC's headquarters and the majority of its employees are still based on their original locations in the US. Therefore, WEC is still regarded to be an "American company" by some and it received diplomatic support by representatives of the US government in the UAE bid (Berthelémy and Leveque, 2011). In this thesis, I refer to the original Westinghouse as well as to WEC simply as Westinghouse.

- A decisive factor that led to Korea's success in the UAE bid was the low cost of its reactors. Berthelémy and Leveque estimated the overnight cost of the Korean UAE reactors at less than 2930 USD/kWe, which is significantly lower than Areva's EPR reference plant at Flamanville whose overnight cost EDF reported at 3860 USD/kWe (IEA, 2010). The GE-Hitachi offer was reported to be even higher. It was, therefore, of great benefit to Westinghouse to have a partner like Korea that allowed them to compete in a lower cost segment of the nuclear reactor market such as the UAE where cost may have been a higher priority than reactor design as such.
- Another important factor in the UAE tender was the credibility of the contractor's claim to deliver the project on time. In this regard, South Korea had an excellent record with six Korean nuclear power plants commissioned during the ten years before the tender and remarkably short construction periods with few delays (WNA South Korea, 2012). Westinghouse was able to capitalize on that experience.

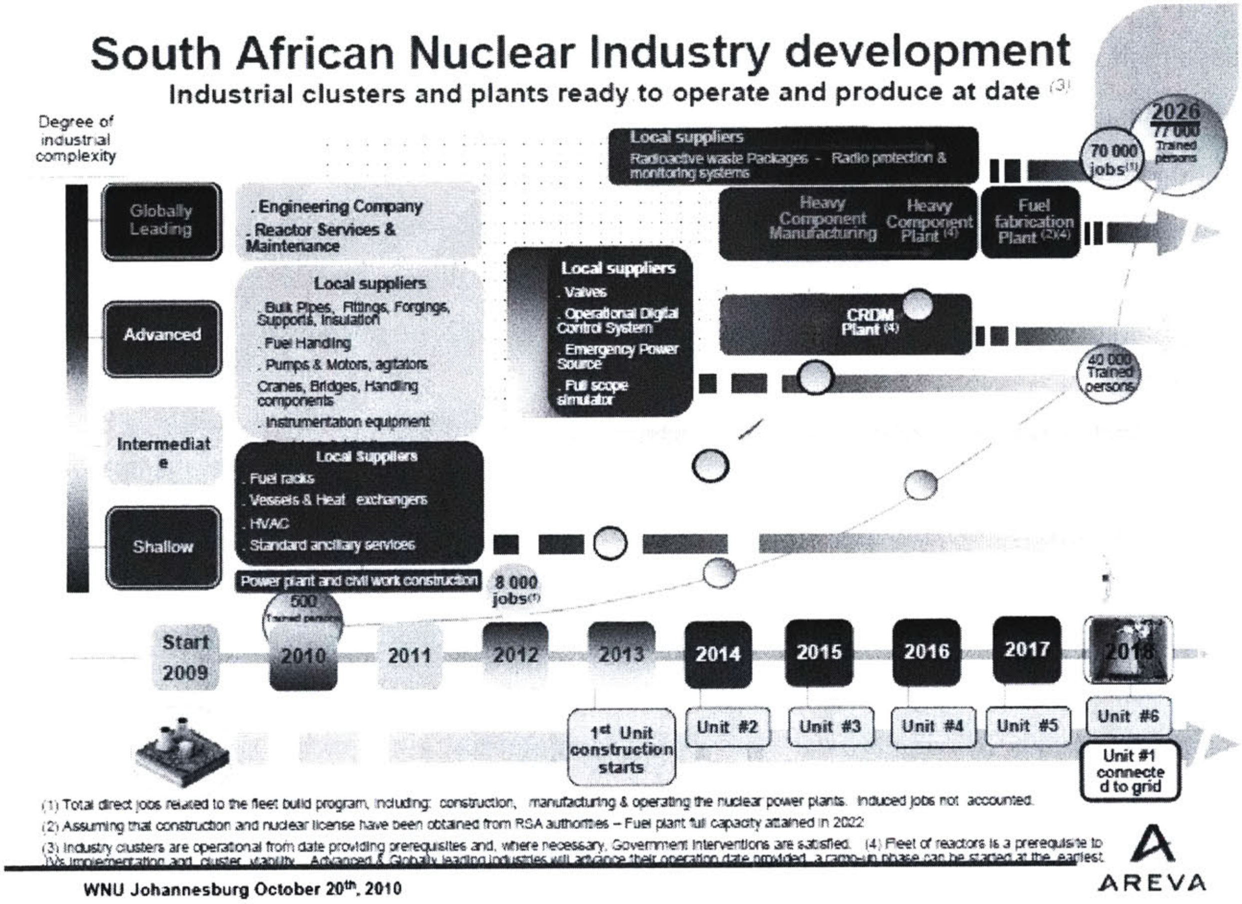
The KEPCO-Westinghouse partnership has been a relationship that offers benefits to both sides. One may justly argue whether Westinghouse could have possibly anticipated these benefits when it first transferred technology to South Korea in the 1970s. However, I believe this argument would miss the point. As we have seen from the statements of Westinghouse representatives in 1985, Westinghouse clearly recognized future benefits of its technology partnerships in a generic sense. While the concrete manifestations of such benefits could hardly be known in the 1970s, Westinghouse's close relationship to the South Korean nuclear industry is not coincidental and rooted in its earlier interactions.

2.4 Localization today

The prominence and scope of localization and technology transfer has not diminished in recent decades. Today's nuclear reactor vendors still offer comprehensive technology transfer packages when competing for new reactor projects, particularly in countries that aspire to build nuclear fleets or nuclear industries of their own.

Nuclear reactor vendors do not tire of pointing out their companies' technology transfer and localization track record. In a brochure, Areva claims that it "embraced 'localization' long before the word became fashionable in business circles" (Areva, 2012). Similarly, Westinghouse VP Tim Collier (Yuan, 2012) stated that "Westinghouse has a track record of technology transfers and localization that is unsurpassed around the world as evidenced by the long-term relationships we have built in places like France, Japan, Korea and other countries that have embraced nuclear energy. We are achieving the same results in China with all-round technology transfers." Rosatom claims that "localization is an inevitable part of Rosatom policy." It wants to "establish multiple alliances and partnerships with global and local players" and "source, develop and transfer technologies to maintain global leadership." The Russian reactor vendors wants to "benefit from global talents and local workforce" (Kouklik, 2012; Samoshin, 2012).

Areva, often together with its partner EDF, organizes road shows, exhibitions and seminars to inform governments and local firms about possibilities and conditions for becoming suppliers to nuclear power plant projects (Interview 10182011). In recent years, Areva held such events in countries like South Africa, the United Kingdom and Poland. In each country where Areva reactors are currently deployed or may be deployed in the future, Areva screens potential suppliers to add them to its list of qualified and approved suppliers. Currently, 36 Finnish companies are validated as approved vendors for safety-critical components and more Finnish companies for non-safety-critical components. 22 companies have been qualified in the UK with 38 prequalified and 3 in Poland with 21 prequalified (De Guio and Robin, 2012). In its presentations, Areva emphasizes that technology transfer can span from the localization of less demanding tasks all the way to full self-reliance, usually depending on the scope of nuclear expansion and on ambitions of local governments and industry. A schedule that lays out a hypothetical path to full self-reliance with major milestones along the way is presented in Fig. 1, illustrated by the case of South Africa whose Department of Trade and Industry requested "identification of sequentially increasing domestic manufacturing opportunities" and "long term procurement plans" (ESEC, 2010).



South African Nuclear Industry development

Industrial clusters and plants ready to operate and produce at date (3)

. Engineering Company
. Reactor Services & Maintenance

Local suppliers
. Bulk Pipes, Fittings, Forgings, Supports, Insulation
. Fuel Handling
. Pumps & Motors, agitators
Cranes, Bridges, Handling components
. Instrumentation equipment

Local Suppliers
. Fuel racks
. Vessels & Heat exchangers
. HVAC
. Standard ancillary services

Power plant and civil work construction

Local suppliers
. Valves
. Operational Digital Control System
. Emergency Power Source
. Full scope simulator

Local suppliers
Radioactive waste Packages - Radio protection & monitoring systems

(1) Total direct jobs related to the fleet build program, including: construction, manufacturing & operating the nuclear power plants. Induced jobs not accounted.

(2) Assuming that construction and nuclear license have been obtained from RSA authorities – Fuel plant full capacity attained in 2022

(3) Industry clusters are operational from date providing prerequisites and, where necessary, Government interventions are satisfied. (4) Fleet of reactors is a prerequisite to IVs implementation and cluster viability. Advanced & Globally leading industries will advance their operation date provided a ramp-up phase can be started at the earliest

WNU Johannesburg October 20th, 2010

AREVA

Fig. 1: Potential localization schedule for South African nuclear power program (De Guio and Robin, 2012)

Similarly, Westinghouse has been working actively to build "broader, more localized supply chains" (Bull, 2010). This involves "supplier development activities" that attract potential local suppliers and educate them about Westinghouse's supply chain opportunities as well as supplier screening and qualification procedures. In line with its slogan "we buy where we build," Westinghouse promotes itself in the context of upcoming and ongoing nuclear tenders as a partner that can not only deliver a state-of-the-art nuclear power plant but also benefit the local economy. In the UK, Westinghouse claims that "UK industry could supply 70-80% of the value of a UK nuclear program" which in sum could make a new nuclear program in the UK lead to "potential 30 billion pounds value to the UK economy" the majority of which would come from local supply chain development. In this context, Westinghouse uses the claim to be "committed to technology transfer with a successful track record" as an important selling point (Patel, 2008).

Like Areva, Westinghouse also differentiates between different levels of involvement of local industry with the scope of the nuclear program as the main criteria. Major categories include the involvement of local industry through "minimum development/investment" such as construction labor and construction commodities, "medium development/investment" such as off-the-shelf commercial equipment and build-to-spec non-safety equipment, and "maximum development/investment" such as qualified safety-related equipment with license agreements and technology transfer. The latter is "usually only viable for national fleet aspirations." Generally, the development of a local supply chain is "phased-in over time based on development of skills and investment" (Patel, 2008).

Rosatom too courts potential customers with promises to localize large parts of expected nuclear power plant projects and to develop local supply bases. In South Africa, Rosatom estimates that it could enable the creation of "15,000 jobs in peak (8,000 in average)" for the South African economy as well as $15 billion in revenue for South African companies (Kouklík, 2012). The Russian nuclear reactor vendor estimates that South Africa can provide about 40% of the value of the nuclear power plants to be built, mainly in domains like construction, electrical devices, instrumentation and control, piping and air-conditioning. In the Czech Republic, Rosatom envisions up to 70% local participation. As of April 2012, Rosatom identified 54 potential suppliers in the Czech Republic of which 20 have already received approval. Rosatom tries to attract potential suppliers by offering "access to its global supplier network" and the "opportunity to expand globally by participating in Rosatom nuclear power plant construction projects worldwide" (Tomicek, 2011). In its advertising materials, the company points out that it plans to build 80 nuclear power plants around the globe by 2030 and therefore offers new members of its global supply chain "stable deliveries for other nuclear power plants in third countries" (Tomicek, 2011).

In this section, I showed how, as before, technology transfer and localization still play major roles for nuclear reactor vendors in the process of securing nuclear reactor projects. In this light, the involvement of and technology transfer to Chinese companies in the context of nuclear power plant projects in China, even to the degree of "maximum development," do not seem to exceed the industry's common practices.

2.5 Localization payoffs

Just as the partnership between KEPCO and Westinghouse led to an offer to the UAE that was stronger than anything each company on its own could have provided, new alliances form over other nuclear tenders in the world. In the UK, which plans to build some 19 GWe of new nuclear capacity, Areva and Westinghouse have been competing with their EPR and AP1000 reactor designs for the 6 GW Horizon project. The energy company Horizon went on sale after German utilities RWE and E.ON withdrew from the project. The new owner of Horizon will have an influence on the reactor designs that will be chosen for the nuclear reactor development sites the company owns. In June 2012, Reuters reported that Areva teamed up with its partner China Guangdong Nuclear (CGN) and Westinghouse with its partner SNPTC to bid for Horizon (Xu and Schaps, 2012) A third bidder is believed to be GE-Hitachi. In this context, both Areva and Westinghouse benefit from their respective relationships with Chinese partners that are the products of years, in the case of Westinghouse and SNPTC, and decades, in the case of Areva and CGN, of technology transfer and other forms of collaboration. The Chinese state-owned enterprises (SOEs) will be able to support their Western partners financially as they are well equipped with capital and backed by Chinese central and provincial governments which have interests in getting a foot in the door of nuclear power markets abroad. Additionally, the Chinese companies may bring Chinese subcontractors to the project such as the nuclear construction company China Nuclear Engineering Construction Corporation (CNEC) and procure equipment from proven Chinese suppliers (Interview 10182011). This way, Areva and Westinghouse could benefit from the experience Chinese players have built up and from unique features of the Chinese nuclear power ecosystem that arguably lead to low cost products at acceptable quality. In turn, partnerships with companies like Areva and Westinghouse help Chinese companies to gain more credibility and to overcome political and public resistance. As another step to overcome potential resistance, Chinese companies agreed to bring in UK utility firms for the operation of the plants (Macalister and Harvey, 2012).

Chinese subcontractors play important roles in the ongoing construction of Areva's EPR and Westinghouse's AP1000 reactors in China as I discuss in more detail in later parts of this thesis. They are now familiar with their Western partners' designs and management styles. Moreover, companies like CNEC have an excellent track record of delivering projects in time and on budget and the quality of their work can be observed in real time as they are involved in multiple ongoing projects. These can be valuable factors contributing to the bidders' success in nuclear projects in the UK. In contrast, GE-Hitachi which does not have a major Chinese partner will have to find ways to compensate on these fronts.

Analogous to the partnership between Westinghouse and KEPCO with its various subsidiaries, we see new partnerships forming between major nuclear power companies that have developed their relationships over years and decades, usually involving technology transfer and knowledge exchange. We can observe how companies capitalize on these relationships over time, most explicitly by forming partnerships to benefit from each other's strengths and compensate for each other's weaknesses. In a time that is characterized by deverticalization and modularization of at least some of the global nuclear power industry, as described in the following chapter, the capability to do so becomes increasingly important. This makes successful and strategic technology transfer and the creation of potential future partners all the more important.

2.6 Summary

In this chapter, I showed that comprehensive technology transfer has been characteristic of the global nuclear industry from its beginnings. Not only did technology transfer become common practice due to political impulses such as the Atoms for Peace program and the bargaining of demand for technology by developing economies, but it also served nuclear vendors as a vehicle for entering new partnerships, creating future markets and developing new suppliers. As the case of Westinghouse and South Korea illustrates, such partnerships can equip companies with crucial competitive advantages and can allow them to benefit from particular features of their partners' nuclear industry ecosystems. In addition, successful technology transfer cases create a track record much desired by countries that are planning new nuclear power plant projects. Successful references of technology transfer in the past, credibility to successfully and sustainably involve local suppliers in nuclear supply chains, and the ability to create and maintain pools of suppliers in different countries are factors that influence the competitiveness of contemporary nuclear power plant vendors.

PART II - DEVERTICALIZATION AND INTEGRATION - TRENDS IN THE GLOBAL NUCLEAR INDUSTRY

After analyzing common practices in the history of the nuclear industry in regard to technology transfer and localization, I discuss in this second part of this thesis global trends that shape the industry today. I find divergent trends in the nuclear industry that affect different parts of the global industry simultaneously: a trend toward greater deverticalization and another trend toward greater integration. In the following paragraphs I discuss how these trends manifest themselves in view of organization and product architectures. I argue that understanding these trends is essential for assessing China's current and future role in the global nuclear industry.

I begin by briefly analyzing the nuclear supply chain and by identifying major tasks and components. I then turn to the case of Areva's Olkiluoto nuclear power plant project to illustrate organizational challenges as they are faced by contemporary nuclear industry actors. I then discuss how concepts of modularity apply to the nuclear industry and the impact of higher and lower degrees of modularity on innovation and corporate strategy. Finally, I point to the implications of the discussed topics for the Chinese nuclear industry and its possible roles vis-à-vis other players.

3 Value in the nuclear supply chain

3.1 Introduction

Nuclear power plant projects are among the most complex and costly engineering projects of our time. Activities and inputs required for building nuclear power plants range from design and engineering services, to project management and construction oversight; from construction itself to the supply of various types of mechanical, electrical and instrumentation and control equipment; from installation and commissioning to operation and maintenance. The different areas require a broad range of expertise and no single corporation is able to build a nuclear power plant entirely on its own. Tasks are spread across a nuclear supply chain, or rather a supply network consisting of multiple supply chains.

In this chapter, I provide a brief overview of major activities and components that are part of nuclear power plant projects and their position in the nuclear value chain. This may help the reader to put the questions of later chapters into perspective - questions concerning product and organization architectures, innovation and corporate strategy as far as they affect the nuclear industry. For the purpose of this thesis, the term "nuclear industry" is synonymous with activities and components spanning the nuclear value chain as presented in this chapter.

3.2 Cost of nuclear power plant projects

Cost estimates of power plants are often given as so called overnight costs. Overnight costs of a nuclear power plant consist of "bare plant costs" which include engineering, procurement and construction costs, and "owner's costs" which include the cost of land, cooling infrastructure, administration and associated buildings, etc. The final total costs incurred by the owner of a plant are a combination of the overnight costs and time-related costs, including inflation and the cost of the capital required to finance plant construction.

Overnight costs are often expressed in US dollars per kW of installed capacity for ease of comparison between different plant types. Scaling that value by the total installed capacity of a plant results in a cost estimate for the entire plant. A compilation of reported overnight cost estimates by the World Nuclear Association in Table 2 provides an initial indication of the order of magnitude of nuclear power plant costs. As can be seen from the table, the 2010 estimates vary widely from $1556/kW in South Korea to $5863/kW in Switzerland. Numbers in Asian markets are considered most reliable as countries such as China and South Korea have actually built nuclear power plants in recent years and numbers can be based on empirical records rather than models. For the purpose of this thesis and for the calculation of percentages of component costs, I assume an average 1000 MWe nuclear power plants to have overnight costs between $3 billion and $4 billion in 2010 dollars, using recent Chinese plants as reference.

The Chinese government's plans to build 200 reactors by 2030 and the Korean government's plans to build 80 reactors by 2030, give a sense of the size of these countries' nuclear programs (WNA China, 2012 and WNA South Korea, 2012). The estimates of the IAEA in late 2011 for total growth of nuclear reactors globally by 2030 amount from 190 as a low case scenario to 350 as a high case scenario (Sarnsamak, 2011). These estimates would translate into a global market for nuclear power plants ranging from at least $570 billion to $1,050 billion.

Overnight cost estimate (2010)	**Reactor type and location**
$1556/kW	APR-1400 in South Korea
$3009/ kW	ABWR in Japan
$3382/kW	Gen III+ in USA
$3860/kW	EPR in France
$5863/kW	EPR in Switzerland
$1748/kW	CPR-1000 in China
$2302/kW	AP1000 in China
$2933/kW	VVER-1150 in Russia

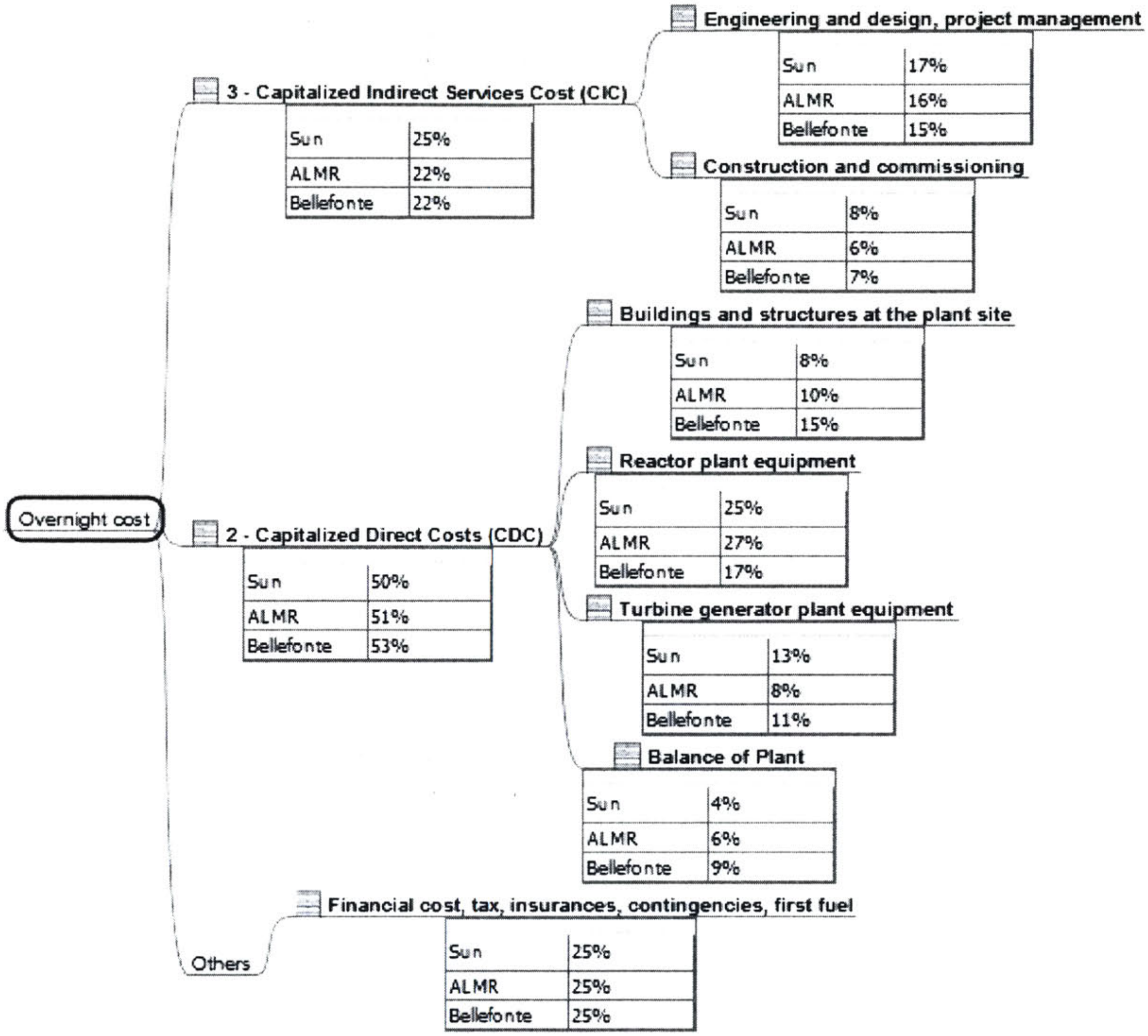
Table 2: Overnight costs in 2010 dollars as quoted in WNA 2012 based on IEA 2010

3.2.1 Financing costs

Financing costs vary and depend on interest rates. Berthelémy and Leveque (2011) determined that financing costs for an EPR reactor as built at Flamanville in France amount to approximately $620 million if the cost of capital is 5% and $1.360 billion if the cost of capital is 10%. Compared to the estimated overnight cost of $3860/kWe this would amount to capital costs of 16% and 35% respectively. Other sources report that actual financing costs for most nuclear power plants lie between 25 and 30% of the final cost (i.e. overnight cost and capital cost) (WNA Econ, 2012).

3.2.2 Overnight costs

A wide range of products and services are included in the overnight cost of nuclear power plants. The Code of Accounts of the Energy Economic Data Base (EEDB) is commonly used for categorizing and structuring the various types of costs (Delene and Hudson, 1990). In this system, all costs are divided into less than a dozen main categories among which are "Capitalized Indirect Services Cost" that include "Engineering and design, project management" and "Buildings and structures, construction and commissioning" as well as "Capitalized Direct Costs" that include "Reactor plant equipment," "Turbine generator plant equipment" and "Balance of Plant" These two categories represent by far the greatest portion of overnight costs. Significant types of costs that are not included here are owner's costs which include the cost of land and the cost of licensing. Safety analysis, however, is part of "Capitalized Indirect Services Cost."



3 - Capitalized Indirect Services Cost (CIC)

Sun	25%
ALMR	22%
Bellefonte	22%

Engineering and design, project management

Sun	17%
ALMR	16%
Bellefonte	15%

Construction and commissioning

Sun	8%
ALMR	6%
Bellefonte	7%

2 - Capitalized Direct Costs (CDC)

Sun	50%
ALMR	51%
Bellefonte	53%

Buildings and structures at the plant site

Sun	8%
ALMR	10%
Bellefonte	15%

Reactor plant equipment

Sun	25%
ALMR	27%
Bellefonte	17%

Turbine generator plant equipment

Sun	13%
ALMR	8%
Bellefonte	11%

Balance of Plant

Sun	4%
ALMR	6%
Bellefonte	9%

Financial cost, tax, insurances, contingencies, first fuel

Sun	25%
ALMR	25%
Bellefonte	25%

Fig. 2: Cost estimates for nuclear power plants by category from three different sources labeled as (1) Sun (2) ALMR (3) Bellefonte

Fig. 2 contains cost estimates from three different sources across the most basic Code of Account categories. Each category includes the costs of all required products and services including construction, installation and other labor costs. The sources used are (1) a paper on the economic potential of modular nuclear reactors by Tsinghua University's INET which involves a comparison of the costs of modular nuclear reactors with a typical Chinese 1000 MWe PWR whose numbers I used (Zhang and Sun, 2007); (2) cost estimates for the DOE's ALMR program from "1994 Capital and Busbar Cost Estimates" (Gokcek et al., 1995) (3) a report by the Tennessee Valley Authority with cost estimates for an 1371 MWe ABWR at their Bellefonte site in Alabama (TVA, 2005).

The reactors referenced are different designs and were built at different times. Nevertheless, there is a large degree of coherence, except for the equipment category. This has partly to do with the different reactor architectures, but it also has to do with different ways of allocating equipment to respective categories (e.g. certain pumps could be counted either as reactor plant equipment or as balance of plant). For the purposes of this thesis, a first approximation is sufficient. For Fig. 3 illustrating the distribution of costs, I used the mean values of each Code of Account category. Furthermore, I simplified the categories into "design and project management," "construction and installation" as well as "equipment and materials."

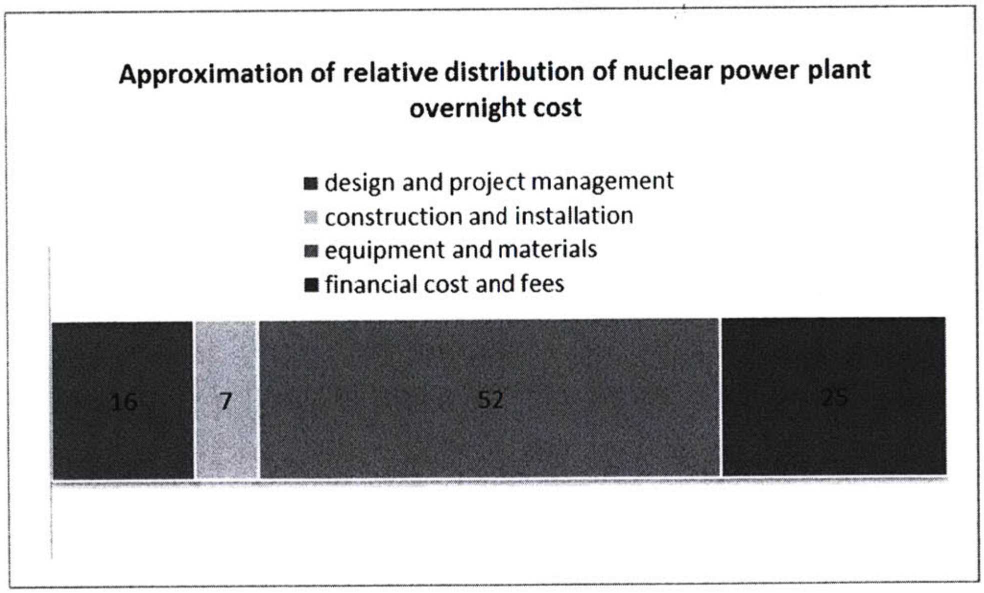


Fig. 3: Approximation of relative distribution of nuclear power plant overnight cost

The largest category is equipment and materials which I divide into further subcategories "commodity materials," "key equipment" and "non-key equipment." In the following sections I describe each category in more detail.

3.2.2.1 Design and project management

The design of nuclear power plants encompasses conceptual design as well as detailed design. Conceptual design involves the layout of the reactor core based on physical principles, the choice of materials such as fuel and coolant materials and related choices for build materials and plant architecture, as well as safety assessments and the development of safety mechanisms. A conceptual design may be represented by diagrams, drawings and computer models, accompanied by calculations and explanations. Since conceptual designs do not contain sufficient instructions for engineers and workers on a building site, the abstract conceptual design needs to be broken down into work packages that can be described in detail and can eventually be scheduled. Required equipment and inputs need to be identified and detailed drawings created that illustrate exact dimensions and locations of all components. The latter is generally called detailed design. Many conceptual designs for nuclear reactors are heavily informed by research at universities and labs as well as accumulated experience with previous designs. Detailed design is often carried out by design institutes or in-house detailed design departments of nuclear reactor vendor companies.

Project management teams have to interact closely with design teams as they take designs and, through scheduling, turn them into sequences. Experienced engineers determine the order in which various construction tasks need to be executed, taking into account the interdependence of different tasks and constraints such as space, labor, delivery of equipment, etc. A central aspect of project management is quality control. This spans from the screening of suppliers and the procurement of equipment to the provision of training to workers on site, inspection procedures and documentation. Project management functions are usually shared across a number of actors, often between the reactor designer and an architect-engineering firm. In some cases, the utility that acts as an owner has developed these capabilities, as in the case of France's EDF or Korea's KEPCO. In other cases, a nuclear reactor vendor may involve an experienced architect-engineering firm. Examples for such configurations are Westinghouse and Shaw or GE and Bechtel.

3.2.2.2 Construction

Construction in nuclear power plant projects involves both civil works and installation. Many of the tasks involved in construction barely differ from those at other large construction projects and can be executed by conventional construction firms (IAEA, 2009). Major capabilities of construction firms involve welding, the pouring of concrete, as well as the transportation and installation of equipment. The biggest difference between nuclear power plants and other large construction projects are in project management functions as laid out above. Documentation plays a central role in this context: both written instructions for executing tasks and required documentation on already executed tasks is generally more detailed compared to construction projects in other sectors.

3.2.2.3 Equipment and materials

Equipment ranges from small off-the-shelf valves to vast machined forgings, from conventional Portland cement to specialized alloys, and from kilometers of plain cable to complex digital control systems. The spectrum is wide in terms of complexity, cost, and degrees of specialization. With equipment and materials making up the largest portion of the cost of a nuclear power plant, I introduce the categories "commodity materials," "key equipment" and "non-key equipment" to differentiate between various kinds of equipment.

The most common commodity materials are concrete and rebar. In most cases, there are no special requirements for concrete and rebar used in nuclear plant projects. They are provided by large organizations like steel and concrete mills who also supply similar commodity materials to other sectors. 1000 MWe sized light water reactor designs tend to require about 200 cubic meter of concrete per installed MWe (Peterson, 2005). Based on concrete prices of 2007 this translates into material costs for concrete at roughly 1% of the total plant cost or roughly 2% of the total equipment and materials cost. The amount of steel needed for a nuclear power plant has been estimated at around 40 metric tons per installed MWe. Based on steel prices of $660 per metric ton in 2007 (Mathews and Jolis, 2007), this also roughly translates into 1% of total plant cost estimates or about 2% of equipment and materials cost.

Key equipment consists of discrete items that perform key functions in the operations of nuclear power plants. These contribute to the bulk of total plant cost. They are often featured prominently in localization reports and promotion programs and their localization commonly serves as a benchmark of industry capability. This type of equipment is usually tailored to the nuclear power industry and their production requires specific manufacturing equipment and training. The following components are generally regarded as key equipment both in regard to their function and cost. In parenthesis are percentages taken from a Deutsche Bank report on

China Power Equipment (Tong, 2010) that estimates the value of these components in relation to the total cost of nuclear power plant equipment: steam generators (8%), reactor pressure vessel/containment vessel (11%), pressurizer (1%), reactor vessel internals (3%), control rod drive mechanism (2%), reactor coolant pumps (4%), turbine (7%), and generator (6%). As for projects in China, prices for these components tend to lie between CNY 50 million (~$8 million) and CNY 700 million (~$110 million). The functional relationship of different kinds of key equipment is depicted in Fig. 4.

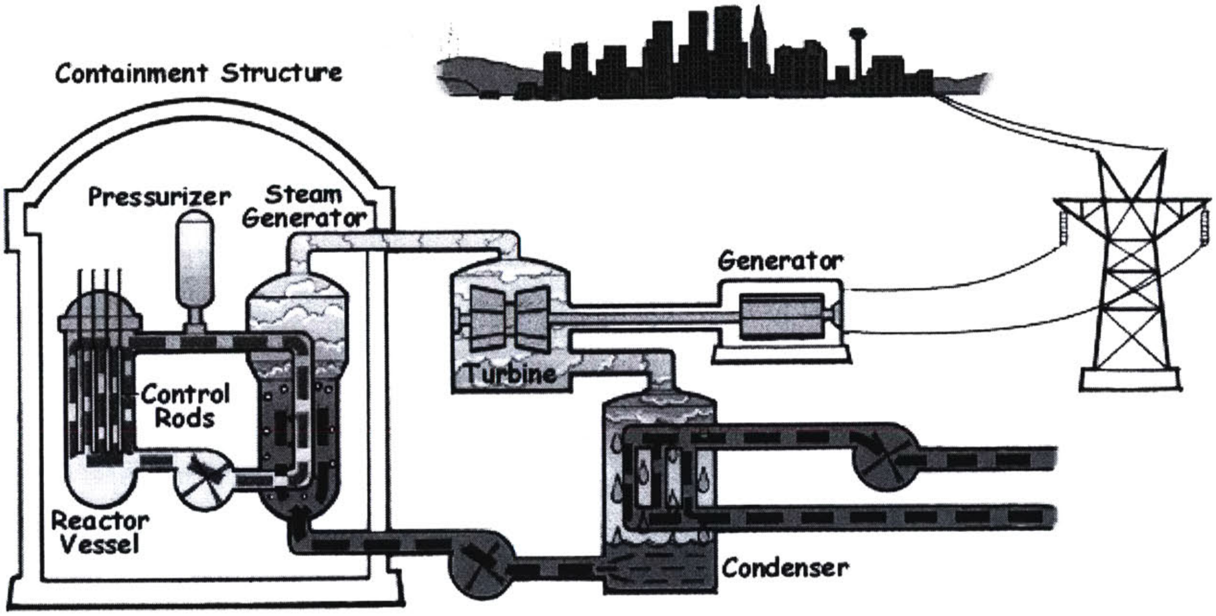


Fig. 4: Schematic of fundamental nuclear power plant components (NRC, 2012)

Despite key equipment representing a range of discrete and high valued components, even the sum of the cost of all key equipment as defined above contributes only about 42% of the total equipment cost of a nuclear power plant. The balance is take up by what I call non-key equipment, as discussed in the following section.

Most suppliers to nuclear power plant projects are neither commodity nor key equipment suppliers. In order to install, connect, monitor, and operate key equipment and ensure normal power plant functioning, additional types of equipment are necessary, the sum of which I define as non-key equipment. This includes a wide range of disparate products such as pipes and valves, pumps, tanks, vessels, cranes, motors, instrumentation, simulators, software for design and project management, and many others. These components are extremely heterogeneous and the one thing they have in common is their small portion of the total cost of a nuclear power plant, with orders usually amounting to less than $10 million. The large number of different kinds of non-key equipment still makes this heterogeneous category very significant.

Non-key equipment can include both nuclear industry specific equipment and off-the-shelf equipment that is also used in other industries, for instance coal, oil and gas, petrochemical, rail industries. Many companies that supply non-key equipment are not purely nuclear industry companies since they participate in and are affected by other major industries as well.

3.2.3 Organizational chart

After discussing the distribution of value across nuclear power plant building projects so far, I bring this section to a close by illustrating the organizational hierarchy within which different actors across the value chain operate. Fig. 5 represents an organizational chart of a typical nuclear power plant project as employed by US nuclear reactor vendor Westinghouse. Using the categories defined above, design and project management activities tend to be centralized around the "Plant designer" and the "Architect/Engineer" which sometimes consist of a single entity and sometimes of separate entities. Construction activities tend to be coordinated by the "Civil Constructor" who in turn draws upon its own network of subcontractors. Producers of key equipment fall into the categories "NSSS Supplier" and "BOP Supplier" while non-key equipment and commodity materials tend to fall under "Tier 2 & 3 Suppliers."

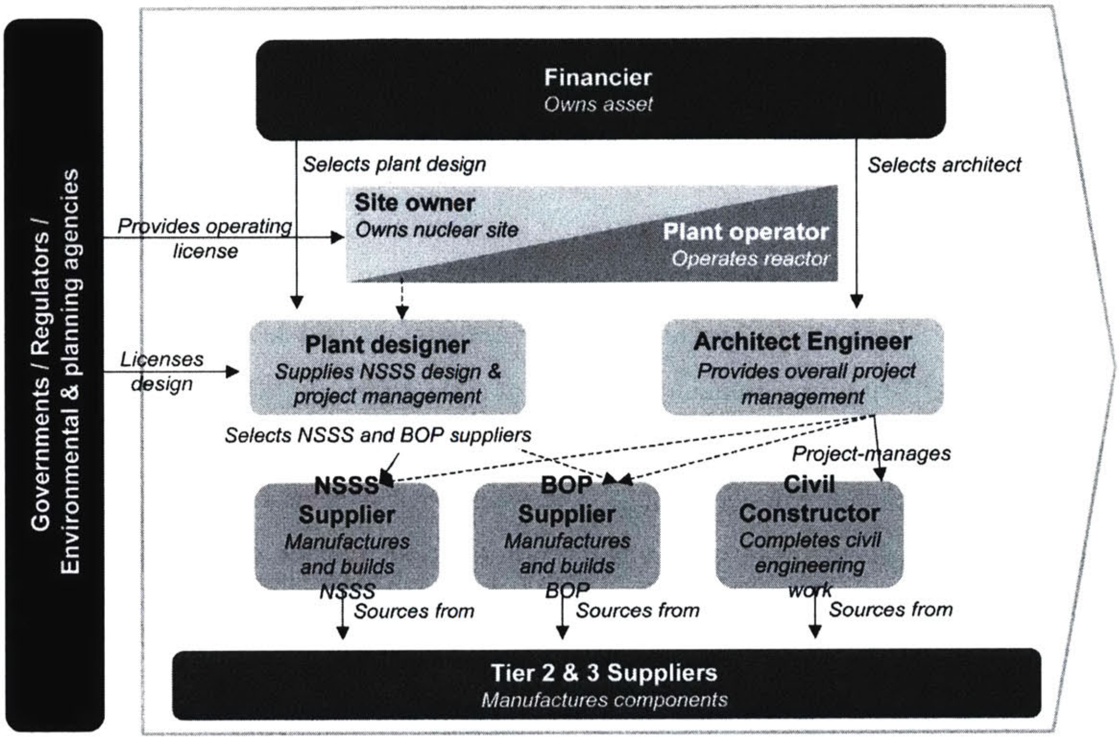


Fig. 5: Organizational chart for nuclear power plant projects as viewed by Rolls-Royce (Molyneux, 2008)

3.3 Summary

In this chapter I showed that the total cost of nuclear power plants is distributed across a wide range of products and services. Even a small share in the pie of a nuclear power plant project can lead to substantial revenues, given the large size of the pie. Components include industry-specific equipment as well as common commodities and off-the-shelf products. Similarly, some services are specifically tailored to unique nuclear industry characteristics while others are just slightly adapted to nuclear power conditions. This makes for a complex and diverse nuclear value chain, involving small and large companies, low and high technologies, commodity and niche products.

4 The nuclear value chain in action: organizational challenges as exemplified by the case of Olkiluoto

4.1 Introduction

After introducing various tasks across the nuclear supply chain, this section presents the dynamics that underlies nuclear power plant projects and the unique challenges posed by the complex division of labor, the coordination of numerous actors, and the special requirements of the nuclear sector.

Much of the modern nuclear industry is still affected by the drop in nuclear development following the Three Mile Island and the Chernobyl accidents in the 1970s and 1980s. Following these events, many companies turned their backs on the nuclear sector due to a lack of new orders and a negative outlook. Consequently, skills, experience and facilities faded over time (Aalto University, 2010). This coincided with a general trend in many industries towards deverticalization and outsourcing. Some of the large integrated organizations of the nuclear industry became leaner while supply chains became longer and more complex. I describe this process in more detail in the following chapter. In addition, reactor designs changed. More advanced reactor core designs, digital automation and new construction techniques made nuclear reactors more efficient and safer. However, many of these improvements were developed in engineering offices and had not yet been tested in the field.

4.2 The case of Olkiluoto

Contemporary challenges and characteristics of nuclear power plant building projects are exemplified by the construction of a reactor that is based on the first new reactor design in Europe since the 1980s: Areva's EPR which is built in Olkiluoto, Finland. The EPR in Olkiluoto is a 1600 MWe nuclear reactor that was developed by Areva based on earlier designs of reactors built in France and Germany but with enhanced safety features. The reactor was sold to Finland on the basis of a turnkey contract under which the reactor vendor carries responsibility and intrinsic risk for the project. Areva collaborates with the German engineering company Siemens on the turbine island and with the French construction company Bouygues on civil works as well as with many subcontractors on other aspects of the project (Areva, 2012). The total number of subcontractors that Areva needs to coordinate is over 1,900. Among those, about 40% are Finnish companies, to exploit the advantages of propinquity and in fulfillment of localization requests; the remaining companies come from 28 different countries. At the peak of construction activities about 4,500 workers were on site, representing 66 different nationalities - numbers that illustrate the management challenge of the project (Aalto University, 2010).

Construction at the Olkiluoto site commenced in August 2005 and the plant was initially scheduled to come online in 2009, with total estimated costs of Euro 3.7 billion (WNN, 2012).

However, the project suffered several delays and in 2012 the plant is still not operating with 2014 as a new target. As of 2010, cost overruns were estimated to exceed Euro 2.7 billion (Brett, 2010). The reasons for the delays are manifold but most can be traced back to unique challenges of the nuclear industry in regard to the management of complex multi-firm networks. The following list provides a summary of problems, as identified by a Case study of Aalto University (2010), which illustrate this aspect:

- Responsibilities for decision-making as well as for providing training programs and inspection services were not clear. For instance, it was not clearly defined which party was responsible for determining the exact composition of concrete. Consequently, large parts of concrete had to be remade due to non-conformance with quality requirements.
- The transfer of documents among organizations was unsystematic.
- The design work was inadequate and many required designs were not ready prior to the start of construction. The time required for finalizing detailed designs was underestimated.
- Project managers were not on site in Finland but at their companies' headquarters in France.
- Because of insufficient quality, recasting of all eight reactor coolant pipes became necessary.
- Welding and metal work on the containment steel liner was unauthorized and insufficient.
- The automation system design was not adequately documented according to regulatory requirements.
- Concrete ingredients lacked the required traceability.
- Safety culture training was not provided as required.
- A subcontractor's design office was in India where engineers failed to take into account local conditions that are unique due to the Finnish climate.

These points can be roughly summarized into: (1) inexperience of the main contractor in managing large construction projects; (2) inexperience of the subcontractors and lack of nuclear-industry related skills; and (3) lack of knowledge about local conditions and regulations.

The problems manifested themselves in a poor flow of information, both from contractors to subcontractors, e.g. for delivering instructions, and from subcontractors to contractors e.g. for reporting abnormalities. The electronic systems for exchanging information were insufficient. In addition, the range of different languages among workers led to frequent miscommunication. The communication challenge was exacerbated by the fact that large numbers of Polish workers were hired as they were significantly cheaper than their Finnish counterparts. Hierarchies and responsibilities were not clearly defined such that certain types of instructions and training were not provided as they fell through the cracks. This was particularly problematic since the stringent quality requirements of the nuclear industry were not internalized by every subcontractor, especially since many companies had had no previous experience with nuclear construction projects. Finally, the importance of involving local firms for their knowledge of local regulations, laws and procedures such as the approval of documentation ahead of construction was underestimated and foreign companies often had to learn about Finnish conditions as they were making mistakes.

Despite its decades-long experience and its involvement in more than 100 nuclear reactor projects in the past, the French reactor vendor Areva found itself in an unfamiliar situation. While for past reactor construction projects it could rely on a close long-term partnership with experienced French architect engineer EDF, EDF did not participate in the Olkiluoto project. Consequently, Areva took on the role of architect-engineer itself, with the support of other construction companies that it had little experience with. The numerous delays and mistakes during the construction of the reactor also reflect Areva's lack of experience in procurement and the management of subcontractors. The fact that many subcontractors had no nuclear experience made matters worse.

4.3 Summary

The Olkiluoto case illustrates the challenges of nuclear power plant construction projects by revealing what can go wrong. The nuclear power industry has particularly high requirements on complying with well-defined quality standards and implementing appropriate quality assurance systems. Documentation and the traceability of each step along the production process are central. The complexity of nuclear power projects requires clear structures and ease of communication across the multiple interfaces of different suppliers. This challenge is exacerbated by the number of suppliers, the diversity and internationality of suppliers, and the maturity and volatility of supplier relationships. The case also stresses the importance of adapting to local conditions. This ranges from project management challenges as laid out to physical conditions such as different climates and different materials and to local regulations and laws. Retaining knowledge and learning within the organization or across networks, effective systems integration, building and managing functional, reliable supplier networks, and the ability to adapt to local conditions emerge as crucial challenges for contemporary nuclear industries.

In the next section, I show how such unique features of the nuclear industry affect organization architectures and product architectures. Today, we find different organization and product architectures among different firms in the global nuclear industry. Each architecture poses particular advantages and disadvantages in dealing with challenges such as those presented above.

5 Global nuclear power supply chains – modular and integrated organizations and networks

5.1 Introduction

As seen in previous chapters, nuclear power plant value chains are vast in scope and complexity and require numerous products and services. Nuclear power plants fit the definition of complex product systems, as employed by Hobday et al. (2005). Effective coordination between different providers of products and services is crucial. The sums of all actors that contribute to complex product systems have been called production networks.

Sturgeon (2002, 2003) has studied production networks extensively and distinguishes between relational and modular production networks, drawing on the concept of modularity which is characteristic of many complex production systems, including automotive, computer and aerospace industries. The concepts of modularity and production networks are closely linked to systems integration. Systems integration in the widest sense encompasses the creation and coordination of production networks with the goal of turning designs into products.

In this chapter, I elaborate on the nature of modularity and systems integration in the global nuclear industry and trace how the industry has changed in regard to those concepts over recent decades. This includes discussing the implications of modularity and systems integration for organization architectures and product architectures, innovation and corporate strategy. Analyzing the role of modularity in today's global nuclear industry contributes to understanding the environment into which the developing Chinese nuclear industry is growing and the role that Chinese actors can play in this environment.

5.2 Definition of terms

5.2.1 Modular and relational production networks

In the 1980s and 1990s, modularity and systems integration became established concepts to describe the organization of complex manufacturing industries and their products (Prencipe, 2003). The increased complexity of products and the divide-and-conquer approach employed to break product systems into simpler subsystems led to suppliers specializing in individual components. Simultaneously, improvements in information and communications technology (ICT) greatly facilitated the codification and exchange of knowledge which led to the standardization of products and interfaces and decreased spatial dependence among those responsible for different subsystems. The internet, computer aided design (CAD), automated manufacturing systems, as well as design, testing and building software fueled this trend (Pavitt, 2003). The standardization of components and the advances in ICT facilitated the allocation of tasks to other organizational units, also known as outsourcing. This offered firms the opportunity to capture value "from vertical dis-integration of a modular sort" by achieving lower costs for outsourced tasks due to greater specialization and competition and greater flexibility in regard to capacity (Sako, 2005). The resulting networks were called modular production networks by Sturgeon (2002). According to Sturgeon, modular production networks are characterized by their dynamic nature which depends on the substitutability of individual suppliers due to the codified and standardized nature of each component.

Modular production networks contrast to relational production networks. In the latter, lead firms and suppliers have more stable, sometimes exclusive relationships, often aided by social and spatial propinquity as in industrial districts (Piore and Sabel, 1984). The close relationships between organizations can lead to greater efficiency, especially if processes with feedback and interdependencies are involved, but they can also lead to captive production networks, i.e. existential dependence of one partner on another. In relational production networks, product and process specifications remain relatively tacit which leads to greater asset specificity than in the inter-firm relationship.

5.2.2 Systems integration

The ability to coordinate modular and relational production networks has been called systems integration and identified as a core capability of modern corporations by Hobday et al (2005).

Systems integration involves a range of tasks affecting corporate strategy, project management, procurement, quality control and other divisions of firms. The central tasks include: (1) deciding to what degree a product can be and shall be produced in an integrated or in a modular manner; (2) decomposing a product and allocating its subsystems, i.e. modules, to either internal or external organizations; (3) choosing suitable external partners and apportioning production and innovation tasks across the value stream; (4) recomposing and delivering the final product from the various subsystems; (5) monitoring the production process in regard to quality and cost and avoiding changes and delays; (6) processing and evaluating feedback to optimize product and production.

The last two points have a particularly high significance in the nuclear industry, as design changes and quality shortcomings can lead to safety hazards and costly delays. The list also indicates how technology transfer and localization decisions impact systems integration as they create new opportunities for partnerships.

5.3 Modularity in the nuclear power industry

In this section, I discuss how characteristic features of the nuclear power industry lead to the promotion of either modular or relational supplier relationships.

5.3.1 Definition of modularity

The decomposition of complex systems into subsystems and the integration into final products requires the definition of interfaces between subsystems. Therefore, analyzing the nature of interfaces becomes a necessary precondition for analyzing the potential for modularity in an industry (Sako, 2005). Most scholars agree that the more standardized and clearly defined the interfaces are between subsystems, the more the system will allow for modularity.

Modularity in nuclear power supply chains is defined in this thesis as the ability to source components of modular designs from a larger pool of suppliers compared to components of non-modular designs. Substitutability among modular supply chain elements allows for mixing and matching of similar components from different suppliers. This is made possible by standardized and codified interfaces. Lastly, this definition of modularity implies elements of modular supply chains to be largely self-contained. Sako (2005) defined a module as "a set of components assembled, which can be checked and tested before final assembly." Thus, a buyer has to be able to rely on the functionality and quality of a sourced component for the product to be truly modular. With this definition in mind, I investigate which characteristics of the nuclear power industry pertain to that type of modularity in supply chains and which characteristics tend to limit it.

5.3.2 Characteristics of the nuclear power industry that relate to modularity

The product system of a nuclear power plant has numerous interfaces, both on a product level between components, e.g. between a steam generator and a reactor pressure vessel or between a valve and a pipe, and on an organizational level between companies, e.g. between installation firms and equipment manufacturers or between construction contractors and architect-engineers. Rather than listing and discussing individual interfaces at this point, I highlight common characteristics of the nuclear power industry that affect most interfaces between nuclear power industry subsystems. I distinguish between features that are susceptible to modularity and those which are not, beginning with the latter:

(1) Different national quality standards

Nuclear power plant construction and equipment manufacturing in all countries with operating nuclear power plants have to comply with national construction laws and quality standards. In addition to general legislation that applies to conventional industries like the construction industry as a whole, the nuclear power industry in most countries also has to comply with specific requirements of government agencies tailored to the unique demands of nuclear power plant environments. Historically, regulators and inspection organizations in different countries have had different emphases in this process and different national standards have evolved. In the US, for instance, nuclear power plant equipment manufacturing has to comply with standards set forth by the American Society of Mechanical Engineers (ASME) whereas in France Règles de Conception et de Construction des Matériels Mècaniques des Ilots Nucléaires PWR (RCC-M) standards apply.

When nuclear power plants are built overseas according to US or French designs, the most economical option is usually to follow the national standards that were used in the plants' home markets. In some countries this is even required by local law. French-designed nuclear power plants in China, Russian-designed plants in China and US-designed plants in China are all built to different national standards: French, Russian and American respectively. Many equipment suppliers only own one set of certificates complying with one national standard as the cost and resources to obtain and maintain such certificates is significant (Interview 10222011; Kwon, 1985). This impedes the development of spatially dispersed or global supply chains as, for instance, a French valve producer with RCC-M accreditation may not be able to sell valves to US-designed plants that require ASME accreditation. Thus, different national quality standards impede the emergence of modular and truly global supply chains in the nuclear industry.

(2) High demands for quality and time criticality

Demands on quality are higher in the nuclear power plant industry than in other industries such as automotive, oil, gas and thermal power plant industries. Modern nuclear power plants are generally designed for a lifetime of 60 years and the integrity of most equipment across a plant's lifetime has to be guaranteed (Interview 09182011). Moreover, the consequences of equipment failure in nuclear power plants are considered to be more serious than equipment failures in most other industries. Therefore, buyers in the nuclear power industry pay much attention to the testing and quality assurance of the components they use (Interview 10282011).

As mentioned above, an important feature of modularity is the independent and reliable testing and quality assurance by the module supplier. To fully take advantage of modular production networks, buyers need to have enough faith in their suppliers' ability to deliver the quality requested. The importance of testing and quality assurance in the nuclear industry is so high, however, that many buyers do not trust suppliers that they have not thoroughly screened or worked with over extended periods of time (Interview 10222011). Consequently, relational suppliers are preferred over modular suppliers. In addition, delays in the delivery of components and the need to rework components because of insufficient quality have far reaching financial consequences due to the high upfront capital costs of nuclear power plant projects (Interview 09142011). As pointed out in previous chapters, financing costs for the construction of most nuclear power plants amount to about 25% of the total plant cost which often corresponds to amounts beyond $1 billion dollars. Delays can increase such amounts significantly through additional interest, inflation and penalties. Because quality and time criticality play a crucial role in the nuclear power industry, procurement departments often hesitate to replace an established and trustworthy supplier in favor of a cheaper but relatively unknown and potentially riskier alternative.

(3) Lack of experience among suppliers in regard to nuclear industry characteristics

Because of the small number of nuclear construction projects over the last 30 years, the pool of knowledge in the nuclear power industry has shrunk. In the US alone, the number of firms with ASME N-stamp accreditation has dropped from about 440 in the 1980s to 255 in 2008 (WNA Heavy, 2012). ASME N-stamps represent firms' abilities to manufacture safety critical nuclear power plant components at acceptable quality standards. While today many companies are taking a fresh look at the nuclear power market, often entering or returning from related sectors, most of these new entrants pose a potential risk to procurers in that they may not be able to live up to the demands of the nuclear industry initially, as they lack knowledge and experience regarding characteristic features of the industry, including the importance of quality, documentation and time criticality (Aalto University, 2010). This is another reason that makes buyer companies stick to established, time-proven suppliers.

(4) Proximity as an advantage for future maintenance

Many components of operating nuclear power plants need to be regularly monitored and maintained. Some components need to be replaced at certain intervals. Physical proximity between the supplier of such components and the plant they are used in allows for timely delivery of products and services as well as familiarity of local suppliers with local plants. For that reason, many component suppliers, particularly for products with capital requirements lower than those of key components, are chosen from or settle in the vicinity of plants (Interview 10182011).

Sometimes this leads to the creation of nuclear power industry parks such as the Haiyan Nuclear Power Industrial Park or the Rongcheng Nuclear Power Industrial Park. A nuclear industry expert described nuclear power industry parks the following way: "Haiyan is a supermarket. It's close to the Qinshan nuclear power plant and all the companies that come here are like a supermarket for CNNC. You come here, and I buy from you. They all want to have local manufacturers, so they can get reliable supply" (Interview 10182011).

This leads to clustering of certain types of suppliers around nuclear power plants rather than to the kind of dispersion that is typical for modular supply chains. The benefits that come from the proximity of suppliers to nuclear power plants represent another factor that hinders the development of modular supply chains in the nuclear industry.

(5) Suppliers as co-developers and co-financiers

Developing new reactor architectures is a lengthy and costly process that even large state-backed organizations can hardly shoulder on their own. In order to spread the risk and financial burden of developing new reactors across multiple actors, lead suppliers sometimes get involved early in the design process. In return for contributing to the new reactor design in various ways, e.g. financially or by providing human resources, test facilities, etc., they receive exclusive supply agreements or interfaces that are tailored to their products (Interview 10142011). At the same time, reactor vendors try to find a balance between receiving support from lead suppliers and keeping interfaces standardized in order to avoid being captured by individual suppliers. To the degree that arm's length relationships occur that involve lead suppliers in the design process in return for exclusive supply agreements, modularization of that part of the supply chain is virtually impossible.

We have seen that there are a number of characteristics of the nuclear industry that work against the formation of modular supply chains. Nevertheless, there are also aspects that are advantageous. They are as follows:

(1) *Change of product architectures is slow and almost always incremental*

From the earliest nuclear reactors in the 1950s onward, the nuclear power industry has suffered a case of technology lock-in which led to light water reactor designs remaining the reactors of choice for large scale dissemination (Cowan, 1990). Today, over 95% of the more than 400 operating reactors globally are water-cooled reactors (IAEA, 2012). Although this case of technology lock-in has often been criticized for rendering the nuclear industry inert to new reactor designs, it is in fact beneficial for modularization.

Since the basic product architecture of light water reactors, including the arrangement and design of steam generators, reactor pressure vessels, reactor coolant pumps, and turbine-generators, has barely changed over recent decades, this kind of inertia has led to a certain level of interface standardization among key components. For instance, steam generators for most nuclear power plants can today be provided by a range of different suppliers globally as steam generator designs for different plant types are very similar (Interview 10142011; Interview 09142011). Nuclear reactor vendors who act as product architects in fact emphasize that their new designs are not radically different from previous designs and are based on "proven technology" (Westinghouse, 2003; Teller, 2010). Westinghouse advertises its "most advanced, yet proven" nuclear reactor, the AP1000, in its brochures as being "based on standard Westinghouse Pressurized Water Reactor (PWR) technology that has achieved more than 3,000 reactor years of highly successful operation" (Westinghouse, 2009).

The type of mixing and matching, as in the case of steam generators, applies to large key components whose vendors often operate globally, have established a reputation and have reference projects to point to which reduces the risk of quality and schedule shortcomings. Most of such key components sell for $10 million and above, in which case thorough supplier screening and the acquisition of multiple national accreditations makes more sense than for suppliers of lower value components. Smaller companies for non-key components benefit less from the inertia and uniformity among product architectures, as obstacles to modularity laid out in the previous section still hold, i.e. the burden of multiple national standards and the importance of being local.

(2) Flexibility in the use of capacity is valued

Building and maintaining capacity for design, construction and equipment manufacturing in the nuclear industry is costly and demand has traditionally been unsteady. Once projects get underway, however, it is critical to be able to ramp up production quickly and deliver in a timely manner. Companies are more likely to succeed at matching supply to demand if large orders can be spread across multiple suppliers (Interview 10142011). If capacity remains within the boundaries of integrated organizations, the risk involved in maintaining that capacity rests with the organization itself. In the case of modular supplier relationships, the risk rests with the suppliers.

To maximize utilization of capacity, suppliers often diversify into other markets such as oil and gas or thermal plant markets. In state-backed nuclear industry environments they may receive subsidies for maintaining capacity or receive guarantees for continuous long term demand through planned nuclear power fleet programs.

To summarize, modular production networks provide nuclear power plant vendors with greater flexibility in utilizing capacity at times of high and low demand and minimize their risk in maintaining respective capacity by themselves (Interview 10142011).

5.4 The status quo of the global nuclear industry

As we have seen from the previous section, some aspects of today's nuclear industry favor relational supplier relationships while others favor modular supplier relationships, depending on the components, organizations and ecosystems concerned. Characteristics that speak against modularity predominate, however, and the industry status quo favors relational rather than modular supplier relationships.

Nevertheless, there is a trend towards greater degrees of deverticalization and modularity in some domains of the global nuclear industry, as I show in the next chapter. This trend is dependent on geography and is most visible among US nuclear industry firms.

Before the 1990s, all of the large reactor vendors such as Framatome (today's Areva), Siemens, Rosatom, Westinghouse and GE provided almost all products and services needed to build a nuclear power plant, ranging from design, to construction oversight, to equipment manufacturing. Everything was provided in-house, through subsidiaries or through established long term partners. They tapped into networks of suppliers that were closely tied to them and mutually dependent (Interview 01142011).

In the case of Framatome's successor Areva and its long term partner EDF, this structure largely prevailed until Areva's recent project at Olkiluoto in Finnland and its bids for projects in the United Arab Emirates where EDF did not join Areva (Berthelémy and Leveque, 2011). The two Areva projects in Taishan, China, come closer to the original model of close cooperation between Areva and EDF, however. Here, the two companies brought their established lead suppliers to China via roadshows and exhibitions in order to fulfill localization requirements by partnering with Chinese enterprises and at the same time resemble established integrated supplier structures the companies are used to (Interview 10182011). Today, Areva still claims on its website "to use its integrated model to consolidate its position as world leader" (Areva, 2012). Similarly, the Korean nuclear power plant vendor KEPCO divides up most tasks in nuclear power plant design, equipment manufacturing and construction among its own departments and subsidiaries such as KEPC E&C, KEPCO Plant Service and established long term partners Doosan and Hyundai as well as a local production network of smaller Korean enterprises. Rosatom refers to itself as a "fully integrated technology company" providing fuel fabrication, equipment manufacturing, design, engineering, construction, operating services, as well as maintenance and upgrading services (Samoshin, 2012). As a consequence, it offers guaranteed supply of future products and services.

Compared to integrated firms like Areva, and Rosatom, the US nuclear power reactor vendor Westinghouse has reached relatively high levels of disintegration and modularization with many input products and services not only sourced from external suppliers but often sourced from multiple suppliers (Interview 10142011 and Interview 09142011). The difference becomes most apparent when comparing staff numbers of the three companies: Rosatom in 2012 had 270,000 employees across more than 250 subsidiaries (Russia Forum, 2012). Areva had 48.000 employees in 2010 (Aubouin, 2010) while Westinghouse had only 15,000 in 2010 (Westinghouse, 2010). The scope of activities of these four companies is very different. KEPCO and its subsidiaries not only engineer and build nuclear power plants but also operate them. In addition to nuclear power, Rosatom also has divisions for nuclear weapons, nuclear medicine and nuclear icebreakers, among others. Such disparate companies may be difficult to be compared but this is part of my argument: Westinghouse, as a lean entity focused on a range of core activities and managing a broad network of suppliers and partners, competes directly with nuclear power companies whose character and organization is very different from itself.

In the next section, I elaborate on reasons for such differences and for the deverticalization of Westinghouse.

5.5 Drivers of modularity in the nuclear industry

At the beginning of this chapter, I discussed generic factors that contributed to a trend towards higher degrees of modularity in many industries. Two major factors were the development and dissemination of information and communication technology (ICT) and increased specialization in the manufacturing of components of complex systems.

Apart from these generic factors, different industries and locales experienced particular factors that accelerated modularization. As Sako (2005) pointed out, in the US computer industry for instance, "the eventual disintegration of the industry into modular suppliers [...] may be accounted for by the inter-firm mobility of technical labor and the availability of venture capital for start-ups." This was complemented by users' demands for better compatibility among components toward mixing and matching.

In this section, I argue that in the US nuclear industry, disintegration was fueled by the sudden drop of demand in the 1980s, an external shock, in combination with a general trend towards modularization particularly in US indusrty, as well as the slow pace of change in product architecture.

5.5.1 External shock: a sudden drop in demand

The Three Mile Island (TMI) accident of 1979 marked a turning point for the US nuclear industry. Fifty-one orders for US nuclear reactors were canceled in its aftermath. While more than 100 reactors had been approved prior to 1979 and were subsequently built in the US, no new reactors were approved until 2012 (WNA USA, 2012). Internationally, only South Korea continued to steadily build a fleet of nuclear reactors, a development driven by the Korean state. In France, the state subsidized its nuclear industry and sustained its integral structure to preserve capacity for building and maintaining nuclear power plants. With more than 75% of French electricity produced by nuclear power this was considered a strategic measure (WNA France, 2012).

US nuclear vendors in contrast received hardly any state support and were forced to adapt to the new market conditions. Leading US nuclear vendors like Westinghouse, GE and CE suddenly found themselves stranded with large integrated organizations overseeing manufacturing capacity and workforce for building multiple nuclear power plants per year but without new orders.

In order to survive and preserve their core competencies, these companies were forced to sell off large parts of their organizations, including much related equipment manufacturing.

Westinghouse for instance sold its turbine division to Siemens and its Reactor Coolant Pump (RCP) division to Curtiss Wright. Today, Westinghouse still works closely with Curtiss Wright, to the degree that the pump manufacturer is involved in the reactor design process. At the same time, Westinghouse has no obligations towards Curtiss Wright and no responsibility for maintaining its manufacturing capacity or workforce. Westinghouse is also free to switch to different RCP suppliers as attractive alternatives emerge.

In regard to heavy forgings, Westinghouse sourced most of its equipment from US Steel and Bethlehem Steel up to the 1980s (WNA Heavy, 2012). For Generation II reactors the US Steel and Bethlehem Steel press capacities of 8,000 tons were sufficient. Contemporary Generation III plants generally require 14-15,000 ton forging presses, however, and since US Steel and Bethlehem Steel have not upgraded their facilities, companies like Westinghouse were forced to diversify their supply chains. Today, Westinghouse sources much of its heavy equipment from ENSA of Spain and Doosan of South Korea (Interview 09142011). It is remarkable that both ENSA and Doosan were former customers of Westinghouse that had benefited from extensive technology transfer in the past and developed their expertise partly because of Westinghouse's earlier support.

The TMI accident and the subsequent drop of new builds coincided with the deverticalization and modularization of supply chains of organizations like Westinghouse. That move did not take place to a comparable extent in firms such as in South Korea that did not experience the sudden drop of demand that US firms experienced. Some industry representatives I interviewed suggested that the move towards more modular supply chains of US firms in particular was not primarily a deliberate strategic decision but rather an inherent necessity for financial survival (Interview 10142011). An alternative explanation is that deverticalization in the US nuclear industry was part of a larger general trend among US companies to move toward more modular supply chains. In any case, managers of major US nuclear vendor companies were able to turn to and learn from the experience of firms of other industries that underwent deverticalization, particularly in the automotive, semiconductor and computer industries.

In making the best of their new circumstances, firms like Westinghouse discovered advantages of the new model and tried to exploit them. This is in line with Sako's observation (2005) that "benefits of modularity may take some time to emerge when outsourcing runs ahead of modularization." While US firms had few alternatives and eventually tried to accept their fate and position their companies newly in global nuclear power markets, deverticalization and modularity was not a path pursued by companies in other countries that had alternatives, for instance through government subsidies. These companies largely remained big integrated organizations.

5.5.2 Modular product architectures

In the previous section, I discussed how factors related to the nuclear industry at large, and even factors beyond the industry as such, like the TMI accident, affected the structures of organizations and contributed to higher degrees of modularity. Sako (2005) condensed differences in the structures of organizations into the concept of "organization architecture." She then contrasted "organization architecture" with the notion of "product architecture" although the two are seen as mutually dependent: "product architecture affects organization architecture and vice versa."

Applying those terms to the nuclear industry, the organization architecture of a company like Westinghouse turned from very integral before the 1980s to more modular after TMI while the organization architectures of companies like Rosatom, Areva and KEPCO remained relatively integral. Sako further observed that "non-modular products are best produced in non-modular organizations. But modular products call for modular organizations." Based on that statement, one would expect Westinghouse's products to have become more modular over time and more modular than those of its integrated competitors, or to have been more modular to begin with.

This is in fact the case: key features of Westinghouse's AP1000, its first major new reactor design after the disintegration process, are modularity in construction and flexibility in choosing suppliers. In its advertising materials, Westinghouse emphasizes for instance that "most equipment and commodities are non-safety class" and that this feature of the design "allows more procurement of materials from commercial grade suppliers" (Patel, 2008). In contrast to other nuclear reactors currently deployed, Westinghouse claims that the AP1000 is "modular in design, promoting ready standardization."

In contrast, Areva's products such as the EPR as well as its organization architecture resemble a more integrated approach. In its advertising materials, Areva explicitly points to its "in-house integrated supply chain for key components" (Areva, 2010). This confirms Sako's observation that "firms with a highly integrated supply chain architecture might be expected to retain a more integral modular product architecture" and "firms that have made a significant investment in both deep and diverse technical knowledge are unlikely to promote modular product architecture that provides competitors with advantages within modules and renders their integrative skills less valuable." My observations also confirm Gulati and Eppinger (1996) in that "product architectural choice influences organizational design, but preexisting organization structures and capabilities also influence product design."

Modular construction techniques and standardization of components have been employed for decades in other industries such as in ship building, but did not get widely adopted in the nuclear industry until recently as in the case of the Westinghouse AP1000 reactor (Interview 09172011). One can argue that it was not so much the sudden availability of new technology that caused the recent trend in modularization of nuclear power plant architectures but that the modularization of the organization architecture facilitated and motivated the modularization of the product architecture, using technologies that had already been around. Additionally, cost pressures that played a much larger role in the privately driven nuclear industry in the US than in state driven nuclear industries in other countries incentivized reactor vendors to innovate in this domain. Modular construction techniques offered greater cost savings and more reliable construction schedules. The US nuclear industry had particularly suffered from extensive construction delays and subsequent cost overruns.

In reality it was likely a combination of factors that drove modularization: growing pressure to take advantage of more advanced modular construction techniques observed in other industries, the expected benefits of modular supply chains, and changing organization architectures that increasingly called for more modular production architectures.

5.6 Modularity and innovation

The degree of modularity and the nature of organization and product architectures impact firms' abilities to innovate. Innovation may take place within discrete modules, often within multiple modules in parallel, and innovation may take place on a systems level, affecting the entire product. Systems-level innovation may be facilitated by an integrated organization architecture which allows for better coordination and flexibility in adapting production processes to new product architectures. This is particularly important for products characterized by interdependencies and feedback between different product components. In contrast, clear separation between modules and clear definition of modules promotes greater specialization and within-module innovation. In summary, different types of product and organization architectures enable different types of innovation across the spectrum from within-module innovation to systems-level innovation.

In the following section, I elaborate on differences between within-module innovation and systems-level innovation. I introduce two cases of within-module innovators, Lightbridge and KSB, and two cases of systems-level innovators, Siemens/KWU and Rosatom, which I then evaluate and discuss.

5.6.1 Within-module innovation

Within-module innovation is characterized by "a clear division of labor between the architect with architectural design knowledge and designers with knowledge of each module." (Sako, 2005) The following two cases illustrate such configurations where designers have developed specialized knowledge of their module and rely on others for architectural integration.

5.6.1.1 Case 1: New fuel assemblies by Lightbridge

Lightbridge is a US-based company that was formed in 1992 with the explicit goal of developing new types of nuclear fuel assemblies. Compared to conventional fuel rods, Lightbridge-designed fuel assemblies use different materials and have different geometries which allow for more efficient heat transfer from the nuclear fuel to the surrounding cooling water. Lightbridge claims to be able to increase electricity production of current light water reactors by 30% , simply by using different types of fuel assemblies (Lightbridge, 2012). Their product is strictly modular as no changes on existing reactor are required. A rough analogy for the replacement of conventional fuel assemblies through advanced Lightbridge fuel assemblies is replacing an inkjet printer cartridge with a newer cartridge of higher capacity while leaving the printer as such unchanged.

Lightbridge has a small headcount of about 15 fulltime employees (Macroaxis, 2012) but has extensive partnerships with labs and research centers in the United States and in Russia. Because of its lean organization architecture the company itself performs the role of a systems integrator in coordinating among its various partners. However, from the standpoint of a nuclear reactor as a final product, Lightbridge innovates strictly within a module: "we don't design new reactors, we design new fuel" and "nuclear fuel is a much simpler project than a whole new reactor" (Interview 10202011).

Lightbridge has been funded partly through venture capital and partly through offering consulting services to nuclear power projects around the world. In 2006, the company became publicly traded on NASDAQ. Lightbridge has not depended on state support and it has not depended on reactor new builds as its products can be used in existing reactors of which the US alone still has more than 100 in operation.

In this sense, Lightbridge is a prime example of a company that is developing a highly modular product. Lightbridge has employed within-module innovation in an environment, the US nuclear industry, which has moved toward ever greater deverticalization over the past 30 years and it has found its sweet spot in an increasingly modular network. Nuclear fuel as such used to be highly monopolized with many reactor vendors contractually requiring their customers to procure nuclear fuel through them only. In recent years, the industry has moved away from this practice, giving nuclear operators more choice in procuring their fuel. Lightbridge's activities are further steps in this direction: beyond choice among alternative fuel suppliers, Lightbridge aims for providing nuclear operators with the choice of alternative fuel technology. All of these developments take place within the module of nuclear fuel and hardly affect reactors as a whole.

5.6.1.2 Case 2: More efficient reactor coolant pumps by KSB

KSB is a German medium sized company that specializes in the production of pumps and has equipped more than 100 nuclear power plants globally with its products (KSB, 2011). KSB is developing a new type of Reactor Coolant Pump (RCP) which reduces maintenance needs and increases efficiency due to lower power consumption. The basic parameters of RCPs are similar in most contemporary nuclear power plants and the pumps are generally mounted between steam generators and primary cycle pipes that come from the reactor pressure vessel. RCPs are responsible for circulating cooling water in the reactor's primary cycle. KSB's new RCP design is a wet winding pump where the pump's motor itself is immersed in water which reduces eddy currents and thereby leads to efficiency gains.

KSB benefits from the well-established and fairly standardized designs of light water reactors. Because of the technology lock-in in regard to light water reactors, similar RCPs can be used by different reactor vendors, e.g. Areva or Westinghouse. RCPs are sufficiently standardized to allow for some degree of mixing and matching across different reactor types. KSB has positioned itself in a discretely defined module within which it has specialized and innovated.

As a Germany company, it did so in an environment where it has lost its strategic long term partner Siemens due to the deverticalization of Siemens' nuclear power department in the 1990s and Siemens' exit from the nuclear power business in the 2000s. Today, KSB is largely autonomous and not bound to any individual partner.

5.6.2 Systems-level innovation

Systems-level innovation is characterized by changes that impact multiple aspects of a given product, sometimes changing the nature of the product itself. The following two cases illustrate such configurations.

5.6.2.1 Case 3: Gas cooled high temperature reactor HTR-Modul by Siemens/KWU

The HTR-Modul, a gas cooled high temperature reactor, was a next generation nuclear reactor architecture that was designed to be inherently safe. The HTR-Modul differed substantially from light water reactors: it used gas and graphite for cooling and moderation instead of water and consequently required very different equipment; it was different in size and capacity and used spherical fuel elements as opposed to fuel rod assemblies. Virtually all key components of the HTR-Modul differed substantially from key components in light water reactors.

The HTR-Modul was developed jointly by Siemens/KWU, the Juelich Nuclear Research Center and Aachen University in the 1980s. At the time, Siemens' nuclear power subsidiary KWU was itself a highly integrated organization and embedded in the larger Siemens conglomerate. Relations between Siemens/KWU, Juelich and Aachen University had developed over decades and were extremely close with many key developers having worked or been educated in all three organizations in the course of their careers. Moreover, an engineer involved in the HTR-Modul design described the proximity to the larger Siemens group as invaluable, given that thousands of experts in all related fields were within arm's length and could be drawn upon if additional expertise was required (Interview 01142011).

The HTR-Modul project was discontinued by Siemens/KWU after public opinion moved against nuclear power in Germany in the late 1980s. However, the design is implemented in large part in the Chinese HTR-PM reactor which is currently under construction in China's Shandong province. It is one of the few reactors under construction globally that are classified as Generation IV reactor designs.

5.6.2.2 Case 4: Sodium-cooled fast reactor BN-1200 by Rosatom

The BN-1200 reactor is another one of the few Generation IV reactor designs whose construction has been approved with expected commissioning by the end of the 2010s. The BNP-1200 is a fast neutron reactor which uses liquid sodium as a coolant. Liquid sodium has very different chemical and radiological properties compared to the water used in light water reactors and, therefore, large parts of sodium cooled reactors require the use of different materials. The reactor design itself is substantially different from light water reactors with different demands on fuel, vessels, pumps, steam generators, etc. The new design creates inter-module dependencies and the need for evaluating large amounts of feedback between what would be considered separate modules in established reactor architectures.

The BNP-1200 is developed by Rosatom, Russia's state-owned nuclear reactor vendor which is a highly integrated corporation that controls more than 150 manufacturing and research organizations in the Russian nuclear industry (Rosatom, 2010). Major stakeholders are subsidiaries of Rosatom, the engineering firm OKBM Afrikantov, the design institute Atomenergoproekt and the research center SSC RF – IPPE.

This new sodium-cooled fast reactor was developed in a large state-owned organization that has been tightly integrated over decades.

5.6.3 Moving across product generations

In the previous section, I laid out cases of within-module innovation and systems-level innovation which corresponded to different organization architectures and led to very different types of products. We have seen cases of within-module innovation corresponding with modular organization architectures and cases of systems-level innovation corresponding to integral organization architectures.

It is difficult to assess which type of innovation leads to more value creation over time. Frankly, we do not have much experience with the introduction of new reactor architectures in the nuclear industry because of the almost exclusive focus on large light water reactors in the commercial energy space. In the past 60 years, most proposed new reactor architectures failed. The experience of other industry sectors suggests, however, that at some point the nuclear industry too may experience disruptive changes toward a new product generations. Hobday et al. (2005) expressed this expectation the following way: "At regular, recurring points existing product architectures must be transcended if performance limits are to be overcome and technological progress is to continue." They add with respect to systems integration: "Systems integration is not simply a static capability concerned with current product generations. It is also a dynamic capability essential for moving successfully from one product generation to another."

Russia and China in particular declared as their explicit goals the introduction of Generation IV reactors and their deployment on a wide scale by 2030 (WNA Russia, 2012; WNA China, 2012). Given their nuclear industries' massive state support and successful track record of recent years, one may argue that next generation reactor architectures are likely to be introduced to the global nuclear market within the coming two decades. Given the systems-level nature of new reactor designs, and the insight that systems-level innovation is associated with integrated as opposed to modular organization architectures, it is not surprising to see Russia and China lead efforts towards the deployment of next generation nuclear reactors. Rosatom emphasizes its ability to innovate is reflected in its "broad development programme" for generation IV fast reactors and its efforts in the domain of small and medium size reactors including floating nuclear power plants (Samoshin, 2012). Chinese nuclear power organizations focus on generation IV fast and gas-cooled reactors as well as small modular light water reactors, and have recently allocated additional resources for a molten-salt reactor program (WNA China, 2012).

There are proposals for new reactor architectures in the US too, but many of them are either evolutionary in nature and based on existing light water reactor technology or they are still in conceptual stages, far from being licensed, let alone deployed. It is doubtful whether firms that move toward higher degrees of modularity such as Westinghouse or even smaller firms that start out focusing purely on design and project management such as Terrapower or Flibe could cope with the demands of detailed plant designs, equipment design, manufacturing and construction oversight without the support of large integrated organizations or tight relational supplier networks.

5.6.4 Modularity trap

A potential future shift toward next generation reactor technologies involving new product architectures with different materials and designs, could pose a threat to established modular production networks. A new product architecture would likely disrupt the decomposition of designs and rearrange modules in the supply chain. For instance, if helium gas cooled reactors became more common, KSB's water pumps could get displaced by helium blowers. Many modular suppliers could find themselves in a so called "modularity trap." According to Sako (2005), "in such a trap, benefits from a shift in an industry from a modular to a more integral phase of technological development cannot be exploited fully by firms due to inertia in organization structure more suited to serving modular product architecture." Companies like Westinghouse and KSB might have difficulties to adapt to such a new situation with their supply chains being well adapted to the established technology's product architecture, i.e. light water reactors. Over time, and with large scale deployment, one would expect new reactor architectures that will likely start out as integrated designs to become increasingly modularized too. Some companies may make the successful transition from a module of the old product architecture to a module of the new product architecture, although the latter may be a different one than the former. Other companies may be displaced by competitors that are better positioned within the new supply chains.

5.6.5 Capturing value from innovation across product cycles

Across product cycles, both within-module and systems-level innovation contribute to the advancement of products. Historically, firms have created and captured value through both types of innovation. But how can firms maximize their participation in the different types of innovation processes?

Using an example from the computer component industry, Hobday et al. (2005) suggest that "product designs can oscillate between modular and 'integrative' states as progress from one design to another occurs." Despite the many differences between the computer components industry and the nuclear industry, we can also differentiate between more modular and more integrative states of nuclear reactor designs over the course of a product cycle. During the development of new nuclear reactor designs, when designs are necessarily in a more integrative state, integrated organizations benefit from their organization architecture (Interview 01142011). It is often those integrated organizations that develop new reactor designs and build so called First-Of-A-Kind (FOAK) reactors for a new product generation. As a next step in the product cycle, standardization may take place and the decomposition of the integrated product into modules. The Nth-Of-A-Kind (NOAK) reactor may then be produced in a more modular way in order to lower cost, optimize the use of capacities and take advantage of within-module innovation. At this stage, organizations with modular organization architectures may be at an advantage.

Charles Fine (1999) introduced the concept of clock speed as a measure of pace at which changes take place in a particular industry. Of course, the difference in clock speed between the nuclear industry and the computer component industry is vast. What may take months in the computer component industry, may take decades in the nuclear industry. Nevertheless, I expect nuclear reactor product designs too to oscillate between integrated and modular states, although this may only take place over relatively long periods of time. At the same time, I do not expect organization architectures to follow such oscillations. Sako (2005) suggests that "assemblers will vertically integrate when the production process, broadly defined, produces specialized, nonpatentable know-how." This suggests that modular organizations tend to integrate as they anticipate opportunities through knowhow in production processes and product designs. However, alternatives to vertical integration for modular firms, while still benefiting from advantages of vertical integration, are to find vertically integrated partners. With close partnerships to vertically integrated partners, modular firms can ensure their ability to carve out new roles in future modular supply chains as transitions to new product generations take place.

Instead of oscillation of organization architectures from integral to modular and back, I present an alternative model of coexistence of modular and integral companies. In this model, integrated and modular companies benefit from each other's advantages through partnerships: modular companies bring within-modules knowhow to integrated partners; integrated partners develop new production generations and carve out future roles for their modular partners as initially integrated product architectures get increasingly modular over time.

I believe the coexistence of modular and integral companies in partnerships to be a more likely model vis-à-vis a model of oscillating reintegration of disintegration due to the high capital investments involved in transitioning between states and the large differences among companies around the world with respect to government support and their local ecosystems.

This view would imply that the types of partnerships that firms engage in and the characteristics of the different partners available become even more important.

5.7 The future of modularity in the nuclear industry

5.7.1 Trends toward mass production

Hobday et al. (2005) emphasized that so called Complex Product Systems (CoPS) such as project-based power plant projects are very different from high-volume products. Specifically, these projects involve less standardization and modularization and more custom and dynamically changing components. This statement applies to the nuclear industry.

There are, however, several trends toward greater levels of standardization. The benefits of standardization of reactor designs and components for national nuclear fleet programs became obvious with the experience of the French fleet build up (David and Rothwell, 1996). In France, a particular nuclear reactor design was chosen and a whole batch of nearly identical reactors built based on the design of the original. After localization of major technologies, South Korea pursued a similar approach and from the 1990s onward deployed OPR-1000 reactors modeled on the CE "System 80" design. This type of standardization guaranteed that within each batch of nuclear reactors the same components and production processes could be employed.

Consequently, this opened up opportunities for certain degrees of modularity among suppliers as the expectation of larger batches of orders increases the incentives for suppliers outside of the relational network to adapt to respective specifications and for procurers to invest in screening new suppliers. This then leads to a greater pool of potential suppliers.

A different trend toward greater levels of modularization comes from so called Small and Medium Reactors (SMRs). These are new reactor architectures that are defined by the IAEA to be of less than 300 MWe capacity (Subki, 2012). More than a dozen different designs are currently being explored, mainly in the US, Russia, Japan, Europe, China and South Korea (WNA SMR, 2012). Most of these reactors consist of very compact and simplified designs with little on-site construction work required and major components manufactured as discrete modules in factories. SMRs are deliberately advertised for their "economies of mass production" versus "economies of scale" characteristics which include more efficient use of labor, the application of industrial learning processes, more efficient procurement, the reuse of specifications, drawings and procedures, and mechanization optimization opportunities. The trend is exemplified by Wallace et al. (2005): "Although building a nuclear power plant is not a typical high-volume manufacturing process, for the PBMR-type of plant [a type of SMR], with its high degree of standardization and relatively small, simplified design, the shift to factory work has a significant impact on overall project cost due to earlier identification and better coordination of parallel construction paths."

Toshiba's 4S reactor, nicknamed a "nuclear battery," and completely mass produced in a factory, pushes the frontier of potential mass production of nuclear reactors. The entire reactor would be contained in a single vessel of size 2 meter height and 0.68 meter diameter (WNA SMR, 2012). A small steam turbine and generator above ground would then produce 10 MWe of electricity. In order to reach higher capacity levels, multiple small reactors would be coupled and operated in parallel. A pre-application for the Toshiba 4S is currently under review by the Nuclear Regulatory Commission (NRC) and submission of the full license application is expected in the third quarter of 2012.

Small factory-produced reactors like the Toshiba 4S would have very little in common with the characteristic challenges of large nuclear reactor building site projects of 1000 MWe and beyond light water reactors such as the Olkiluoto project. If small reactors do reach the scale of diffusion that some industry observers predict, they could impact the nuclear industry as a whole. Employing the techniques involved in nuclear equipment manufacturing on a mass scale would almost certainly also influence equipment manufacturing for large reactors by making it more standardized and modular.

5.7.2 Value stream positioning

In more modular supply chains, firms have to constantly reevaluate and readjust their position in the value stream. In the words of Hobday et al. (2005): "At the level of industry value stream, systems integration is the capability by which a firm decides where and how to situate itself, influencing how a firm competes, who it collaborates with, and who it competes with." Hobday et al. showed that companies in modular supply chains "are moving from both down- and upstream positions to try and capture the higher value territory situated between manufacturing and services."

We observe this process taking place in a wide range of industries. Firms such as Alstom, GE and Ericsson have increasingly tied services to their hardware products. For instance, Alstom developed a train management system which it marketed along with its trains. Similarly, the servicing of train fleets has become a major business opportunity for Alstom, as it often provides more revenue over the lifetime of a train than the train purchase itself (Hoday et al., 2005).

Companies in the nuclear industry face similar challenges. The more modular a company the more important is the question of where in the value stream it is situated. A company like Westinghouse that has moved from being an integrated provider of most parts of the nuclear value chain to becoming an engineering company focusing on design, maintenance and fuel services has to choose carefully which activities to focus on. Margins in the manufacturing of heavy key components tend to be low and require high initial investments and associated risk (Tong, 2010), so it is no surprise that Westinghouse is hardly involved in this area any more. One possibility for Westinghouse in the future is to move further downstream. While outsourcing larger portions of design and project management, it could focus on activities with even higher margins such as branding, financing and consulting.

Sako (2005) describes a possible scenario in the automotive industry "in which OEMs will focus purely on styling and marketing, withdrawing from manufacturing and assembly altogether. In this scenario, some OEMs would wish to delegate systems integration tasks to powerful suppliers that can design a whole car." Hobday et al. (2005) introduces a similar case from project based industries: "The prime contractor can be separated from the systems integrator which means that, in some cases, the systems integration task itself is outsourced to a supplier firm." Could such scenarios be possible in the nuclear industry? How far away from the production process can a company move and interpret systems integration as coordination of other systems integrators? For its AP1000 projects in China, Westinghouse has already outsourced detailed design tasks to SNERDI in Shanghai (Interview 09072011). If engineers in Shanghai turn out to be more competitive than engineers in Pittsburgh, Westinghouse may stick to this approach and expand its collaboration with SNERDI to other projects. However, Sako warns that "product system makers which outsource design often have to retain substantial knowledge about production process and product design in-house." This poses the question of the extent to which systems integrators like Westinghouse can retain systems integration capabilities without direct involvement in production and construction activities. This is an important question – though outside the scope of this thesis - that deserves attention in the future. In this section, I showed that deverticalization and modularity pose new challenges to companies in the global nuclear industry. With the industry becoming more dynamic due to leaner and more modular players, all industry actors, deverticalized or not, are forced to stay on top of global and regional industry trends. They need to know their potential partners and competitors and constantly identify new opportunities to reposition themselves across the nuclear value stream and in relation to other organizations.

5.8 Summary

The global nuclear industry today is characterized by a polarity. In contrast to other industries that exhibit general trends towards higher degrees of modularity or higher degrees of integration, companies in the global nuclear industry have pursued both paths. Different environments led to different organization architectures, some more modular and some more integral.

For a number of reasons, companies like Westinghouse increasingly deverticalized and came to embrace skills and strategies similar to firms of other sectors that are characterized by modular production networks. Modular organization architectures impact an organization's ability to source globally and to involve new suppliers in their supply networks. From that perspective, technology transfer and localization shine yet another light: they contribute to expanding and diversifying global supplier networks and to making them more modular in nature. The ability to develop and manage such supplier networks in and of itself becomes an important capability in the toolset of systems integrator firms such as Westinghouse.

Companies like South Korea's KEPCO and China's CGN pursued a different strategy; they grew into large integrated organizations. For them, much systems integration takes place within their own organizations. These organizations can deal with interdependencies and feedback across product systems effectively and are well positioned to develop and deploy new generations of products.

Instead of observing a single trend from integration to disintegration, as in many other industries, I observe two trends that take place at the same time: one toward greater disintegration and one toward greater integration. This is exemplified by companies like Westinghouse on one side of the spectrum and companies like KEPCO on the other.

Modular and integrated organization architectures coexist and each organization architecture has unique advantages. Modular architectures promote within-module innovation, allow for more flexibility, lower costs and deeper localization. Integral architectures allow for systems-level innovation, better communication and greater reliability. Additionally, integral architectures are often supported by national governments and can draw on various types of benefits this entails.

One way for both modular and integrated organizations to compensate for their weaknesses and take advantage of their counterparts' strengths is to form partnerships to take advantage of the best of both worlds.

The partnerships between Westinghouse and KEPC and between Westinghouse and SNTPC illustrate such partnerships.

Westinghouse does not have the advantages a state-backed integrated organization has, such as the ability to build and maintain large production capacity and relational supplier networks. Working closely with partners like the Chinese nuclear industry helps Westinghouse compensate for these shortcomings. Westinghouse can also benefit from SNPTC's strong financial background from the Chinese state, even for projects overseas as in the UK where the two companies are preparing a joint bid. Westinghouse can draw from a pool of new suppliers and subcontractors that are emerging in China for its global projects. It is sourcing more and more of the components for its nuclear reactors globally, at low margins, and has an interest in broadening its production network. This increases competition and pressures margins even more. At the same time, Westinghouse needs to position itself carefully, so as to not lose control over its supply chains and to remain on top of global developments in the industry.

For its part, the Chinese nuclear industry with its highly integrated organizations invited Westinghouse on board and has since been developing a new standalone nuclear organization, SNPTC, which is meant to learn from Westinghouse. SNPTC is set to become leaner and more modular than its competitors and partners, the China National Nuclear Corporation (CNNC) and CGN. SNTPC can use Westinghouse's brand name to get a foot in the door internationally, again, as seen in the UK.

The extent to which such new configurations are stable or transient remains to be seen. Nevertheless, the spectrum from modular nuclear organizations on the one side to integrated nuclear organizations on the other side is real and represents the global environment into which the Chinese nuclear industry is growing. Chinese companies are chosen as partners, and are choosing partners, in order to position themselves in the nuclear value chain domestically and globally. To understand the development of the Chinese nuclear industry, we cannot look at it in isolation but rather view it as an actor in a global dynamic process of nuclear industry development and consolidation.

PART III - CHINESE IDIOSYNCRASIES

After discussing trends in the global nuclear industry and how they relate to the Chinese nuclear industry, I now turn to characteristics of the Chinese nuclear industry itself. I find idiosyncrasies that stem from China's peculiar path of economic development and manifest themselves in the nuclear industry as well as in other industries. In the following paragraphs I discuss four central ones in some detail. I argue that the Chinese nuclear industry exhibits unique features that need to be understood both by Chinese and foreign actors involved.

6 Idiosyncrasies of Chinese economic development and their impact on the Chinese nuclear industry

6.1 Government support and industrial policy

China's efforts in the field of nuclear fission can be traced back to the 1950s. At the time, the Chinese government pursued the development of nuclear weapons, resulting in the testing of its first nuclear bomb in 1964. In the 1970s and 1980s much of the capacity in the nuclear weapons industry was transformed into a civilian nuclear power program. The Second Ministry of Machine Building turned into the Ministry of Nuclear Industry, which eventually became CNNC, China's largest nuclear power company today (NTI, 2012).

However, as Xu (2010) demonstrated, the Chinese civilian nuclear power program was fragmented and lacked coherent leadership and political support until the 2000s. It was only in 2002, when two-thirds of China's provinces faced power shortages, pollution was severe nationwide, and the transportation network suffered bottlenecks from coal transport that China developed a coherent long-term energy policy with nuclear power playing a significant role.

In 2008, the National Energy Administration was founded to guide nuclear power development under a comprehensive energy policy. Earlier, nuclear power had not been able to compete with expanding coal capacity both for cost reasons and for lack of a credible long term policy that would have created a reliable investment climate. Nuclear power was now recognized by the Chinese government as a proven "new energy" technology that was readily available and could help the country achieve energy security and pollution mitigation (Xu, 2010).

China's economy has been growing at double-digit and high single-digit rates since the opening and reform policies of the late 1970s. Energy demand naturally grew to fuel the booming economy. In 2010 and 2011, electricity consumption grew by 14.56% and 11.7% respectively, with total consumption reaching 4693 billion kWh by the end of 2011 (WNA China, 2012). Installed capacity in 2011 was 1052 GWe and is expected to reach about 1600 GWe in 2020 and 2000 GWe in 2025. In 2011, investments into electricity infrastructure amounted to CNY 705 billion (~$107 billion).

In 2002, the State Planning Commission - predecessor to the National Development and Reform Commission (NDRC) and China's central planning body at the time - began to set targets for nuclear power development as part of overall energy infrastructure development. China plans to create 800 GW of new electricity generation capacity by 2020, 32 GW of which is to come from nuclear power (Xu, 2010). In subsequent years, the nuclear target was revised to 36 GW, 40 GW, and 70 GW. By 2011, the target had been lifted to 80 GW. As a consequence of delays in nuclear power expansion caused by safety investigations following Fukushima, the target was lowered again to 70 GW in 2011 (Hua and Stanway, 2012). In 2006, the NDRC presented a Medium- to Long Term Nuclear Energy Development Plan specifying details of the planned nuclear expansion. The "active development" of nuclear power was also highlighted in the 11th Five-Year-Plan (2006-2010) and in the 12th Five-Year-Plan 2011-2015. Since 2008, additional funds have been made available to companies in the nuclear industry through the Chinese economic stimulus plan (Interview 09202011). The State Council Research Office determined that by 2020, an additional CNY 1 trillion (~$151 billion) will be spent on nuclear power development, in addition to units already under construction (WNA China, 2012).

Today, three companies are allowed to hold majority ownership in nuclear reactors in China: CNNC, CGN and SNPTC. All three are SOEs and subordinate to the State-owned Assets Supervision & Administration Commission (SASAC). CGN is 45% owned by the Guangdong provincial government, 45% by CNNC and 10% by CPI. SNPTC is 60% owned by the State Council and 10% by each of the following entities: CNNC, CPI, CGN, and the China National Technical Import & Export Corporation (WNA China, 2012b).

CNNC has more than 100 subsidiaries and 100,000 staff members (NTI, 2012). According to the WNA, CNNC planned to "invest CNY 800 billion (~$120 billion) into nuclear energy projects by 2020," part of which may be financed through public offerings. An IPO is expected to raise funds for five nuclear power plants, amounting to CNY 173.5 billion, or roughly $27 billion (Shen and Takada, 2012).

CNNC is not the only state-owned nuclear company raising funds. According to press reports, in 2009, CGN set up a "fund-raising agreement with Bank of China, China Development and other institutions [...] to raise a total of 10 billion yuan" (Klamann, 2009). CGN has more than 30 subsidiaries and more than 20,000 staff members (Interview 09032011).

6.1.1 Summary

We have seen that there are a number of programs and policies in place indicating China's long-term commitment to nuclear power development and the state's willingness to provide large funds to fuel that development. Apart from the government-backed SOEs, private firms -- equipment suppliers for instance -- can apply for subsidies from national or local governments. The scale of available funds and the political determination behind China's nuclear power program as a national key project, distinguishes this from other nuclear industries.

6.2 Synergies across industries in the context of economic development

With its wide range of required components and skills, the nuclear industry overlaps with other industries in many areas. Many products and services used in the building of nuclear power plants are similar or virtually the same as those involved in projects in other industries. Thus, we can draw two linkages: the nuclear power industry can benefit from developments in related industries; and related industries can benefit from developments in the nuclear power industry. I provide examples for each in the following paragraphs.

In the domain of steel, for instance, only a small portion of the total amount of steel used in building a nuclear power plant needs to be certified as "nuclear-grade" steel (which requires extensive and expensive testing). The bulk of steel employed is common carbon steel, mostly used as rebar (Interview 09172011). Consequently, the nuclear industry can benefit directly from the development of even conventional local steel industries.

With regard to skills, the degree of overlap with other industries is reflected in a statement by Lewe and Couchman (1977) of NUS Corporation: "Besides key lead engineers, only a small fraction of the project team needs to have previous nuclear experience." The majority of the 3000+ workers that are usually deployed at the peak of a nuclear building project do not have nuclear-specific educational backgrounds and have often been recruited from related industries (Interviews 09182011). These include electricians, builders and welders, or university graduates majoring in mechanical, electrical, and chemical engineering.

Etel Solingen (1996) investigated the effects of spin-offs and linkages to and from the nuclear industry in Brazil and Argentina. She observed: "On the one hand, metallurgical skills have been critical to the establishment of a nuclear industry. On the other hand, development of new and superior metals can improve the performance of other important industrial sectors, including machine tools, electric power generation, jet engines, and railroads. Even critics of the nuclear program in Brazil acknowledged a few gains in this area, specifically in the production of high quality steel components."

Similarly, Clyde B. Tatum, a practitioner in the nuclear construction industry, has noted how "innovative approaches" in the nuclear construction industry can be transferred "to other segments of the construction industry [and] will improve overall performance [...]" (Tatum, 1983).

The benefits run both ways: conventional construction industries can also benefit the nuclear construction industry. In a report on "Advanced Construction Methods for New Nuclear Power Plants" by the IAEA (2009), the author states: "The construction methods available for new nuclear power plants are generally the same as those used for other large construction projects. There have been numerous improvements in construction methods in the past few years, and recent experience in nuclear power plant construction has shown that those advanced methods are fully applicable and can help shorten construction schedules."

In his book "Concrete Technology – Theory and Practice," M. L. Gambhir (2009) points out that "for nuclear concrete it's not so much the materials that are special or difficult but rather the way they are processed, mixed, dried, etc." Consequently, much of the materials for nuclear concrete can be sourced from the same pool that conventional construction industries source from.

These were examples from the literature that illustrate a potential for cross-fertilization between nuclear and related industries. The nuclear industry benefits from advances in the local production of raw materials such as steel and concrete, more advanced construction and project management techniques, improvements in metal work, as well as more and better human resources on the labor market and in other domains.

In summary, the Chinese nuclear industry can benefit from the technological progress in many other sectors of the economy due to cross-fertilization. In the course of its development since the 1970s, the Chinese economy has made progress in many related industries that the nuclear industry could benefit from. I develop this argument by presenting the case of the Chinese construction industry in more detail in the following section. Similar cases of cross-fertilization can be found in other domains, such as project management, procurement, quality assurance, metal handling, welding, instrumentation and control, etc.

6.2.1 Case study: the Chinese construction industry

The Chinese nuclear construction industry is dominated by the China Nuclear Engineering Construction Corporation (CNEC) who played a central role in constructing each of the 14 nuclear power plant projects in China, as well as in the units currently under construction. In addition to CNEC, other large Chinese construction companies have moved into the nuclear sector as contractors (Dynabond, 2010). Contractors in turn hire subcontractors out of an even larger pool of Chinese construction companies.

CNEC has five subsidiaries: CNI23, CNF, Huaxing, CNI22, and CNI24. Among them, CNI23 is most active, shouldering almost 80% of the contracts (Dynabond, 2010). In the past, different subsidiaries worked in relative isolation from each other, signing separate contracts with the general contractor. Recently, there has been a push towards more integration to improve cooperation and communication among the subsidiaries.

Before 1999, CNEC was a part of CNNC. After CNEC split off from CNNC, funding became a persistent problem. Despite revenue generated from CNEC's involvement in all Chinese nuclear power plant projects, it lacked a steady income stream. (Nuclear power plant orders are placed at intervals and payments are dispersed). By contrast, CNNC and CGN had constant revenue streams from operating existing plants. CNEC employs more than 20,000 people and has substantial machinery assets. In order to sustain its capacity, the company was forced to diversify into other industries, such as petrochemicals. Because of that, around 70% of CNEC's activity still lies in the non-nuclear domain (Dynabond, 2010). Thus, CNEC has had much exposure to other construction fields, their practices and actors.

CNEC and the Chinese nuclear construction industry at large have over time increased their competitiveness. This took place through (1) ongoing involvement in projects and learning-by-doing and (2) as part of an ongoing process of modernization and learning in the Chinese construction industry as a whole. I elaborate on both points as follows.

(1) CNEC describes itself as "the world's leading nuclear construction enterprise" (CNEC, 2012). Whether that is accurate may be open to debate, but CNEC is certainly the only construction

company globally that is simultaneously involved in more than two dozen nuclear power plant projects. There is little doubt that some forms of learning will take place as a result (Interview 10282011). In fact, CNEC's own slogan is "practice makes perfect."

The company has collected data from each project it was involved in, which it utilizes for future projects. CNEC's experience has cemented its position as a construction company of choice for nuclear power plant projects. CNEC has taken further steps towards modernization. It has founded a subsidiary called Huahui whose goal is the development of a computer-based nuclear construction management system for experience management. The system is currently used at construction sites for the new AP1000 reactors in Sanmen and Haiyang. CNEC has also mastered advanced construction technologies in the domains of lifting and erection, modular construction, advanced concrete pouring techniques, and automated welding techniques (CNEC, 2012).

This has gone hand in hand with an effort to standardize and optimize construction procedures. CNEC encountered foreign management philosophies and management systems through its involvement with American, French, Canadian and Russian companies. Nevertheless, as a state-owned company, CNEC is still known to be slow to adapt to new concepts and has been described as still culturally and structurally quite different from its foreign counterparts (Dynabond, 2010).

(2) Other construction companies such as thermal power plant construction companies and railway construction companies have been moving into the field of nuclear construction in recent years. For civil construction at the Taishan nuclear power plant for instance, the project owner CGN has signed a contract with China Railway No. 2 Engineering Group. The Chinese nuclear regulator NNSA has to date granted certifications for nuclear construction to 14 companies. Some of the most prominent cases involve the Shandong Electric Power Construction Company which built the conventional island of the Haiyang nuclear power plant and the Guangdong Thermal Power Construction Company (Dynabond, 2010).

With tenfold growth from the mid-1980s to the mid-1990s. the construction industry was one of the first in China to take off (Vickridge and Lu, 1999). In fact, one could even say that the construction industry was the very backbone of China's rapid economic development, which was heavily driven by infrastructure spending. In the late 1980s, a dedicated ministry, the Ministry of Construction, was established to boost the industry's development. Already in 1994, China had 460 international contracting companies and 50 Chinese-foreign JVs in the construction sector (Ahmad and Yan, 1996). There was a strong base to begin with: 10,250 design institutes, with 752,000 employees in 1994.

Since then, the Chinese construction sector matured through domestic projects and partnerships as well as overseas contracts. Chinese companies have built tens of thousands of kilometers of railway and highway and hundreds of power plants, dams, airports and bridges. (Vickridge and Lu, 1999) Over time, companies introduced competitive bidding, advanced technology, efficient management and quality control. Inspection companies also emerged. In 1996, there were already 1,383 supervision agencies employing more than 70,000 staff (Ahmad and Yan, 1996).

Capacity expansion and productivity growth continued into the 2000s (Xue et al. 2008). In 2011, 22 Chinese companies featured in the top 100 list of global construction contractors assembled by Engineering News-Record (ENR, 2011), more than any other country. According to this ranking, four of the five top global construction companies are Chinese.

Evaluating the strengths and weaknesses of the Chinese construction industry, several studies concluded that abundant manpower, low cost construction materials, close government relations and experience on large scale projects are key strengths. Weaknesses include a high level of separation between design and construction activities, weak financial capabilities of construction firms themselves, low levels of innovation and relatively slow adoption of state-of-the-art technologies (Lu et al., 2009; Zhao et al., 2009). Chinese construction companies continue to modernize and to learn from their foreign competitors. There has been increasing foreign investment in Chinese construction companies and reforms towards international practices. This cross-border cooperation may help advance the Chinese construction industry beyond its present weaknesses.

Given the experience and evolution of the Chinese construction industry, as well as the synergy between the construction sector at large and the nuclear construction industry, it is not surprising to hear from a French nuclear industry expert in China that Western construction companies "cannot live up to the level of construction companies in China." The industry expert praised their expertise in civil engineering and stated: "their processes are very good." As a consequence, "because of their efficiency," he predicted that Western nuclear reactor vendors will work with Chinese nuclear construction companies overseas (Interview 10182011).

6.2.2 Summary

The case of the nuclear construction industry illustrates how Chinese economic development and its manifestation in various sectors impact the nuclear power industry. In regard to construction, this process is driven by nuclear construction companies being widely involved in non-nuclear projects and by construction companies in other sectors being increasingly involved in nuclear construction projects. Skills, materials and processes in nuclear and non-nuclear construction sectors are similar, and to a large extent nuclear and non-nuclear construction firms can draw on the same pool of human resources.

I argue that similar cases can be made for other industries and that the Chinese nuclear industry as a whole benefits from such synergies between the developing nuclear industry and the developing economy as a whole.

6.3 Labor in all variations: vast and diverse labor market

Synergies between different manufacturing sectors described above create a large mobile pool of human resources. This has already been discussed in the previous section but deserves more elaboration due to its importance for the competitiveness of many Chinese firms.

In my interviews, interviewees repeatedly praised Chinese labor for its distinct qualities (Interview 09072011; Interview 09052011; Interview 10282011). Chinese employees are generally described as "hard-working" and "eager to learn" (Interview 09052011). Both workers and engineers are described as having "a different type of drive" compared to other parts of the world. Another important factor is the fact that the Chinese ecosystem provides a wide spectrum of skills and labor costs. The president of a European equipment manufacturer said, "There is every level from very good to very bad" in China (Interview 09052011). The levels of qualification tend to correlate to the cost of labor, with graduates from Chinese top universities demanding salaries as high as in many Western countries and graduates from other universities and common workers demanding less.

For an American supplier of power plant equipment and EPC services this was a decisive factor in choosing China as a location for detailed engineering. Although headquartered in the US, the China president of the enterprise described his enterprise as a "truly global company" with "a global division of labor" (Interview 09072011). The company has an "innovation center" in Europe staffed with the "lead technical guys, the grey-haired staff," detailed engineering and design teams in Shanghai and manufacturing in Guangdong. The detailed engineering and design facility in Shanghai employs 200 Chinese staff, of whom 100 are engineers. Today, even for projects in the US, conceptual engineering takes place in Europe, detailed engineering in Shanghai and equipment manufacturing in Guangdong. The former US location for detailed engineering and design is "no longer needed."

The company's location decisions were not informed merely by low-cost labor available in China; rather, by the fact that they could find low-cost low-skill labor as well as high-cost high-skill labor in the same region. While there are big differences in labor skills and costs across different universities, everyone in the company's Shanghai office has a university degree and most have Master's degrees. The interviewee praised Chinese engineers for their high efficiency and young age. In addition, Chinese engineers "have a very strong technology background, great design abilities." The interviewee considered graduates from good Chinese universities such as Fudan and Tsinghua better trained than many graduates from Western universities.

A foreign nuclear reactor vendor presented a similar example. This company had outsourced some of its detailed design operations to a partner in China. In addition to their strong motivation, representatives of this company also praised Chinese engineers for their knowledge of the local ecosystem (Interview 10142011). Many of them had previously worked for local suppliers and are familiar with equipment, local materials and regulations. "China is where all the suppliers are." Moreover, the proximity to manufacturing and construction sites is helpful for resolving problems and misunderstandings promptly. Most engineers spend a considerable amount of time on building sites or in manufacturing plants, getting exposure to real problems as they occur. This then informs their work in engineering and design (Interview 09072011).

The last example is of a European manufacturer of cable trays. The company began to set up manufacturing operations in China last year. Although their products require rather sophisticated manufacturing processes (due to quality requirements and long product lifetimes), company management considered the move to China inevitable: "If we don't localize, then the Chinese power plants will at some point use Chinese suppliers" (Interview 09202011). The move to China was facilitated by the availability of a large pool of human resources. The company chose a location in China that has a large steel mill and "a lot of local factories that produce similar products." This way, the company found it "easy to recruit talent [away] from other companies."

6.3.1 Summary

For many companies, Chinese labor means more than merely cheap labor. Companies value large and diverse pools of low-skill low-cost and high-skill high-cost labor, benefitting from synergies across sectors, educational policies, and certain Chinese cultural values. The broad spectrum of different qualifications and costs, hands-on experience, and knowledge of local ecosystems makes Chinese labor increasingly attractive for a variety of activities undertaken by global companies. Like other industries, the nuclear industry has capitalized on these ripe conditions.

6.4 Scale-up nation and innovative manufacturing

Related to government support and funding, but with its distinct features, is the Chinese ability for rapid scale-up. In recent decades, China has become a global manufacturing center. Nahm and Steinfeld (2011) called China a national system "specialized in rapid scale-up and cost reduction." The Chinese abilities for scale-up and cost reduction manifest themselves across diverse industrial sectors. Nahm and Steinfeld cite examples from wind turbine, solar photovoltaics, and consumer electronics sectors.

In my research, I came across strong parallels to Nahm's and Steinfeld's observations, particularly as observed in the wind turbine sector. Similar to the nuclear industry, wind turbine manufacturing received extensive government support. The industry is supported by strong domestic and international demand. Localization requirements and bulky products, expensive to ship, further benefit local actors. Both the Chinese wind and nuclear power industries consist of SOEs, private firms, foreign companies and partnerships as in joint ventures.

In the following section, I present cases that show how rapid scale-up and cost reduction are important characteristics of companies in the nuclear power industry in China. For that purpose, I distinguish between companies with low supply chain complexity and those with high supply chain complexity.

6.4.1 Low supply chain complexity

Among non-key equipment, many inputs to nuclear power plants have relatively simple and short supply chains, sometimes only requiring raw materials such as steel, plastics or graphite. Companies in this category produce components like pipes, cables, seals, cable trays, etc. For these types of goods, competitiveness is largely determined by product quality, cost, delivery time and attached services. These factors are influenced by the choice of raw material suppliers, the origin and quality of manufacturing equipment, the management systems in place, and workforce skills level.

Chinese companies have benefited from improvements in the quality of Chinese-made raw materials (Interview 09052011). Often, such raw materials are priced significantly lower than those of international counterparts, an advantage that carries over to companies further downstream. Additionally, many Chinese companies have invested in state-of-the-art manufacturing equipment from foreign companies, as well as in training on that equipment (Interview 09202011; Interview 09202011). Enabling factors for these types of investments are the high demand created through government policy as well as subsidies, for instance, from the 2008 stimulus plan. Chinese companies bought manufacturing equipment from foreign suppliers, entered joint venture partnerships or, in some cases, wholly acquired foreign companies in an attempt to not only obtain their machinery but also to absorb their process knowhow. This is often accompanied by extensive testing and trial-and-error to gain manufacturing experience. Sometimes local design institutes become involved and provide more systematic and academic knowhow.

6.4.1.1 A Chinese stainless steel pipe company

An example is a Chinese pipe company from Jiangsu province (Interview 09202011). The company is privately owned and has become a national leader in the production of stainless steel pipes. It is the first Chinese private-owned enterprise that was able to produce pipes for nuclear power plants that comply with European and American standards. In 2011, it entered European and US markets. Its products are used in nuclear, chemical, oil and gas, shipbuilding, papermaking, medical, food processing, aerospace, military and sea water desalination industries.

About four years ago, the quality of domestic stainless steel pipes was still poor anywhere in China. Since then, the company has been able to produce pipes at quality levels that comply with required standards. The company saw especially rapid development after purchasing an Italian machinery company and production lines from German machine tool companies. The pipe company had originally focused on other process industries but in its recent development made a push into the nuclear industry. For that purpose, it obtained government support representing a Key Industry Project of the 2011 Central Budget Investment Plan. In 2010, the company invested CNY 1 billion to expand its factory floor threefold, by 200,000 square meters, introducing 20 new production lines from abroad.

The Chinese pipe company has a supply contract for high-grade nuclear pipe steel with one of three Japanese steel companies that can supply the type of raw material required. In addition, the Chinese company has nuclear-grade pipe steel inventory that amounts to a few months of production. Having secured reliable access to this raw material, whose global demand currently exceeds supplies, the Chinese company now has a competitive advantage. As expected, the company is doing well and receiving more international orders.

The company recently recruited a renowned former professor of metallurgy to head its R&D department of 20 staff. The professor previously led a lab at a local design institute. The company has also purchased testing equipment from the design institute. The R&D department is now responsible for developing new production and quality control techniques.

Important factors in the pipe company's success were a long-term outlook with the promise of sustained high demand in China, as well as government funding through the stimulus program. Given these circumstances, the company was able to invest in state-of-the-art manufacturing equipment and training. Other important factors include strategic raw materials sourcing and involvement of local talent through recruitment from the design institute. Lastly, the company could capitalize on previous experience it had gained in related sectors, such as the petrochemical and oil and gas industries.

6.4.1.2 A Chinese graphite seal company

Graphite seals are used in many areas of power plants, usually to prevent leakage in pumps, valves, pressure vessels, and between pipes. Originally, the market for nuclear power plant seals in China was dominated by American and French firms. Chinese companies produced seals for conventional industries only, as those seals had looser quality requirements. However, "since

2008, Chinese companies have won every tender for these [nuclear] seals. We [Chinese seal companies] have matured now." (Interview 09202011). A Chinese valve company I interviewed offers large seals for nuclear power plants for one-third of the price of Western competitors. A large portion of the company's cost savings comes from sourcing the graphite raw material from a local Chinese supplier instead of a foreign supplier. The rings are then manufactured using new imported presses and other imported equipment, a process that is well-established and does not involve much tacit knowledge according to one of the company's engineers. Testing is done using advanced equipment bought from a German company. According to the company's CEO, companies like this one have expanded rapidly in recent years and largely taken over the Chinese nuclear seal market.

The Chinese graphite seal company successfully entered a mature consolidated market. It managed to do so by adopting established modes of manufacturing while substantially lowering cost, mainly through local procurement of raw materials. The big price differential helped the company to expand rapidly in the Chinese market. This company too benefited from previous experience in a related sector, namely the chemical industry.

6.4.1.3 Summary

We have seen two examples of successful Chinese companies in the low supply chain complexity end of the nuclear industry. The two companies developed and expanded rapidly in recent years due to circumstances peculiar to the Chinese ecosystem. They married the adoption of modern manufacturing processes and corresponding management systems with the ability to lower costs in procurement, labor cost, and process optimization. These firms were able to draw on experiences gained in related sectors before entering the nuclear industry. Other enabling factors were a stable long-term outlook that created an environment conducive to large investments, as well as government funding and support.

6.4.2 High supply chain complexity

Another group of companies are characterized by high complexity in their supply chains. This includes companies that produce products with many different components - such as pumps, turbines, motors and generators, valves, etc. - requiring assembly. Different principles apply to such companies, which I point out as follows.

Designs usually play a more important role in nuclear industry companies of high supply chain complexity. Often, such companies obtained their initial designs through cooperation with foreign partners, through reverse engineering, or through internal technology transfer (in the case of foreign-owned enterprises in China) (Interview 09052011; Interview 10312011). Similar to the case of the wind turbine industry presented by Nahm and Steinfeld, oftentimes these companies' products are adapted to the Chinese manufacturing environment. The China president of a European pump company that I interviewed called this process "chinesefication of a product" (Interview 09052011). "Chinesefication" by that definition includes substituting materials for cheaper or more accessible alternatives; adapting the manufacturing process to local parameters, for instance the availability of low-cost labor; and organizing the supply chain according to strengths and weaknesses of the surrounding ecosystem. The latter may involve integrating parts with high margins, crucial intellectual property components and high demands to quality and time-critical delivery, while sourcing others at low cost.

This group of companies benefits greatly from the variety of products and skills concentrated in regions like the Pearl River Delta. Here, companies can acquire manpower and skills for setting up in-house operations and for sourcing. Firms benefit from high industry density and advanced transportation infrastructure, making it easier to visit partners and suppliers, for example.

In sum, these factors contribute to products achieving high quality standards at low cost. Capitalizing on the unique characteristics of Chinese ecosystems such as around the Pearl River Delta endows companies with a competitive edge to compete in markets domestic and global. Companies in nuclear supply chains can equally benefit from these factors. Many companies in the nuclear industry have attempted to exploit advantages described in this chapter to their maximum extent. Companies that have not done so face increasing pressure to follow (Interview 10222011).

6.4.2.1 A European pump company

The points outlined above are well illustrated by a European company that produces pumps and other types of metal machinery in Guangdong province. The company is a wholly foreign-owned enterprise. Its workforce in China numbered around 1300 staff in 2011, with 200 new employees being added every year (Interview 09052011).

The company produces designs in China that originate from different "product homes" around the world, mostly from Europe. Designs are transferred from their respective product homes to the China location through internal technology transfer. In China, the company has engineering teams that adapt production processes and sometimes the designs themselves to the local environment. This usually leads to different bills of materials with substitutions of original materials to comparable materials easily accessible (and cheaper) on the Chinese market. The designs need to be divided into components that are to be produced in-house or sourced externally.

According to the China president of the company, designing and monitoring supply chains is a core capability of the company. About 70% of all parts of a typical product are sourced externally. The interviewee referred to Guangdong as a unique region where virtually every component the company needs is manufactured locally, usually by a number of companies at different quality levels and price levels. In this environment, the pump company's management aims to optimize make-buy decisions and organize supply chains in a way that achieves large cost savings for some parts while guaranteeing quality and reliability for other parts.

For cases where quality and timely delivery are crucial, the European company investigates ways to integrate these activities. Since the company repeatedly encountered problems with externally sourced steel castings for pumps, it eventually decided to build its own foundry to forge casings in-house, which it did in cooperation with another European company. The in-house casings foundry is now located next to its Guangdong manufacturing facility.

For sourced components, quality and delivery issues have been virtually eliminated over recent years. This was accomplished through the use of a Supplier Relationship Management System that allows for tracking of supplier-side progress at close intervals. About 40 employees track progress in the factories of a few hundred suppliers daily. Each supplier is required to upload predefined test results, photographs and manufacturing reports to an online system at regular intervals. If a supplier fails to deliver updates, the European company's quality department follows up quickly. In special cases, a quality department representative is dispatched to the supplier's base within one day. The European company's China president stressed how transportation and IT infrastructure in the Pearl River Delta has made a big difference for his company, particularly in regard to its sourcing strategy. The local train and highway systems allow his employees to arrive at supplier sites within a few hours and within a radius of a few hundred kilometers. The interviewee summarized this by saying: "Everything grows together so quickly here."

The company now claims to be able to produce pumps and other equipment at European quality levels but significantly cheaper than European based competitors. At this point, about 10% of the production in China is sold back to Europe, the remaining portion is sold within China, Stan countries, South Korea and Australia. In Europe, the company still deals with a problem of product and quality perception and with prejudices. Although Chinese quality may match European quality in this case, many European customers still prefer European-made products.

6.4.2.2 A Chinese and a European turbine-generator company

As another case, I present differences between a Chinese and a European turbine-generator company (Interview 10312011). The Chinese company has its headquarters, engineering and manufacturing departments in the same location in Northern China. The European company has its headquarters and engineering departments in Europe and a joint manufacturing location with its Chinese partner in Northern China as well as in other locations globally. The joint venture buys forgings, steel plates, cables, seals, plastics, consumables and other components from suppliers. It then machines and assembles turbines and generators. Low labor costs are less important to these capital-intensive companies. Most of their processes are automated by heavy manufacturing equipment from Germany and Italy. Long production lines are programmed and operated by only a few staff.

Both companies use detailed production documents for each product, specifying production inputs and processes. The European company offers full customization of its products and creates a completely new set of production documents for each order. This means each order has to be processed by the engineering department in Europe, which costs more time and resources, and can lead to miscommunication. The interviewee who had worked for both European and Chinese companies in this field stated, "In the European case, all changes have to go back to R&D to be recalculated."

The Chinese company, however, works toward standardization of its designs. For each order only small changes are made and they are made incrementally on top of a generic basic design.

The basic design was transferred from a foreign company through an earlier partnership. Due to the incremental changes, less engineering services are needed overall and management and communication are simplified. Production documents can be modified rather than completely remade. The interviewee said, "There are only a few changes, the rest is the same [in the Chinese company's designs]. But then, China needs to produce lots of the same things. So that may increase the speed and lower the cost." The Chinese company has been able to sell its turbines and generators at lower prices this way. The turbines and generators of the European company tend to be more efficient in turn. The European company is now trying to decrease its prices while the Chinese company is working to improve efficiency and quality.

Management of the European company has aimed for cutting costs at its China location by 30% each year. In 2010, cost cuts of 22% were achieved. Most cost cuts stemmed from the substitution of materials and the localization of the supply chain. For instance, a special type of fiber tape used for insulation originally sourced from an American company is now sourced from a Chinese company at lower cost. Heavy forgings and steel plates, formerly imported from Japan other foreign competitors now come from China. The representative of the European company said, "We want to achieve 100% localization."

The two companies are converging. The European company tries to learn what the Chinese company has done well: producing at low costs by adapting to the unique conditions of the Chinese ecosystem. The Chinese company tries to learn what the European company has done well: employing state-of-the-art machinery, processes and management systems.

The diversity of actors forces efficient and high quality companies to become more cost-effective and low-cost companies to become more efficient and of higher quality. In this case too, substituting materials as well as standardizing and simplifying designs play important roles, leading to products of increasingly better quality and cost. Organizing and managing supply chains in the unique Chinese manufacturing environment became a core capability for these companies.

6.4.3 Summary

In this section I introduced cases that illustrate characteristics of Chinese manufacturing ecosystems that led to companies adapting modern manufacturing techniques, scaling-up and expanding their operations quickly and balancing between quality and cost. The principles behind these cases can apply to many branches of manufacturing industries. They certainly apply to parts of nuclear supply chains, as illustrated in this section.

6.5 Summary

In this chapter I highlighted distinct characteristics of the Chinese manufacturing ecosystem that affect its nuclear power industry. These characteristics include synergies across different industry sectors, a credible long-term demand outlook in the nuclear power industry, a broad and diverse pool of human resources and an ecosystem conducive to rapid adoption and scale-up of manufacturing at low cost and at reasonable quality. These factors distinguish the nuclear power industry in China from nuclear power industries in other parts of the world. Although other nuclear power industries may share individual characteristics aspects, the combination of all is unique to China.

In this thesis, I discussed characteristics of the global nuclear power industry with a special focus on the Chinese nuclear power industry. To assess and fully appreciate characteristics of the Chinese nuclear industry development, one has to take into account three major perspectives:

7 Conclusions

In this thesis, I discussed characteristics of the global nuclear power industry with a special focus on the Chinese nuclear power industry. I addressed three specific perspectives in detail: technology transfer and localization, global deverticalization and integration trends, and idiosyncrasies of the Chinese manufacturing ecosystem as much they affect its nuclear power industry.

I started out by investigating a prominent claim that surfaced in many debates on China's nuclear expansion: Does the transfer of technology to the Chinese nuclear industry represent an unprecedented case of naïveté that jeopardizes the future competitiveness of foreign nuclear power companies? My research showed that technology transfer to the Chinese nuclear industry far from represents an extraordinary case but rather follows common industry practice. The nuclear power industry has been, from its inception, characterized by extensive cross-border collaboration and transfer of equipment and knowledge. Furthermore, nuclear reactor vendors have come to benefit from these relationships by developing and deploying new products, expanding their supplier pools and growing future partners.

To understand the Chinese nuclear power industry going forward I proposed examining two aspects. First, the status quo of the global nuclear industry into which the Chinese nuclear industry is growing. Second, unique features of the Chinese manufacturing and construction ecosystem that affect the nuclear power industry in China.

On the first point, I identified two trends in the global nuclear power industry. The differences in these trends are somewhat related to locations, government policies and corporate cultures; they form two extremes of a spectrum. At one end of the spectrum are deverticalized, private companies like Westinghouse while at the other are highly integrated, SOEs like KEPCO. The two types of companies each have their strengths and weaknesses across the innovation and product cycle. One way for organizations to capitalize on their strengths and to mitigate their weaknesses is to enter into cooperation with complementary organizations. For that reason, partnerships between different nuclear power industry actors across the globe are becoming ever more important. This also sheds new light on technology transfer and its implications. The knowledge about other organizations, combined with trust and technological overlap that come with technology transfer and localization, can be enabling factors for long-term partnerships crucial in a dyadic world that demands co-development, bringing in new supply chains, sharing financial burdens, capitalizing on brand names, and taking advantage of state support.

Idiosyncrasies of the Chinese manufacturing and construction ecosystem – indeed of the country's economic development – affect the nuclear industry. I identified strong state support and a reliable long-term demand outlook, synergies across developing industrial sectors, a large and diverse pool of human resources, the ability to scale up and expand rapidly, and the marriage of reasonable quality at low cost as important factors that helped nuclear power industry firms mature in China.

I suggest these three major topic areas and their subtopics as crucial pillars upon which a thorough understanding of the development of the Chinese nuclear power industry can rest.

Chinese and foreign companies both need to understand the dynamics of global nuclear supply chains and the Chinese nuclear industry in order to best position themselves to exploit opportunities and avoid pitfalls in a global nuclear power industry with China as a major actor.

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