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Nuclear Power Technology in Post-Industrial Civilization

A Comparative Study of France and Japan

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July 2022

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Kazunobu Oyama

Abstract

This article presents both descriptive and normative analyses of the nuclear power industry based on civilization theory, which hypothesizes that civilization is created by human ignorance. Our limited rationality created various civilizations, resulting from our random trial-and-error solutions and thoughtless imitation of ad hoc acceptable solutions. Technological innovation can be considered an endless trial-and-error process to overcome risks that inevitably follow new technological solutions. Several economic and civilizational theories, such as A. Toffler's Third Wave, J. Rifkin's Entropy, A. Gerschenkron's theory about economic development history, W. Abernathy's Productivity Dilemma, and F. Hayek's liberalism sociology, are applied to analyze technological innovation. We hypothesize that radical civilizational changes are triggered by serious social risks. For example, hunter-gatherers' civilization dramatically changed to an agriculture-cattle society because of animal and fruit shortages. Humans invented hunting tools with limited rationality to overcome the shortage, which accelerated the shortage and caused drastic changes to agriculture-cattle civilization. The Industrial Revolution was caused by mass starvation in the agricultural society, and the high-tech information society was caused by pollution and work-alienation problems in the industrial society. Technological innovations are triggered by the technological risks caused by limited rationality. The "technological hierarchy" concept, which illustrates the technological innovation process as a trial-and-error decision tree leading to a final practical product, is useful for understanding various industrial developments, such as the automobile, aircraft, and nuclear power generation industries. Humans cannot simply abandon technology that entails risks because of the benefits enjoyed but try to overcome the technological risks using new technology, which inevitably raises new risks. Humans continue technological innovation like continuing to eat the "forbidden fruit". Based on the "technological hierarchy" concept, after a standard model is established in any industry, technological safety, efficiency, and cost reduction rapidly improve. Otherwise, we cannot find a useful solution for technological problems, and the technology will dead-end. Is nuclear power technology a dead-end because of unsolvable radioactive problems? Alternatively, can we regard standard reactor models, such as the light water reactor (LWR), the European pressurized reactor (EPR), and the small modular reactor (SMR) as dominant stable models, which will lead the nuclear industry to the growth stage? We investigated the related political leadership and the national consensus construction process by comparing France and Japan. In France, the authoritative liberal approach, which makes a democratic means compatible with authoritative decision-making, realizes social consensus to maintain over 70% of nuclear power generation.

After the Fukushima accident, the Japanese government failed to propose a concrete road map to recover nuclear power generation. A precise understanding of nuclear technological risks based on an investigation of nuclear accidents such as Chernobyl and Fukushima reveals what a nuclear power technological policy should be in the future.

Keywords

Civilization, bounded rationality, law of entropy, Industrial Revolution, technological innovation, technological hierarchy, power generation, nuclear power technology, dominant design, product lifecycle, mass production process, Products Portfolio Management

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I stayed at FFJ-EHESS in Paris as a visiting researcher from April 2021 to March 2022 to research the case of nuclear generation in France. My stay at FFJ-EHESS was realized through the significant support of Professor Sébastien Lechevalier, President of the Fondation France-Japon de l'EHESS. We have mutually visited our university in Paris and Yokohama several times. Since 2013, we have cooperated to survey technological innovation history from economic and managerial perspectives.

I wanted to study French nuclear power policy, especially decision-making and the national consensus constructing process to maintain the high percentage of nuclear energy in France. Not with standing a progress possibility, after the Fukushima accident, critical scientific and economical discussions concerned with nuclear technology have been avoided in Japan.

During my stay in France, I could fruitfully search through many books, journals and interviewed some EDF members, the Areva company, and anti-nuclear persons. I want to express my sincere thanks to Professor Sébastien Lechevalier, President of the Fondation France-Japon de l'EHESS.

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Nuclear Power Technology in Post-Industrial Civilization

– A Comparative Study of France and Japan –

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Preface - Paradox between Ignorance and Civilization

In this article, nuclear technology in post-industrial civilization will be investigated by comparing Japan and France. Nuclear technology certainly has some risks, similar to any other technology. How can the risk associated with the technology be overcome? Is nuclear technology a dead-end without an effective pathway to amelioration?

Even if it seems pedantic, the process of civilization and humans' limited rationality have to be investigated as the first step. Future nuclear technology can be predicted through the analogies of several existing technological development processes. Given humans' limited rationality, they have a long history of using trial-and-error to improve technologies. This history implicitly exposes the future technological states.

First, I would like to propose the hypothesis that civilization developed only because of human ignorance or limited rationality. This hypothesis is contrary to the general belief that the development of our civilization is due to humans' intelligence. However, our history clearly proves otherwise.¹

The concept of limited or bounded rationality is important and has attracted the attention of the Austrian School. Scholars such as F. Hayek discussed this concept in the context of economic activities and human civilization,² while H. Simon discussed this concept in the context of actual decision making.³

If a human possesses unmatched intelligence or unlimited rationality, similar to that of God, humans would always be able to find the best and most immediate solutions to their problems. If that were the case, most of our problems would be solved by a relatively small number of solutions. Thus, the variance in our civilization's solutions would depend only on the world's different climates.⁴

However, there is extensive variety across the world's civilizations. For instance, there are various methods for solving problems such as lighting a fire, cooking fish or meat, and staving off cold or heat; the existence of these different solutions is not only attributable to differences in climate, but also to differences in the sequence of experimental trials.

Due to our limited rationality, human beings cannot accurately predict any result without conducting trials. Therefore, we must undergo a very long process of trial and error. Moreover, human beings never have an unlimited supply of time, energy, or resources. Accordingly, we are inclined to adopt the first solution that adequately meets our criteria. Of course, there is no guarantee that the first adequate solution will be the best. However, because of our limited rationality, we usually stop engaging in our examinations or trials when we arrive at such a solution. Only perpetual research can identify the best solution. The first adequate solution, however, is identified according to the order in which experimental trials are performed. Differences in adopted solutions across civilizations are a result of differences in the order in which they appeared during the trial phase.

Furthermore, human beings have a habit of indiscriminately replicating an adequate solution to economize their limited rationality. Thus, once an adequate solution is found, it rapidly diffuses to the surrounding area, which is limited by geographical barriers (e.g., seas, lakes, mountains, rivers, or deserts) or climatic differences. These limitations determine the region of civilization. People living in other areas must create or find their own adequate solutions for the same problem through a different sequence trial and error, without the benefit of replication. Thus, different solutions form the basis for different civilizations.

This is why a large number and variety of civilizations have emerged. Therefore, we can conclude that our civilization was created through ignorance. However, no solution is perfect. Every solution carries its own set of problems or has weak points that must be improved step-by-step. Owing to our limited rationality, we cannot fully anticipate any solution's problems or weak points *a priori*.

Given that any improvement method also has its own drawbacks, we must continue our efforts toward improvement until the drawbacks become negligible or have been minimized. This continuous process is the history of technological innovation. Once we begin inventing technologies, we must keep improving them or invent newer ones to solve the inherent problems of older technologies.

Just like "forbidden fruit," which cannot be relinquished once tasted, technology too, once invented, must be continuously improved or innovated upon.

We can overcome the risks associated with technology with the understanding that our civilization is the fruit of our ignorance and of innumerable trial-and-error efforts, given our extremely limited rationality. Without this mindset, humans will encounter catastrophe through our own fault, brought on by excessive arrogance.

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1. Technology and Risk

In this chapter, we investigate how technological risks have been overcome. To investigate this problem, we must understand the process of technological development and the characteristics of technological progress.

Technological progress is a gradual process that involves limited rationality. From a broader perspective, modern industrial society seems to have made rapid technological progress. However, from a more detailed perspective, the actual development of technology occurs gradually.

Nuclear industrial development is also understood as a gradual trial-and-error process in industrial civilization. Improvement involves risks and solutions as we move toward post-industrial civilization in the future. Nuclear energy politics can be analyzed by investigating existing cases of other technological development processes.

1.1. Technology as forbidden fruit for humans

Technological risks go hand-in-hand with technological performance. For example, although automobiles are more convenient than bicycles, automobile accidents are more serious than bicycle accidents. Similarly, although airplanes are more convenient than automobiles, airplane accidents are far more serious than automobile accidents.

The risks associated with technology are calculated as the product of the damage caused by an accident and the possibility of such an accident occurring. The amount of damage caused by an accident inevitably increases with technological progress. For example, the amount of damage caused by an accident is inevitably proportional to any augmentation of the transport technology's speed or size.

Therefore, to constrain the risk associated with a technology, the possibility of an accident must be reduced. Of course, the amount of damage from an accident can be partially controlled using a new technology. For example, seatbelts and airbags can control the amount of damage caused by automobile accidents to some extent. However, the damage that arises from accidents involving large high-speed transportation technologies is always very serious. Therefore, the main means of reducing technological risk is to reduce the possibility of an accident.

We can reduce the damage from and the possibility of accidents by developing new technologies. However, because of our limited rationality, any new technology, far from being perfect, will inherently present more problems than its predecessors. Newer technologies must resolve these problems. Consequently, we cannot stop developing these technologies. In this sense, we can compare technology to a kind of “forbidden fruit” for humans.

When we invent new technologies, we must also invent several new devices or methods to overcome the various problems associated with the new technology. Moreover, the new devices or methods pose additional problems in turn. Therefore, we end up creating more new devices or devising novel methods to solve these problems.

This process gradually resolves problems associated with new technologies. A solution often means that the original problem posed by the new technology has been broken down into smaller problems by newer technologies or devices. If the problem of the new device is more serious than the original problem, the new device does not gain currency as the solution.

A device or method that causes a more serious problem than the original one, I call “devil’s solution” or “dead-end technology,” which can actually be selected for use in urgent cases, given human’s limited rationality.

Thus, the solution identification process can be constructed as a hierarchical structure called means-ends analysis. I have termed this structure the “technological hierarchy”.¹ This concept is useful for gaining an understanding not only of the development process that produces any particular technology, but also of the entire history of the development of technology.

The concept of the “technological hierarchy” was developed based on W. Abernathy’s “design hierarchy”. Abernathy analyzed the history of automobile development in the United States.² He expressed the historical process of automobile development as the design hierarchy. I developed the concept of a hierarchy of problems and solutions within a technological innovation process for the benefit of future research and development (R&D) activities.

Human beings have created new technologies and improved existing technologies to enhance technological performance. Technological progress is certainly accompanied by progress in terms of the technology’s scale and complexity. An increase in scale and complexity also increases the risk associated with the technology, which consists of the amount of damage an accident would cause and the possibility of the incidence of the accident itself.

Advanced technology is often protected by sophisticated hierarchical problem-solving structures. An accident occurs when the impact of a severe condition or a mistake destroys the hierarchical structure’s order. Therefore, by investigating the accident process, we can understand how to overcome the drawbacks of these technologies in the future.

Thus, the history of technology is the history of human trial and error, given our limited rationality. Owing to our limited rationality, we cannot anticipate all possible accidents. Hence, it

is almost impossible to make predictions *a priori*. New products are created through trial and error. Moreover, most trials are triggered by actual accidents.

1.2. Endless technological innovation

The technological development process entails trials and errors to identify weak points in new technologies and methods to resolve them. When a new technology's many problems can be distilled into smaller problems through a step-by-step trial-and-error process, the final practical products or processes are achieved.³

However, the resultant new technology is never perfect because of our limited rationality. It will still have various flaws. We can enjoy using the new technology until an accident or problem occurs.

For example, we enjoyed automobiles' technological performance for over 50 years without anxiety about air pollution. It was not until the next 50 years that we took note of the climate change problem due to global warming caused by increasing carbon dioxide (CO₂) emissions from automobiles.

After accidents occur or problems arise, we have two options to maintain our prosperity and preserve our existing lifestyle. The first option is to abandon the new technology because it caused a serious accident. To exercise this option, we must replace the new technology with another, which may include other new technologies or older ones.

Currently, the nuclear power industry is at a crossroads between improvement or abandonment, that is, whether to replace nuclear power with renewable energy. While France has continued to operate nuclear power plants in the wake of the Fukushima nuclear accident, Germany decided to stop running its nuclear reactors. These decisions may be judged by investigating the characteristics of technological development and nuclear accident cases. In Chapter 4, the case of the Fukushima nuclear accident is analyzed through a comparison with the Chernobyl case.

The innovation of a new technology usually involves a long period of R&D. Therefore, we must use existing technologies until a new one is invented. However, we must not forget that the older technologies have been replaced with new ones because of some serious defects. For this reason, the temporary use of older technologies instead of a problematic new one is also problematic. Of course, we can try to improve the existing technology. This choice is included in the first option.

The second option is to improve the new technology by working on the flaw that caused the accident according to the technological hierarchy, which is the hierarchy of problems and solutions, mentioned above.

To exercise either option, we must continue to attempt, through trial and error, to invent better

technologies, according to the technological hierarchy. Our continuous efforts have led to endless technological innovation.

The motivations or stimuli for endless technological innovation are roughly categorized into two types. The first type of motivation is the user's need for technology or products. The second type of motivation results from R&D.

In the first category, user's needs create a demand for innovation or improvement in terms of better quality or lower cost. Of course, the demand for overcoming serious defects in a technology is an important motivation for technological innovation. Private enterprises that engage in technological innovation are especially sensitive to market demand.

In the second category, R&D advances motivate scientists and engineers, spurring them to propose new scientific theories or invent new technologies through the discovery of novel phenomena.

This self-motivated type of R&D is a fundamental driving force behind technological innovation, which is independent of user demand. This type of R&D is concerned with achieving breakthroughs. We must investigate technological innovation with a clear understanding of the fundamental differences between breakthroughs and improvements.

1.3. The law of entropy in technology

The law of entropy is the original law governing heat dynamics, and its core concept refers to irreversibility. For example, in the first situation, there are two water tanks divided by a partition; the tanks contain hot water at 95°C and cold water at 5°C. After the partition is removed, the hot and cold water mix gradually. This mixing process results in increasing entropy. Finally, the temperature of the water in both tanks become equal at approximately 40°C. At this stage, entropy is maximum.

The temperature of the water never reverts to the first condition until it is partitioned again, so that one side is hot, and the other side is cool. This phenomenon is called entropy. J. Rifkin applied this concept to explain human civilization's progress as an irreversible change.⁴ He tried to explain the change from a hunter-gatherer civilization to one based on agriculture and stock raising, followed by an industrial and then a post-industrial civilization.

This entropy concept is useful for understanding technological innovation as both endless and irreversible. Once we have experienced a technology's utility, we cannot return to life without the convenience of that technology. Therefore, even if the technology poses some risks, instead of abandoning it, we are inclined to make efforts to overcome the risks through newer technological innovation.

When we realize the inherent risks of a technology, we hesitate to use it for a while. However, this technology cannot be abandoned altogether. For example, people who lost loved ones in

automobile and airplane accidents may dislike using automobiles or airplanes for a while. However, they cannot completely abandon their use.

In Japan, traffic accident mortality peaked in 1970, when 16,765 people were killed.⁵ However, as people cannot abandon automobile use, instead, we made efforts to improve security using new technological devices such as seatbelts and airbags. Moreover, we educate people and create safe driving campaigns, instead of abandoning the technology.

These technological and social devices are obviously effective in increasing automobile security. In Japan in 2017, 3,694 people lost their lives in traffic accidents.⁶ Although more than 3,000 people are still killed by automobile accidents annually, we cannot revert to a pastoral epoch when there are no automobiles.

Furthermore, after a technology's diffusion, our social life is designed based on the assumption that the technology will continue to exist. For example, high-rise buildings are constructed on the assumption that electrical devices such as air-conditioners, elevators, and water distribution systems will continue to exist.

Although we can economize electric energy by restricting the use of electronic devices, we cannot live without electricity. We will never be able to return to the epoch without electricity. We can similarly recount infinite examples of products that are produced based on the assumption of a continued electricity supply. For example, several kinds of ready-to-eat food items are sold widely on the assumption that electric refrigerators and ovens will continue to exist.

The law of entropy in technology indicates the irreversibility of the technology. This law is another driving force behind endless technological innovation.

1.4. Social factors associated with technological risk

Technological risk arises not only from technological causes, but also from social causes, such as human error. Human errors are sometimes brought about by problematic habits, immorality or low morale among personnel, carelessness, and so on. Technological devices can control human errors, to some extent. For example, a security apparatus such as an alarm or automatic stopping system can be installed to guard against manipulation mistakes. However, social measures such as education, awareness campaigns, and social systems are fundamentally important in overcoming the social factors that contribute to technological risk.

For example, drunk driving is a major cause of serious and often fatal traffic accidents. Such social problems must be resolved through social measures. Governments have made various efforts to curb this risk through awareness campaigns, education, and legal punishment.

In another example, France is the leading user of the carpooling system "Blablacar". In European Union (EU) countries, travelers usually exchange travel information over the Internet. They can easily find mutual destinations, dates, and routes on their personal computers (PCs).

Travelers with the same destination on coinciding dates and routes can arrange to share the same car. S. Lechevalier emphasizes that this social system helps counter some of the harmful effects of automobile use, such as air pollution, traffic jams, and excessive CO₂ emissions.^{7,8}

Air pollution and CO₂ emissions can be mitigated using new technologies, such as desulfurization equipment. Because new technologies also have several problems, newer technologies must be created to solve new problems. This eternal process is reminiscent of the history of “forbidden fruit”. However, the “Blablacar” system is an interesting example of a technological risk solution put forward by the social system. Although “Blablacar” users may be motivated by the incentive of reducing their fuel expenditure, their economic motivation contributes to public welfare by reducing pollution and CO₂ emissions. Government awareness campaigns encouraging people to utilize public transportation instead of their own private vehicles, are also a social device to solve technological risks.

We can recall the classical “bottle collection” system, where sellers buy empty bottles from buyers. This is a social device that restricts pollution in the form of empty bottles, while also reducing the danger posed by broken bottles. Today, sea pollution due to plastic products has become a problem of vast magnitude. This problem, which requires the production of a new type of material, may be mitigated using social devices such as bottle collection systems. Of course, this problem will ultimately be solved by the innovation of a newer technology that will lead to the invention of decomposable materials.

In the case of the nuclear power industry, widespread anti-nuclear public opinion may be a type of social security device. Particularly after the Fukushima accident, severe social criticism of nuclear accidents and incidents pushed the nuclear power industry to implement strict self-control.

We can summarize the relationships between technological and social causes and devices in the context of technological risk, as shown in Figure 1.

The technological causes of risks, such as air pollution due to automobile use, can be resolved using new technological devices such as desulfurization equipment. Moreover, the technological problem can also be solved using social devices, such as carpooling systems.

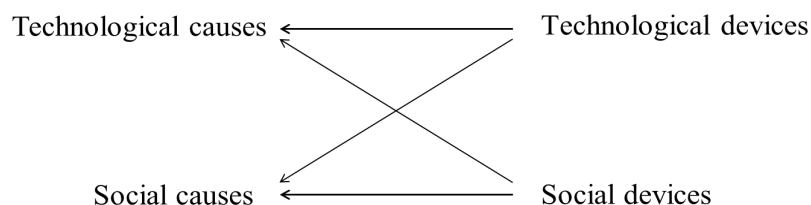


Figure 1. Causes and solutions of technological risk

On the other hand, the social causes of technological risk, such as human manipulation errors, can be solved using technological devices such as an alarm or an automatic stopping system. Such

problems can also be solved using social devices such as education, security-related motivation or campaigns, and the punishment of violent actions.

However, serious technological defects that cause of dangerous accidents must be rectified by newer technological devices. The problem of overly complicated manuals must also be solved using technological rather than social devices.

1.5. Conclusion

In this chapter, several concepts to understand the relationship between technology and risk was proposed, such as the technological hierarchy, law of entropy, endless innovation processes, and technological and social causes and resolving devices of accidents. Humans developed industrial civilization with limited rationality through trial-and-error along technological hierarchy.

New technology's performance is rising with its risk, and newer technology to solve existing risks inevitably contain some new problems because of our limited rationality. Since once we experience the convenience of technology, we cannot go back to the earlier society without the technology, and instead we make an effort to improve the technology rather than abandon it even if it has some serious flaws. Then, humans continue the endless innovation process.

These concepts analyzed in this chapter will be useful to investigate the history of nuclear power industry and to predict its future in following chapters.

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2. How Risk Contributed to Civilization

In this chapter, we investigate how human civilization has developed through risk throughout history. In the Preface, I pointed out the paradox between human ignorance and civilization. Moreover, we can observe that civilization developed through risk throughout human history. Historically, the four main kinds of civilizations are hunter-gatherers, agriculture-cattle, industrial, and post-industrial high-tech information societies. A. Toffler identified three large, drastic changes in human society that he referred to as waves. The first wave was the agriculture-cattle revolution ten thousand years ago, the second wave was the Industrial Revolution three hundred years ago, and the third wave began fifty years ago.¹

2.1. *The Industrial Revolution in England*

The second wave of drastic change

Toffler identified industrial society as the second wave following the first wave, which was an agricultural society. Ten thousand years ago, humans have changed our lifestyle to agriculture and cattle farming from hunting and gathering. Toffler termed this radical change in human society the first wave.

In general, this change from hunting-gathering to agricultural society is understood as a development in human civilization that resulted in a higher standard of living. However, Rifkin opposed this general explanation.² He argued that such a radical change must have been precipitated by a critical crisis, namely a serious food shortage brought about by the hunter-gatherer lifestyle.

Rifkin's understanding is probably correct because it is based on Simon's decision-making theory. Simon held that successive decisions are rapidly programmed as ordinals or operational decisions because of humans' limited rationality,³ which is largely economized through programming decisions that are repeated without evaluating the causality of each action. When successful decisions are repeated, they become stable.

Based on decision-making theory, if humans could have acquired enough food by hunting and gathering, their lifestyle would not have changed; rather, it would have continued as it was prior to the radical change. Agricultural life is more complicated than hunting and gathering because of the hard work required for planting, breeding, and constructing various equipment; arduous tasks include water and soil maintenance and long fence construction. Thus, the drastic change that ushered in a more complex lifestyle must have been triggered by a crisis.

Rifkin's logic can also be extended to other sweeping social changes. The agricultural lifestyle crisis can be said to have precipitated an industrial society. For example, T. Malthus claimed that agricultural productivity decreased due to the availability of cultivable land⁴ and that the marginal production rate decreased due to a shortage of high-quality land. Agricultural

machines have been created to overcome this crisis.

Humans' ignorance created civilization

As I mentioned in the Preface, our civilization was created through humans' ignorance. This is the key theory on which this article is based. Humans never identified the best solution to any problem *a priori*. Protracted trial-and-error is required to obtain acceptable solutions. This process may lead to stumbling upon an acceptable solution, which others may imitate thoughtlessly. This tendency has resulted in civilizations growing in bounded locations by the sea, rivers, mountains, and deserts.⁵

Although humans have limited rationality, we have achieved several objectives, such as inventing tools to hunt large animals, which improved hunting efficiency. However, this advancement contributed to animal shortages, which in turn stimulated the invention of new hunting weapons. These mutual accumulative interactions between animal shortages and the development of hunting instruments resulted in the disappearance of several animal species as a consequence of human ignorance.

Faced with an animal shortage, humans had two main options. The first was to follow large animals to new continents. The second was to change their lifestyle by becoming an agricultural civilization.⁶

The relationship between ignorance and the progress civilization continued after the adoption of an agricultural lifestyle, which was more complicated than hunting and gathering. However, the former offered stability, which greatly benefited future generations. Therefore, in an agricultural community, humans reproduce, and the population grows exponentially, which results in large-scale starvation. For the next ten thousand years, demographic quantity remained constant. However, starvation crises likely stimulated the creation of tools and machines to cultivate the land, thereby resulting in the emergence of an industrial lifestyle.

The iron manufacturing industry at the beginning of industrial society

Iron tools and instruments have improved agricultural and cattle productivity. Ashton's work summarized the early stage of the Industrial Revolution in England.⁷ During the first decades of the 18th century, charcoal was the main fuel for the iron manufacturing industry. However, by the middle of the 18th century, the forests around London disappeared due to indiscriminate deforestation. Furthermore, coal mining began in the mid-18th century, and coke produced from coal became the main fuel for the iron manufacturing industry.

Iron manufacturers supplied steel to the tool and machinery industries. At that time, iron tools and machines were primarily used for agriculture, but they were also necessary for horses and traffic instruments. The machine industry was founded on the iron manufacturing industry. The

Industrial Revolution was sustained by several inventions and innovations related to mining, iron manufacturing, and metal-working industries. For example, toward the end of the 18th century, all shallow coalfields had been mined. Coalfields deeper than 200 feet were then mined using various tools and machines produced by the metal-working industry.

These new industries founded in London and other urban areas as a result of the Industrial Revolution accepted many village children. In Britain in the 1820s, 10% of children aged 5 - 9 and 75% of children aged 10 - 14 worked in industrial shops.⁸ Ashton pointed out that the rapid population increase was due to the increasing number of youths, around five years old, who were the main labor force in factories.⁹ At the beginning of the Industrial Revolution, labor conditions were poor. Many children working in factories or mines faced severely dangerous and unsanitary conditions. However, these children could not survive in an agricultural society, given the limited productivity in their families and villages;¹⁰ new industrial societies could sustain them, even though their circumstances were far from ideal.

England's industrialization was characterized by a long period of trial-and-error involving various inventors and innovators. For example, in 1776, Watt invented the first steam pump, which was utilized to drain vertical shafts in mines. It took 28 more years for Trevithick to invent the steam engine in 1804. Another 21 years passed before Stephenson invented a practical steam engine train in 1825. From the year of the invention of the first steam pump, it took 49 years of trial-and-error to realize the steam engine train. The first runner had no technological model to use as precedents, which meant that the first challenger had to experiment with numerous methods.¹¹

2.2. The spread of industrial society through less developed countries' imitation

What is the competitive advantage of backwardness?

Several backward countries have imitated England's developing industrial society. For example, the United States promptly adopted England's industrial development process. A. Gerschenkron analyzed backward countries' competitive advantage,¹² and found that they can imitate advanced countries' successful technologies, manufacturing processes, and industrial institutions. Specifically, the United States imitated relevant innovative technologies such as steam engines, steam engine trains, and iron manufacturing technologies, among others.

Backward countries can rapidly adopt successful technologies through imitation. According to Gerschenkron, this is a competitive advantage. However, Gerschenkron also showed that each backward country had a unique means of improving industrialization. For example, in America, mass production systems accelerated industrialization.

Indeed, imitating advanced technologies and processes constituted a new means of

technological development in backward countries that would have been impossible without the example of advanced countries. For instance, although some backward European countries imitated advanced technologies, they also utilized their unique traditional skilled worker system, also known as the craftsman system, to advance modern industrial civilization.

Similarly, Japan relied on Western technologies and industrial systems used in the United States and Europe. However, the country created a unique cooperative system between governments and private enterprises.¹³ In Japan, large private companies existed before the Meiji period, which began in 1868. Mitsui, Sumitomo, and Konoike are famous private enterprises that, along with Mitsubishi (which was founded at the beginning of the Meiji period), were known as the conglomerate Zaibatsu. During the first stage of the Meiji era, the Japanese government created large textile, steel, and shipbuilding factories in cooperation with advanced countries. After several years, the government sold the factories to the Zaibatsu at very low prices. The Japanese government then attempted to foster capitalism. Instead of remaining private enterprises, Zaibatsu cooperated with the government and showed a deep commitment to governmental policies.¹⁴

Russia also imitated advanced technologies and methods. However, it employed socialism to rapidly improve industrialization through governmental leadership and authoritarian totalism.¹⁵ Gerschenkron explained that Russia did not have any traditional private enterprises. In the 19th century, Russia consisted of landed aristocrats, a functional government, and peasants. The private sector was not substantial enough to manage large organizations and large amounts of capital. Therefore, the government continued to manage large factories created through governmental leadership.

Gerschenkron stated that backward countries were more inclined toward rapid totalitarian government-oriented industrialization. Backward countries observed advanced countries' successful technologies and industrialization strategies. If the backward countries had repeated England's long slow process of trial and error, they would not have achieved such rapid progress.

Finally, according to Gerschenkron, Marx's opinion that forward countries provided a blueprint for backward countries to follow was only a half-truth regarding the history of industrialization. The other half is that each backward country employed its own unique strategy to realize rapid industrialization under the conditions prevalent in its day.¹⁶

The mass production system as typical modern industrial society

Mass production systems were a typical feature of modern industrial society in the United States from the end of the 19th century to the beginning of the 20th century. A. Chandler analyzed the modern industrialization process in the United States¹⁷ and highlighted the necessity of mass distribution systems as a predecessor to mass production systems. Without a mass distribution

system, mass production systems can only create non-distributable inventories.

Chandler investigated the initial industrialization period, which he identified as occurring before the beginning of the modern industrialized period, when various machines or tools utilized natural power, such as human or animal power, wind, or water flow. These machines and tools were strictly limited in terms of credibility, durability, and regularity, as their efficiency depends on the weather and season. For example, when the river is frozen in winter or dry in summer, a water wheel is useless. In contrast, artificial energy, such as steam, gasoline, or electric power, provides credible, durable, and constant energy, without seasonal or weather limitations.

Chandler explained that modern industrial society was constructed on the foundation of mass distribution and production systems that provided sustainable, credible, and durable sources of artificial energy. In the United States, mass distribution systems were realized using steam engine trains for transportation instead of canal systems, which were restricted by weather and season.

Mass production systems also involve product standardization, which differs from that of craft-working in Europe. Thus, it can be hypothesized that America's historical background as a country of immigrants helped to improve standardization processes. Almost all labor in the United States consisted of unskilled immigrants, mainly from Europe. As their cultural backgrounds and languages were different, they probably could not understand each other easily.¹⁸ Consequently, product standardization and division of labor were useful for managing divided or isolated unskilled workers.

Standardized stereotyped products created through mass production were quite different from the high-quality products skilled workers produced in Europe. Mass production systems cannot compete with crafting systems in terms of quality. However, mass production procedures offered a competitive advantage: Standard quality could be achieved at low prices, which resulted in two important economic effects.

The first effect is related to economies of scale,¹⁹ according to which large-scale production reduces the unit cost. The unit cost is calculated by dividing the total cost by the total quantity of the products. The total cost consists of fixed costs (e.g., cost of equipment) and variable costs (e.g., cost of energy and materials). Increasing the product quantity decreases the unit fixed cost, thereby decreasing the unit cost.

The second effect is that of specialization consisting of set-up cost elimination and the learning effect.²⁰ In the mass production system, relatively simple monotonal partial processes are divided, similar to in the parts combination processes. Therefore, mass production systems realize both product and process standardization. As every worker is assigned a specialized role, no one needs to prepare for other types of work. Therefore, eliminating the set-up cost improves the efficiency. Moreover, because every worker repeats the same task many times, their skills improve rapidly. This learning effect through experience also improves the efficiency of mass production.

Thus, the decreasing unit cost and increasing efficiency are naturally reflected in low prices.

While the mass production system realized a huge competitive advantage due to low prices, it introduced new social problems, such as human task alienation. That is, workers could not derive a sense of accomplishment or fulfillment from their work in factories because they repeated the same simple tasks every day. Moreover, the factories were dirty, noisy, and dangerous because of the various large-scale production machines.

The mass production system was based on mechanization. The first stage of mechanization based on artificial energy was mainly sustained by steam engine systems. Steam engine-based machines in factories were large, difficult to use, and dangerous. Although machine electrification improvements gradually realized the miniaturization of the machines, coupled with the adoption of safety procedures, a noisy, dirty environment covered with oil and characterized by monotonous labor continued to exist.

Therefore, mass-production systems created new management problems related to work efficiency and motivation for companies and workers. Industrial companies then faced a management problem, which they tried to solve using management theories, such as scientific management, management science, and motivation theories. These theories naturally influenced backward countries as well.

Electric power as the dominated energy source

Abernathy investigated the American automobile industry at the beginning of the 20th century through a historical analysis of Ford Motor Company.²¹ He identified three types of core technologies that existed at the end of the 19th century: steam, gasoline, and electric engines. Each engine has advantages and disadvantages. The steam engine was high-powered, but it took a long time to start because it needed to boil hot water to make steam. The gasoline engine was both high-powered and quick to start, but it had a serious problem of potential accidental explosion due to its fuel. The electric engine is safe and quick to start, but it is not high-power.

When the automobile industry was in its early stages at the end of the 19th century, the steam engine car dominated the American market. The cost of such a vehicle was extremely high at approximately \$-5,000, which made it a luxury good for rich people. After many technological improvements, gasoline engines overcame the potential for dangerous fire accidents and dominated the automobile market at a price of approximately \$-2,000. In 1908, Henry Ford sold the Model T for \$-980. This model soon became the dominant gasoline car.

In the same period, three types of energy sources for factory machines were invented as alternatives to natural power from animals, water, or wind. Similar to the automobile, in the early stages, various steam engine machines dominated factories in the late 19th century. Some gasoline-powered machines were also invented. However, steam and gasoline machines became very

dangerous as a result of scale expansion. Large-scale steam and gasoline machines reached very high temperatures and produced significant noise. Moreover, the explosion risk increased because of the increased difficulty in controlling the high temperatures. Furthermore, the energy loss associated with the steam and gasoline engine mobility was high; that is, it was difficult to efficiently transport the energy generated by these engines.

From this viewpoint, electric energy was safer than steam and gasoline generation, especially for large equipment. Moreover, it is quite easy to transport electric energy via electrical wiring, while steam and gasoline energy must be produced near the machines that utilize these energies. Therefore, a large-scale electric power plant located far away from the factories it supports could produce enormous amounts of electric energy for specialized use. Given that large-scale power plants can realize economies of scale then electric energy has become very low in cost.

Electric energy can be easily transported to residences, in addition to large-scale manufacturing factories, by controlling the electric current or voltage. In addition, electric energy can be utilized to instantly transport signals to distant places. Morse's electric telegraph system utilized this function in the middle of the 19th century. Signal transportation using electric energy was also used to invent several new models beginning in the middle of the 18th century.

Adjusting and controlling electric mechanisms brought about a new stage characterized by a drastic change in human society. Toffler called this the third wave,²² referring to the transition to a post-industrial society based on the electronics industry, to which electric energy is crucially important.

2.3. Post-industrial society's energy source

The third wave of drastic change

Toffler placed the third wave at the end of the 20th century, which marked a significant change in human society, in which electronics replaced the electric machine industry as the primary industry. Specifically, computer-aided design and manufacturing are the most popular types of factories. The high-tech information society, which is the civilization associated with the post-modern industry, is sustained by small, portable devices with a large capacity. Extremely high-speed computers have also emerged. These computers are powered by electricity, making the steam engine and gasoline engine obsolete in the electronics industry. The use of gasoline engines is common in the automobile, agricultural machine, airline, and maritime transportation industries. Meanwhile, hybrid engines that combine electricity and hydrogen gas with gasoline engines are also gaining popularity in the automobile industry. Furthermore, the use of electric energy is inevitable in the control systems of various transport machines, despite the significance of the steam and gasoline engine system including the nuclear-powered ship and the jet-gas turbine system that is considered a major power resources.

Therefore, with the onset of the third wave, although steam and gasoline engines have survived in some industries, the use of electric energy is growing, owing to its utility, which stems from merits such as light equipment, the electric motor's portability, signal transportation that facilitates communication and combination with light-fiber systems, and the ability to adjust and control various machines, including computers.

Steam- and oil-powered systems still exist to produce electric energy by moving electric generators, and industrial power plants continue to produce electric energy. However, contemporary power plants are controlled using electronic devices, and the power plant itself is industrial equipment. Ironically, steam engine survives mainly in generating systems of electric power, which drove it to dead-end technology.

We must now clarify the meaning of each of wave proposed by Toffler. After the first wave, agricultural and cattle civilizations began on a full scale. However, hunting and gathering lifestyles never actually disappeared. For example, the fisheries industry is still fundamentally based on hunting, and honey gathering still exists. This is important. Indeed, after the second wave, aquaculture and beekeeping were incorporated into hunting and gathering.

Similarly, agriculture and cattle rearing did not disappear after the second wave, as we continued to rely on agriculture and cattle for food. However, after the second wave, agricultural machinery and the mechanization of cattle rearing were introduced. Following the same logic, after the third wave, for example, every fishing boat has been equipped with a fish finder, agriculture is now controlled using electronic equipment, and so on. After the third wave, the need for electric energy persists, and it is produced by large-scale power plants that are controlled by high-tech electronic systems.

Strategies for managing electric energy generation

In the near future, electric energy will continue to be the most convenient energy source because of its ease of use to produce light, moving power, control systems, and communication via signal transportation, in addition to the fact that it can be easily transported over long distances via electrical wiring. The main problem is the generation of electric energy. The major generation types are hydroelectric, thermal, and nuclear power. Renewable power generation may advance in the future. Which generation type or combination is the best? In the next chapter, the technological and social problems associated with each type of generation will be investigated.

Recall Rifkin's hypothesis that radical change, which Toffler called a new wave, was realized through great risk during the last stage of the former civilization.²³ For example, recall that at the last stage of the hunting and gathering civilization, critical animal and fruit shortages ushered in the agricultural and cattle rearing civilization, and mass starvation coupled with the limitations of agricultural productivity brought forth mechanization and industrial civilization. What risk

precipitated the rise of high-tech information civilization?

Recall the serious risks present during the last stage of industrial society, such as a large number of mining and traffic accident victims and large-scale environmental pollution. Specifically, there were many serious coal mining explosions in the 1950s; the incidence of automobile accidents was higher in the period 1960-1980 than in 2000-2020; and although there were fewer flights 50 years ago, airplane accidents were more frequent. In addition, many new illnesses arise as a result of environmental pollution due to the use of various chemical-based materials.

We have overcome these risks by using new electronic technologies to make adjustments and controls. The principal among these devices are computer systems that can control various factors rapidly, correctively, and sensitively before accidents occur. Through their use, we overcame the risks associated with industrial civilization by the onset of the third wave of high-tech electronics.

Although the fundamental energy of electricity continues to be the principal fuel for high-tech electronic information society, it is generated by large-scale power plants from industrial civilization. These large plants are, of course, controlled by high-tech electronic devices.

Toffler identified decentralization, such as individual rooftop solar energy generation panels, as a characteristic of the third wave.²⁴ However, large volumes of energy are still generated in large generating centers, as in the second wave. Accidents at these generation centers are directly connected to the serious damage that high-tech electronic information civilization may suffer. How should we manage large-scale generation centers? First, we need to investigate the accidents that have occurred there.

2.4. Conclusion

In this chapter, we identified each human civilizational new wave as ushered in through a crisis in the last stage of the former civilization, such as animal and fruit shortages precipitating an agricultural and cattle-rearing civilization, mass starvation caused by limited agricultural productivity bringing about industrial civilization, and pollution and other social problems due to mass production system inducing high-tech informational civilization.

Moreover, the diffusion process of industrial civilization was investigated through backward countries' imitation and their unique method of catching up with the forward countries. Through this investigation, we found that the mass production system is a typical technological and institutional device in industrial civilization.

We also identified that the activities in former civilization are retained under the influence of a new civilization, and electricity was selected throughout the industrial and post-industrial society as a fundamental source of energy because of its various utilities. Electric power is then

generated in large-scale plants controlled by high-tech electronic devices in post-industrial society.

In the next chapter, we will analyze electric power generating plants' management and compare each type of generation system from the perspective of future possibilities using the life cycle hypothesis and the technological hierarchy concept.

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3. Electric Power Plant Management

In this chapter, I predict the future of nuclear energy compared to other sources of electricity using the technological hierarchy concept discussed in Chap1, Section 1.1.

Through the technological hierarchy, we can gain a systematic understanding of the various sources of electric energy. Moreover, we can situate the cause of the Fukushima accident within the technological hierarchy's decision tree, as will be noted in the next chapter. Consequently, we can come to understand the seriousness of the real cause of the Fukushima accident.

At the same time, we can identify some solutions to the problems that contributed to the accident based on the technological hierarchy as a means-ends analysis of problems and solutions.

3.1. The technological hierarchy of an electric power plant

Currently, there are three major core technologies used in electric power plants: hydroelectric, thermal, and nuclear power generation. There are also some types of renewable energy generation, such as solar, wind, geothermal, biomass energy, and sea wave power generation.

Although most countries prioritize renewable energy generation, national renewable energy percentages are very low overall, except in Denmark and Northern Europe. At present, there are three main types of electric generation systems, as mentioned above.

I investigate these three types within the framework of the technological hierarchy. Although each type of electric power generation has some variance in terms of the mechanism, I will delineate the technological hierarchy of all three based on the fundamental core technological concept.

Hydroelectric power generation's core technological concept is generating electricity using water flow to directly power a generator. This differs from the technological core concepts underlying thermal and nuclear power generation, which involve generating electricity by using steam produced from boiled water to move a generator.

The difference between thermal and nuclear generation lies in the mechanism for boiling water. Of course, there are different fuel options for boiling water, such as coal, oil, and gas. In this sense, we can regard nuclear power generation as a type of thermal power generation, despite the use of different energy sources, such as uranium.

However, the core technological concept of heating water through nuclear fission arising

from a radioactive substance is quite different from burning coal, oil, or gas. Therefore, nuclear power generation is clearly distinct from thermal power generation. Although there are various kinds of nuclear plants, for all nuclear power generation, the core technological concept is heating water through nuclear fission of radioactive substances such as uranium.

The technological hierarchy of hydroelectric power generation

The fundamental principle of hydroelectric power generation is the use of water flow to move a generator motor directly. Making water flow is a common problem. There are some solutions such as utilizing natural rivers or man-made pools, constructing dams, or pumping water.

However, each of these methods is flawed. Water supply is restricted by weather and season. For example, there are water shortages in the dry season, summers droughts pose a serious problem, and water freezes during winter.

These problems can be mitigated by utilizing large rivers that have a stable quantity of water and are situated in warm areas where the water will never freeze. Pipe water can also be used to prevent freezing. In addition, dams are an effective tool for drought preparedness and utilize cheap electricity during off-hours like midnight, which is useful for operating water pumping systems.

However, the issue of coastal erosion, which has recently gained attention due to its severity, remains unresolved. Because dams block rivers' water with flowing sand, ocean waves constantly encroach on the land. In the absence of a dam, sand is brought to the river's mouth along with the water, where it would prevent ocean waves from eroding the coast.

Although concrete blocks are placed along coastlines in place of natural sand, they are essentially useless because ocean waves destroy them within 10 or 20 years. To produce the large volumes of concrete blocks that are needed, a large quantity of rocks and sand are scraped off mountains. Hence, dams contribute to both mountain depletion and coastal erosion. In addition, the broken concrete blocks littering the coastal landscape are eyesores.

Furthermore, dams are becoming less useful because of the decreasing volume of water they store, as dams become shallower as more sand accumulates over time.

In summary, according to the technological hierarchy concept, hydroelectric power generation utilizing dams may either be at the saturation or declining stage of its technological life cycle until problems such as coastal erosion and shallowing of dams is addressed. Given the unsolvable problems of coastal erosion and dam shallowing, it is imperative to gradually phase out hydroelectric power generation.

However, other types of hydroelectric power generation without dams may offer hope since they are free from carbon dioxide (CO₂) and are renewability.

The technological hierarchy of thermal power generation

The fundamental principle of thermal power generation is the movement of a generator using steam from hot water. Heating water is the primary problem. Options include burning coal, oil, or gas. Another problem is the elimination of noxious gases, such as nitrous oxides (NO_x), contained in the exhaust when fuels are burned. One solution is desulfurization equipment.

However, the problem of elimination CO₂ is still unresolved. Recently, many countries have focused on the CO₂ problem because increasing atmospheric CO₂ contributes to global warming. Since the Kyoto Protocol in December 1997, global warming has become one of the most important global environmental concerns.

Based on the technological hierarchy, we can identify thermal power generation's technological life cycle as being at the saturation stage because of the CO₂ problem, notwithstanding the debate about the existence of global warming.

In the future, innovative devices may effectively eliminate CO₂ and toxic gases as products of burning coal, oil, or gas. However, complete elimination of the eradication is impossible, suggesting that the burning of fossil fuels has reached the saturation stage.

The technological hierarchy of nuclear power generation

Nuclear power generation can be regarded as a solution for eliminating CO₂, since unlike burning fossil fuels, producing steam from water heated via nuclear fission does not discharge CO₂. The fundamental scientific knowledge underlying nuclear principles is that nuclear fission creates a great deal of energy. The energy was then initially weaponized. After World War II, attempts were made to harness this energy to produce electricity.

Therefore, the primary problem associated with nuclear power generation is the achievement of sequential nuclear fission to produce electric power. The principle of nuclear generation is that nuclear fission creates heat that boils water, which in turn produces steam that moves the generator motor. Controlling the fission level poses a challenge. The solutions were mainly water cooling and control rod systems. Cool water keeps the nuclear reactor cool and maintains a certain level of nuclear fission. Nuclear fission can also be restricted by charging the control rods between the fuel rods.

According to the technological hierarchy of nuclear generation, the Fukushima accident occurred at a lower hierarchical level populated by alternative electric power source devices. These devices represent a subsidiary method for solving a subsidiary problem in the technological hierarchy. Aggravated by the tsunami the Fukushima nuclear accident resulted from the loss of an alternative electric power source, demonstrating the importance of protecting backup electric power from large ocean waves.

In Japan, banks are currently being constructed along the coast of some nuclear plants. This

is among the solutions suitable for protecting alternative power sources from tsunamis. However, constructing a high tower upon which an alternative power source can be placed may be easier.

The higher level of nuclear power generation's technological hierarchy includes several risks. In general, controlling nuclear fission is difficult because of the reaction's time lag. To manage this, operators must be experienced and highly skilled. Because the reaction's time lag naturally increases with the scale of the reactor, miniaturization of the reactor is another solution to this problem.

Moreover, there are some serious problems related to radioactive waste nuclear power generation. One of the most effective solution is to establish a nuclear processing and reprocessing cycle using mixed oxide (MOX) fuel and a breeder reactor. However, eliminating high-level radioactive waste remains a pressing issue despite the development of the glassification method.

Renewable energy generation

Several types of renewable energy generation exist at present, such as solar, wind, geothermal, biomass, and ocean wave power generation. In general, renewable energy is inefficient. Wind and solar power generation are restricted by season and weather, such as the natural power sources before the beginning of industrial civilization. For example, there is no sunshine on rainy and overcast days or at night, and wind turbines cannot move on low-wind days.

Chandler pointed out this restriction before the beginning of modern industrial society.¹ Natural sources, such as rivers and wind, are not sustainable in all seasons and weather. As I already mentioned during the course of explaining hydroelectric power generation, natural rivers freeze during winter, floods, or dry up in summer.

Therefore, solar and wind power have a serious reliability problem, as in the period "before the beginning" of industrialization. Solar power is particularly problematic as large-scale solar paneling requires significant deforestation. Given that individual solar panels produce only weak electric power an immense forested area must be developed to drive an adequate number of solar panels.

Diamond directly linked deforestation to the collapse of civilization, based on the investigation of salient historical cases pertaining to the Maya civilization as well as to Easter Island, Greenland, Australia, Africa, China, Japan, and others.² Buildings' roofs are used to house solar panels. Exchanging extensive deforestation for some electric power is a suicidal act for human beings.

Given that all renewable energy generation is based on young technologies, there are strong possibilities for improvement. This means that renewable energy generation is at the introductory stage of the technological life cycle.

3.2. Technological selection in the nuclear system

It is useful to analogize the technological hierarchy of nuclear power generation and Abernathy's automobile design hierarchy, as mentioned in Chapter 1.3. During the early stages, there were three fundamental engine types in the automobile industry: electric, steam, and gasoline engines. Then, each core technological concept had a hierarchy of subsidiary devices to solve the respective subsidiary problems.³

Currently, nuclear power generation still has various fundamental core technologies for utilizing the heat that nuclear fission produces. This variation in core technologies means that the nuclear industry is at the fluid stage of its life cycle, at least partially. That is, the industry has not yet matured. Evidently, each nuclear power generation core technology has subsidiary devices within the respective technological hierarchy. In sum, nuclear power generation must be categorized as being in the growing stage in its technological life cycle, which corresponds to beginning of "Star" in the Product Portfolio Management (PPM) theory constructed by Boston Consulting Group.⁴

Core technologies of nuclear power generation

There are four main types of nuclear reactor categorized according to their coolant, fuel, moderator, and enrichment levels. The first type of nuclear reactor is the "light water" reactor (LWR); its core technology entails boiling water using the heat nuclear fission produces.

This type of reactor is cooled and moderated with regular water (H₂O) and uses uranium-dioxide as fuel, which is popular in Japan. This type of reactor is further divided into two types: the "boiling water" reactor (BWR) and the "pressurized water" reactor (PWR). The BWR boils water using the heat nuclear fission produces, while the PWR boils water using the heat produced by nuclear fission to 300 °C under high pressure. In a BWR, steam is generated inside the reactor and goes directly to the turbine, while in a PWR steam is generated outside the reactor in a secondary heat transfer loop (stem line) connected to the pressurizer. PWRs are found on nuclear powered ships and are used for electricity generation. PWR is widely used in France. On a nuclear power ship, steam goes directly to steam turbines connected to a screw, not to an electric generator.

The second type of nuclear reactor is the "heavy water" reactor (HWR). Almost all the HWRs are PWRs. HWRs utilize heavy water (D₂O) as the coolant and moderator. HWRs can use either uranium-dioxide or metal as fuel. Moreover, HWRs can produce plutonium as well as electricity.

The third type of nuclear reactor is the "graphite moderated" reactor (GMR), which uses graphite as a moderator. The two types of coolants are gas and water. Both types of GMRs can produce plutonium as well as electricity. Gas coolant GMRs use uranium dicarbide (UC₂) or uranium as fuel, while water coolant GMRs use uranium dioxide or metal.

The gas coolant GMR is widely used in Britain, while the water coolant GMR was used in

the former Soviet Union. For example, the former Soviet Union created an original nuclear reactor in Chernobyl, known as the Reaktor Bolshoy Moshchnosti Kanalnyy (RBMK), which combined the use of a graphite moderator type and a water coolant.

As will be mentioned in Chapter 4, the Chernobyl disaster on April 25, 1986, is assumed to have been caused by reactor manipulation difficulty, because of the wide time lag of the reactor due to its large scale. It was known as the largest reactor in the world, and it must have been constructed to pursue economies of scale. However, this type of reactor will be phased out.

The fourth type of nuclear reactor is a “fast breeder” reactor (FBR). The most common type of breeder is the “liquid metal fast breeder” reactor (LMFBR), which can produce plutonium as well as electricity. The chemical composition of the fuel is plutonium dioxide and uranium dioxide in various arrangements.

LMFBRs use molten liquid sodium, which has approximately the same specific gravity as water and a boiling point of 880 °C, making it a convenient nuclear reactor coolant. LMFBRs are used to enrich nuclear fuel. For example, an LMFBR can breed plutonium 239 from uranium 238 through fission. LMFBRs can also use MOX fuel produced from spent nuclear fuel containing plutonium 239 and uranium 238.

However, uranium 238 is not fissionable. Moreover, natural uranium contains 99.3% unfissionable uranium 238 and 0.7% fissionable uranium 235. Therefore, the enrichment function of LMFBR, that is, changing uranium 238 to plutonium 239, is quite important, especially for countries that are naturally resource-poor.

As mentioned above, there are still a variety of fundamental nuclear reactor technologies. The existence of various core technologies indicates that the nuclear industry has not yet matured. In the near future, some subsidiary technological devices or core technologies may be phased out.

Ultimately, nuclear energy’s most attractive characteristic is the tremendous power it produces using a small amount of fuel. However, there is also a serious risk arising from the difficulty in operating nuclear plants. This is specifically attributable to the fact that the nuclear reaction has a time lag, and that irregularity often occurs with acceleration. The time lag is longer for large plants, making operation even more challenging in the Chernobyl case, as mentioned above.

An additional risk associated with nuclear technology is widespread radioactive pollution in the wake of an accident. The larger the nuclear plant, the more widespread the radioactive pollution will be in the event of an accident. The world has experienced serious nuclear accidents. Safeguarding the future will require considerable effort, not only to improve the security and efficiency of nuclear technology to reduce the probability of nuclear accidents, but also to create an effective management model to overcome nuclear accidents, such as effective radioactivity decontamination processes and reactor decommissioning programs.

The technological hierarchy of nuclear generation will become more sophisticated as new devices are added and existing dead-ending technologies are phased out through trial and error.

The concept of a dominant design

As mentioned in Chapter 1, Abernathy discussed the “design hierarchy” in his book.⁵ He explained the historical development of the automobile industry through a detailed investigation of the Ford Motor Company. He insisted on the existence of a dilemma between productivity and innovativeness.

When the automobile industry was in its beginning stage, which he called the “Fluid stage,” there were many radical innovations concerned with core technologies; for example, different types of engines, such as electric, steam, or gasoline engines were invented and tested in practice.

However, a dominant design emerged after many trials and errors. The phase “dominant design” means that a technological design satisfies both the manufacturer and the customers. Abernathy regarded the first dominant automobile design as the Ford Motor Company’s 1908 Model T.

The first Model T was equipped with a gasoline engine, propeller shaft, rear wheel drive, and mechanical brake system. Ford developed its design hierarchy step by step so that it would be well suited to a mass production system. This design hierarchy produced performance that satisfied users’ needs in terms of speed, safety, ease of driving, price, and durability.

Therefore, the Model T became the first dominant design, as it satisfied both the manufacturer and costumers. Once the dominant design was established, major innovation ceased. For example, gasoline became a fixture, along with subsidiary technologies such as the transmission, gears, throttle, steering, and brakes.

On the other hand, productivity rose rapidly after the dominant design was established. By virtue of the fixed technologies in the hierarchy, product standardization was improved, facilitating mass automobile production. As a result, unit costs and prices decreased rapidly, leading to higher productivity.

Once Ford achieved high productivity, the company was inclined to maintain it because it was very profitable. Radical innovation requires the destruction of the highly productive mass-production system. Therefore, after reaching the high production stage, an industry matures, and radical technological innovations tends to be avoided.

In summary, high productivity cannot be achieved at the fluid stage, which is characterized by radical innovation. However, once a highly productive mass production system is established, radical technological innovations are apt to be avoided. This creates a dilemma between innovation and productivity.

We then recognized that there is a variety of fundamental core technologies in the nuclear

power generation industry. This means that the nuclear power generation industry is still partially in the fluid stage. The nuclear power generation design hierarchy has not yet been established. Trial-and-error efforts to create a technological hierarchy for nuclear power generation are ongoing. In other words, the dominant design for nuclear power generation has not yet been established.

3.3. What is a dead-end technology?

A dead-end technology has little chance of being improved so that it may become a practical technology. There are various examples of application attempts involving dead-end technologies. First, with dead-end technology, there is an essential problem with the fundamental theory or technological concept from the outset. In such cases, all application methods are pointless because of the problematic core technology. For example, many people tried to produce a helicopter based on Léonard da Vinci's 15th century sketch. However, no application of this basic idea could yield a practical product because of the theoretical error in the fundamental concept exhibited in the sketch.

Second, application limitations preclude the development of a promising application process. In such a case, no subsidiary device can solve the primary problem hindering its successful application. As discussed in Chapter 1-1, the technological hierarchy reveals the relationship between the application problem and the solution; that is, the application process can eventually yield a practical product if application problems are incrementally minimized.⁶

For example, when Problem A arises on an application pathway, solutions for Problem A are critical. Even if Device B can solve Problem A, Device B will present some problems of its own. If Device B causes of Problem C and Problem C is smaller than Problem A, then Device B is useful in the application pathway.

However, if Problem C is more serious than Problem A, then Device B is not useful. In such a case, the devices cannot ameliorate the application problems, and Device B is, in a sense, a dead-end technology. If there is no promising device that can aid application, the fundamental core technology is also a dead-end technology.

The third case is when a superior technology precipitates an inferior technology's decline into dead-end technology. For example, the aircraft industry forced the airship industry to become a dead-end technology. At a glance, the 1937 Hindenburg disaster, which was reported all over the world, triggered the airship industry's demise, despite practical post-disaster airship improvements such as the utilization of helium gas as the float gas in place of hydrogen gas, which is highly flammable. Although this adjustment improved airship security, the rise of the aircraft industry rapidly forced the former to become a dead-end technology.

In the third case, a new breakthrough technology forced an existing fundamental technology

to become a dead-end technology. Other examples include the semiconductor that replaced the vacuum tube and the electric motor train that replaced the steam engine locomotive.

In general, technological breakthroughs drive existing technologies, as the new fundamental technology establishes the dominant design. As mentioned above, at Abernathy's fluid stage, that is, the period during which the dominant design is being established, a new fundamental technology cannot replace an existing one.

For example, after the Model T established the dominant gasoline engine design, the steam and electric engines became dead-end technologies. Other examples include the propeller airplane that survived after the establishment of the dominant design of the jet airplane based on the gas turbine engine, which was a real breakthrough. This is because the propeller airplane is economical for short-range transportation and other uses.

How can we predict when the propeller airplane will disappear completely and when a new engine system emerges through the next breakthrough? Furthermore, how can we predict the future of nuclear power generation as a breakthrough in thermal power generation? Competition types provide a hint when predicting future technological conditions.

The relationship between product life cycle and competition type

M. Tsuchiya advocated changing competition to suit the product life cycle, based on Abernathy's and M. Porter's theories.⁷ Tsuchiya insisted that during the beginning stage of the product life cycle, called the introduction stage, competition is primarily concerned with product quality in terms of ensuring security, credibility, durability, sustainability, and so on. He situated this type of competition in Porter's differentiation strategy.⁸

The fluid stage is characterized by many instances of trial and error related to various core technologies, whereupon the dominant design is subsequently established and the product enters the growth stage of the life cycle. Once the dominant design has been established, radical innovation is replaced with relatively minor improvements.

Tsuchiya insisted that during the growth stage, the competition focus changes from quality to price. In other words, the competitive strategy changes from a differentiation strategy to cost leadership in the context of the life cycle shift from the introduction to the growth stage.

During the growth stage, companies seek to decrease costs and offer low-priced products. During severe low-cost competition, the saturation stage is gradually realized. Low costs and prices reach their limitations, and market demand also reaches maturity.

At this mature stage, the company or individual tries to create a new product model to stimulate the re-growth stage of the life cycle. Tsuchiya pointed to the example of General Motors' luxurious Cadillac road-cruiser at the end of the 1920s. This renewed automobile model replaced Ford's Model T. The new model changed the dominant automobile design in terms of appearance,

rather than core technology.

Abernathy called this regrowth stage the “Industrial Renaissance”.⁹ Tsuchiya pointed out that in the regrowth stage, competition changes from cost leadership to the differentiation strategy, once again because of the change in focus from product price to quality.

Of course, this type of the model change is never a breakthrough because of the continued use of the same core technology, that is, gasoline engines. Therefore, the regrowth stage remains on the same technological S-curve,¹⁰ without fault.

The regrowth stage eventually reaches saturation, and the cost-leadership strategy is reinstated as the main strategy. Tsuchiya insisted that these waves of strategic or repeated changes are evidenced historically for all products. Therefore, we may predict the appearance of a new model, dominant design, or breakthrough through observation of competition in the context of the product life cycle.

Incidentally, a hybrid engine, that uses hydrogen gas is a real breakthrough because it involves core technological innovation. The hybrid automobile deviates from the technological S-curve that applies to the Model T and other luxury vehicles. Of course, the cost is always important for any company. However, regarding hybrid cars, competition is at present mainly concerned with quality rather than price or cost.

We can therefore state that the nuclear power industry is not mainly engaged in price competition. This suggests that the nuclear industry may be still at the beginning and fluid stages. Although the dominant nuclear power plant design is partially emerging as will be mentioned in Chapter 5-1 and Chapter 6-1, we can understand that an important trial-and-error process is ongoing in the current nuclear power plant industry.

When selecting the dominant design, some core technological concepts will inevitably disappear, just as the RBMK disappears after the Chernobyl disaster due to its fundamental construction flaw.

3.4. Conclusion

In this chapter, I summarize the technological hierarchies applicable to four types of electric power generation: hydroelectric, thermal, nuclear, and renewable energy generation. According to the technological hierarchy concept, I sequenced technological problems and solutions in the context of each power generation system’s application process.

Moreover, I identified each power generation system’s current life cycle stage through the lens of the technological hierarchy concept. Due to the unsolvable issues of coast erosion and dam shallowing, hydroelectric power generation is in the saturation or declining stage, that is, “Cash-cow” or “Dog” per the Boston Consulting Group’s PPM theory.¹¹

Thermal power generation is in the saturation stage, which is equivalent to the “Cash-cow”

category in the PPM theory. However, there is little room for thermal power generation improvement through the innovation of new devices to eliminate the toxic gas and CO₂ that fossil fuels burning emits.

Nuclear power generation is in the growth stage, which is equivalent to “Star” in the PPM theory. However, it is also partially in the fluid or introduction stage because a dominant nuclear reactor design has not yet firmly been established.

Because there is considerable room for improvement given the short history of renewable power generation, this type of electric power generation is in the introduction stage, which is the “Problem child” stage in the PPM theory.

I propose that we design an energy portfolio for the future that includes the gradual abandonment of hydroelectric power generation, maintenance of thermal power generation, and innovation in nuclear and renewable power generation.

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4. The Case of the Fukushima Nuclear Accident

In this chapter, we will investigate the 2011 Fukushima nuclear accident based on “Figure 1” in Chapter 1. This entails researching the real causes of the accident, which must be combined with technological and social factors to find solutions to mitigate the risk associated with nuclear energy and accurately predict the future of nuclear technology.

First, we will investigate the technological causes of the accident. Second, the social causes

will be probed. We can identify the specific technological causes of the Fukushima accident through a comparison with the Chernobyl accident. Moreover, we will identify the flaws in Japanese management and leadership and classify them as the social causes of the Fukushima accident through an investigation into Japanese management and leadership's ability to prevent accidents.

Gaining a clear understanding of the damage caused by the accident as well as the factors that contributed to its occurrence are fundamentally important in investigating the function of Japanese management and leadership. Finally, we can conclude that Japanese management and leadership cannot control Japanese culture or its social atmosphere. Western researchers sometimes express admiration for Japanese management. However, Japanese leaders' professional knowledge, skills, and bravery do not preclude their struggles with the overall social atmosphere.

4.1. Differences between the Fukushima and Chernobyl accidents

The International Nuclear and Radiological Event Scale (INES) ranks the severity of damage caused by nuclear accidents from 1 to 7. The Fukushima accident was categorized as Level 7, similar to the Chernobyl accident. The Japanese government, led by Prime Minister Naoto Kan at that time, was concerned with raising the INES classification to Category 7.

However, some nuclear specialists have criticized the Kan government's decisions. Mark Tran introduced the following criticism from Murray Jennex, associate professor at San Diego State University:¹

I think raising it to the level of Chernobyl is excessive. It's nowhere near that level. Chernobyl was terrible – it blew, and they had no containment, and they were stuck. Their [Fukushima] containment has been holding, the only thing that hasn't is the fuel pool that caught fire.

Tran analyzed the difference between the Fukushima and Chernobyl nuclear accidents, by comparing official data. For example, in the case of Chernobyl, the reactor itself exploded while it was still active. However, at Fukushima, the reactor did not cause the accident; rather, the plant's cooling system was crippled by a tsunami.

Tran also drew attention to the amount of radioactive material released during each accident. While the Japanese Nuclear Safety Commission estimated the radioactive material released by the Fukushima plant's reactors to be more than 10 petabecquerel (PBq), that released during the Chernobyl incident was estimated at 5,200 PBq.

Moreover, in the case of Chernobyl, Tran pointed out that 50 emergency rescue workers died from acute radiation syndrome and related illnesses. Furthermore, 4,000 children and adolescents had contracted thyroid cancer.

At Fukushima, however, no radiation-related deaths have been reported, and only 21 plant workers were affected by minor radiation sickness.

James Mahaffey has investigated various atomic accidents since the 1950s.² He also investigated the Fukushima and Chernobyl accidents in depth. I will now summarize the important differences between the Fukushima accident, which occurred on March 11, 2011, and the Chernobyl accident, which occurred on April 26, 1986, based on Mahaffey's work and official reports. Although both accidents were categorized as INES Level 7, as previously mentioned, there were serious differences.

First, the cause of the accident at Fukushima was a 49-foot tsunami that occurred after the Great East Japan Earthquake, which had a magnitude of 7.2. With the onset of the earthquake, all reactors in Units 1, 2, and 3 stopped automatically. Emergency isolation condensers and diesel generators started to operate, and they effectively cooled the reactors. Approximately 50 min after the earthquake, a large wave inundated the entire plant.

However, the accident at Chernobyl was caused by human error and procedural violations during an experimental test. Mahaffey noted a dangerous construction problem concerning the RBMK at Chernobyl, whereas Fukushima's Mark-1 (M-1) BWR had no such defects, although it had some weak points that I will describe later.

Second, the Chernobyl accident involved the explosion of a core reactor that was working during the accident. Fukushima's reactor buildings in Units 1, 3, and 4 exploded because of hydrogen gas. However, Mahaffey found that the reactors and fuel pools in each unit were intact despite their bedraggled appearance.

The building in Unit 2 did not explode, even though the reactor in Unit 2 was active because of the hail caused by an explosion in neighboring Unit 1. On the other hand, the building housing Unit 4 exploded, even though the reactor in Unit 4 was not active, because of a shared exhaust pipe through which hydrogen gas was discharged to Unit 4 from Unit 3.

Mahaffey commented as follows on a photograph of the accident at Chernobyl: "It is completely destroyed and unrecognizable as a power plant." In contrast, he made the following remark on the tragic photograph of the Fukushima accident. "The damage, which appears devastating, is not quite as bad as it looks. The top floors of the reactor buildings, which were built only to keep rain off the refueling equipment, have been blown away, but the solid concrete structures that hold the reactors and the fuel pools are all intact."

Third, the damage caused by the Chernobyl accident was far more serious than that caused by the Fukushima accident. As previously mentioned, the number of directly attributable fatalities and the amount of radioactivity released differed greatly. Moreover, the areas affected by radiation were also significantly different. In the Fukushima accident, radiation levels exceeding the annual limits were seen over 60 km to the northwest and 40 km to the southwest, while in the case of

Chernobyl, an area up to 500 km away was contaminated, according to the United Nations.

4.2. The Tokyo Electric Power Company's failure to heed good advice

The management of the Tokyo Electric Power Company (TEPCO) ignored important advice from Bruno Pellaud, who was a vice-general in the secretariat of the International Atomic Energy Agency (IAEA). The advice pertained to the M-1 produced by the American company General Electric; it consisted of the following four suggestions, which were made in 1993, 18 years before the accident.³

a) Strengthen vessels and buildings.

Pellaud pointed out a weak point in the M-1 reactor equipment: The reactor was too close to the building. As the space between the reactor and the building was narrow, when hydrogen gas is emitted, the buildings could easily explode. To prevent such an explosion, the vessels and buildings in each unit must be strengthened.

b) Diversify the power sources.

Pellaud recommended that an alternative power source be established on a hilltop to protect against submergence by a large ocean wave. Like all other nuclear power plants in Japan, Fukushima 1 is built on the coast so that the cooling system can utilize seawater. In other words, Pellaud was afraid that a large wave might inundate the entire plant.

c) Build a device that can combine hydrogen and oxygen to form water, thereby reducing the hydrogen gas pressure.

He also recommended the installation of an emission device for oxygen gas in each unit. Since such a device can form water by combining with hydrogen gas from the cooling system emissions, it will protect the building from a hydrogen explosion.

d) Install a hydrogen gas ventilation device to remove radioactivity from the gas.

When hydrogen gas is generated rapidly, ventilation is the most useful method to avoid hydrogen explosions. Because the hydrogen gas is radioactive, a ventilation system that can remove radioactivity is necessary.

If TEPCO had implemented these suggestions, the nuclear accident could have been prevented. They would not even have needed to implement all the suggestions; implementing b) alone - the most critical suggestion- would have prevented the accident.

After close investigation, we can see that the Fukushima nuclear accident was not caused by an accident at the nuclear plant itself, but rather by a failure in the cooling system's alternative energy source caused by the tsunami.

Why did TEPCO disregard Pellaud's suggestions?

Pellaud speculated as to why TEPCO rejected his advice: "The leaders of TEPCO were too arrogant as if they thought they would have been God. They might accept advice from the General Electric Company, which produced Mark-1. However, they treated me as an outsider completely."⁴

Arrogance was certainly the reason TEPCO rejected Pellaud's advice. However, we must pay attention to why they were arrogant. Therefore, we will briefly examine the history of Japanese nuclear development.

During World War II, Japanese scientists were at the forefront of nuclear technology, but after Japan was defeated in 1945, the General Headquarters of the Supreme Commander for the Allied Powers prohibited the country from developing nuclear technology. Nuclear development did not resume until after Japan recovered its sovereignty in 1952.

In 1955, the Atomic Energy Fundamental Act was passed; the Atomic Energy Commission of Japan and the Japan Atomic Energy Research Institute were organized in 1956; and the Japan Nuclear Power Generating Corporation was founded in 1957. In 1963, an electric power supply generated using nuclear energy was established in Tokai-mura village.

At that time, Japanese public opinion supported nuclear development, notwithstanding the horrible experience of the atomic bombings in Hiroshima and Nagasaki in 1945. The Japanese believed that nuclear power was an important alternative to thermal and hydroelectric power. Moreover, the severe gasoline shortage during World War II likely boosted social opinion. In 1949, Dr. Hideki Yukawa won Japan's first Nobel Prize in Physics in the field of atomic theory, which might have also pushed public opinion toward supporting nuclear development.

At the same time, in Europe and the United States, there was extreme optimism about nuclear energy. For example, face powders, face creams, and soaps containing both thorium and radium were introduced in France in 1933, and these products were sold in Europe until the early 1960s.⁵ Similarly, in New York, radium powder was sold as fluorescent paint.

Japanese nuclear development accelerated through cooperation with American companies. Cooperation among General Electric, Westinghouse Electric, Hitachi, Mitsubishi Heavy Industries, and Toshiba greatly contributed to the development of the nuclear industry.

Moreover, two oil crises, in 1973 and 1978, accelerated nuclear development despite the various problems associated with nuclear plants. After these two oil crises, oil prices rose from less than \$20 to \$110 per barrel. As 99% of Japan's oil is imported, the country desperately needed to develop nuclear energy.

The 1970s saw significant improvements in nuclear plant technology in Japan. Through these improvements, the average nuclear plant operation rate rose from 40% to 60% in the 1970s to 70% and 80% from the 1980s to the early 2000s. T. Nakase mentioned that these successful

experiences engendered arrogance among Japanese electric companies including TEPCO, and successful performance created an atmosphere in which no one could criticize the upgraded nuclear technology.⁶

Furthermore, mounting discussions about global warming protection also promoted the development of nuclear technology in the 1990s. In particular, the Kyoto Protocol at the United Nations Framework Convention on Climate Change pushed the development of nuclear technology, which can reduce atmospheric CO₂ emissions.

On the other hand, after the Three Mile Island accident in 1979, the anti-nuclear movement gained traction, particularly in the United States, where the movement was highly emotional. The accident at Chernobyl in 1986 strengthened the anti-nuclear movement worldwide. Even in Japan, there is a large anti-nuclear undercurrent connected with the antiwar and anti-nuclear weapon movements.

The management of Japanese nuclear electric companies had to confront the anti-nuclear movement and the necessity for the development of nuclear energy to reduce atmospheric CO₂. While it is true that the leaders became arrogant after the successful upgrading of nuclear plants, these severe anti-nuclear circumstances laid the groundwork for ignoring Pellaud's advice.

The management of nuclear electric companies had to guarantee safety in persuading anti-nuclear leaders to sanction the construction of nuclear plants in each prefecture. Of course, a 100% safe technology will never exist. However, they still had to declare the plant's absolute safety at every public hearing. In the absence of such a declaration, they would not have been permitted to build nuclear plants in any prefecture because of the anti-nuclear atmosphere in Japan.

Nuclear energy leaders skirted from scientific and logical explanations, so to speak, to deflect emotional agitation. They avoided the challenging negotiation that the scientific approach would have triggered. Once they declared that the nuclear plants were 100% safe, they must have had great difficulty accepting devices that would have improved the plants because doing so would have proved that the nuclear plants still had safety weaknesses.

Their arrogance also pushed them to ignore Pellaud's advice. A third or even half of the leaders might have believed that their nuclear plants were indeed 100% safe.

4.3. The characteristics of Japanese leadership and the decision-making process

We have observed an atmosphere characterized by unreasonableness and emotional avoidance with regard to nuclear technology in Japan after the Fukushima accident. Given Japanese cultural characteristics, such an atmosphere is likely to dominate people. Therefore, mass media usually tries to control the atmosphere.

Japanese leaders seldom debate any topic that contradicts prevailing opinion. For example,

before the Fukushima accident, the leaders of Japanese electric companies rarely discussed the security of nuclear technology with anti-nuclear advocates. Management cavalierly assured the public that their nuclear plants were 100% safe to avoid intense scientific debate. They managed to let the counterforce go past without controversy. This is characteristic of Japanese leadership, and it is one of the social causes of technological risk (see Figure 1 in Chap. 1).

A 100% safety declaration prevented further improvements. The same phenomenon reappeared in the wake of the Fukushima accident. Even today, Japanese leaders, including statesmen, government officials, and corporate executives, avoid tough debate with anti-nuclear forces about the future of nuclear energy policy, just as they did before the Fukushima accident. Therefore, we must recognize the serious limitations of this traditional Japanese leadership style that prioritizes conflict avoidance.

The importance of a science-based standard

Traditionally, Japanese leadership has coordinated a diversity of opinions, but this leadership style is mainly concerned with members' emotions, so to speak. Certainly, this leadership style has the merit of maintaining emotional harmony in an organization. However, it is also problematic because avoiding disputes makes it difficult to identify the truth and achieve some important objectives. Specifically, as I have already mentioned, Japanese leaders are inclined to submit to or flatter dominant opinions in order to avoid difficult discussions. This is a serious flaw in Japanese leadership.

In the future, Japanese leaders of all organizations must be brave enough to argue with anyone about anything in an attempt to find the truth in the interest of public welfare. In fact, a scientific basis is important in any discussion or dispute. Japanese leaders must utilize science-based data and knowledge to persuade opponents without relying on emotions.

4.4. Conclusion

In this chapter, I investigated the case of the Fukushima nuclear accident from the perspectives of both technological and social causes. It was found that the technological causes were neither the construction or functioning of the nuclear equipment nor the incidence of the earthquake itself, but rather the loss of backup electric power due to the submergence of the plant under a great tsunami after the earthquake.

Whenever an earthquake of a certain magnitude occurs, all Japanese nuclear plants are stopped automatically, including the Fukushima plant. Moreover, in all plants, substitutional electric power starts immediately to cool the atomic reactors.

Therefore, the real technological cause of the Fukushima accident at Nuclear Plant 1 was neither the nuclear technology nor the great earthquake; rather, the accident is attributable to the

lack of an alternative electric power source, which, according to Pellaud 's recommendation, should have been situated on high ground, where it should have been safe from the tsunami.

Nevertheless, in the grips of panic, the Japanese government decided to stop all nuclear plants and dig into the ground at each one to examine active fault lines that are over one million years old, at a cost of several billion yen.

Furthermore, we investigated the social causes of the Fukushima nuclear accident and found weaknesses in Japanese leadership and management. Specifically, Japanese leaders are usually poor at holding intense discussions involving scientific logic without employing emotional manipulation. They are inclined to easily accept excessive demands or restrictive security levels.

In the next chapter, I will investigate nuclear energy in France. Through a comparative analysis of the French and Japanese cases, we can gain an understanding of the reasons underlying the different energy rates of the two countries.

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5. The Nuclear-Power Industry in France

This chapter analyzes the French nuclear power industry covering its history, problems, and risks. As it is clear that a national consensus is needed to maintain the current high rate of nuclear energy (over 70% of total energy produced), this section will explore the processes through which energy policy is made in France, with the aim of identifying a characteristic consensus-building mechanism.

5.1. The history of the nuclear power industry in France

Until 1977, France's operable nuclear power capacity was less than 5,000 MWe (Megawatt electric). By 1988, it had increased to 50,000 MWe, and the capacity has remained over 60,000 MWe since 1997. In 2018, France produced a total of 582TWh (terawatt hours) of energy in the following categories: nuclear 71%, hydro 12%, natural gas 5%, wind 5%, biofuels and waste 2%,

coal 2%, solar 2%, and oil 1%.¹ The percentage of net export energy was 10.8%. In June 2020, France had 56 active nuclear reactors. (See *6-1*, provides a description of energy mix in Japan).

In 1974, immediately after the first oil shock of 1973, the government decided to promote this electricity generation mix. France sought to improve its ability to generate nuclear power by cooperating with the Westing House to gain access to nuclear technology and drawing on its own substantial expertise in heavy industry. The generation of nuclear power could advance the country's energy policy and security through energy independence. Alternative sources of energy resources, such as coal, oil, and natural gas compelled France to depend on other resource-holding countries.

Since the Kyoto Protocol in 1997 and the Paris Agreement of 2016, nuclear power has enabled French electricity producers to achieve extraordinarily low CO₂ emissions per capita. Given its declining life cycle, hydroelectric power, which produces no CO₂, is unlikely to become a significant source of power in the future, as mentioned in Chapter 3 (3-1).

The first national energy debate was announced in early 2003, in response to loud demands from the French public, who felt misinformed about energy issues and concerns. According to a national vote, 67% of the public considered environmental protection as the most important energy policy goal, while 58% believed that nuclear power generation caused climate change.² This debate provided a context for designing the energy mix for the next 30 years.

In mid-2004 the board of EDF (*Électricité de France*) decided in principle to build the first unit in an expected series of Areva European pressurized water reactors (EPRs). In May 2006, after the national debate, this decision was confirmed by the EdF board. In Flamanville, Normandy, a new 1650 MWe EPR unit was constructed. This decision was deemed “an essential step in renewing EDF nuclear generation mix.”³

In 2005, the government enacted a new energy policy and security guideline. Although 58% of the population had expressed concerns about the link between nuclear energy and climate change during the national debate, the guidelines prioritized nuclear power, with a plan to build the 40 series of EPRs. The guidelines also confirmed a research policy centered on developing innovative technologies to reduce carbon dioxide emissions and improve renewable energy production. These guidelines appeared to have been determined by government authorities, rather than democracy. This section investigates the decision-making process.

In 2008, the top-level Nuclear Policy Council (*Conseil Politique Nucléaire - CPN*) was established. This body chaired by the President, included the Prime Minister and cabinet secretaries responsible for energy, foreign affairs, economy, industry, foreign trade, research, and finances among its members. Moreover, the Atomic Energy Commission (*Commissariat à l'Énergie Atomique et aux énergies Alternatives-CEA*), was led by the Secretary General of National Defense and the Military Chief of Staff on the Council. The CPN was an authoritative

organization, with the power to determine the nation's fundamental nuclear energy policy.

In January 2009, President Sarkozy announced that EdF would build a second 1650 MWe EPR at Penly Normandy. A public debate on the project was held in 2010. However, the ASN (*Autorité de sûreté nucléaire*) did not accept EdF's application to build the unit. The Nuclear Policy Council directed Areva and EdF to improve mutual cooperation in technology and commerce before building the EPR. In July 2011, Areva and EdF agreed on the design, building, and maintenance of the EPR at Flamanville 3.

In 2012, President F. Hollande announced a policy designed to reduce the percentage of nuclear power in the energy mix. He encouraged a new broad national debate on energy transition, which ran for eight months until July 2013. According to the Ministry for Ecology, Sustainable Development, and Energy, 170,000 people participated in 1,000 regional debates, and 1,200 online submissions contributed to the national debate. The debate uncovered people's concerns about the risk of nuclear power and their willingness to reduce dependence on nuclear energy.

French public opinion was clearly influenced by the accident at the Fukushima Daiichi Nuclear Power Plant in March 2011. However, in September 2013, the Office *Parlementaire d'Évaluation des Choix Scientifiques et Technologiques* (OPECST) reported that France was at risk of a power price shock if it pursued a speedy reduction of nuclear power, as there were insufficient renewable energy alternatives.⁴

In October 2014, based on the results of the national debate, the Energy Transition for Green Growth Bill was passed by the National Assembly. Further, in July 2015, the bill was enacted as the Energy Transition for Green Growth Act, which declared that the share of nuclear energy in the national energy mix would be reduced to 50% by 2025. However, in December 2017, President E. Macron moved the target date to reduce the share of nuclear energy to 2035, citing nuclear energy as the most carbon-free, renewable form of energy available.

In mid-2015, Areva declared that cooperation with EDF was simplifying construction the new model of EPR and would help realize a significant (25%) cost reduction. In July 2015, EDF agreed to own 51 - 75% stake in Areva Nuclear Power (NP). In July 2017 Framatom, renamed New NP held all existing Areva assets related to the design and manufacture of nuclear power and other equipment and services.

In February 2018, after various consolidations, Orano was founded with stocks shared among the French government (45.8%), Areva S. A. (40%), Mitsubishi Heavy Industry (MHI) (5%), Japan Nuclear Fuel Ltd. (JNFL) (5%), and CEA (4.2%). Orano intended to focus on generating a positive net cash flow in 2018, establishing service activities in 2020, and earning more than 30% of its revenue from Asia by 2020.⁵

5.2. Risk in the nuclear power industry

The major risks associated with the nuclear power industry are nuclear waste and plant accidents. Nuclear waste can be reduced by reusing waste as fuel in the fuel cycle. At the final stage of the process, nuclear-concentrated wastes are stocked in underground storage facilities; high-level nuclear wastes are stored 445-490 meters underground. The present study investigates the current state of the nuclear fuel cycle, nuclear waste disposal, and accident risk management.

The nuclear fuel cycles

As mentioned in Chapter 3-2, fast-breeder reactors (FBRs) constitute a critical technology in the nuclear fuel cycle, as they use MOX fuel, produced from spent nuclear fuel containing plutonium-239 and uranium-238. As 99.3% of natural uranium is uranium-238, which is not fissionable, an important function of FBR is to breed plutonium-239 from uranium-238 through fission.

Despite this, the two French FBRs are currently inactive because of frequent accidents and political decisions. First, the Phenix reactor, which began operations in 1974, was closed for modifications during 1998-2003, and then shut down completely in 2009, following a test operation for waste-disposal research.⁶ Second, the Super-phenix reactor, which began operations in 1996, was closed down for political reasons at the end of 1998.

Although EDF intends to continue the FBR reconstruction project in the future, the nuclear fuel cycle is almost entirely sustained through the using of MOX fuel in PWRs (Pressurized Water Reactors). Currently, fifteen PWRs in France use 90 % of the MOX produced from spent nuclear fuel (see *Note 5-1*).

Nuclear waste disposal

The nuclear-waste disposal problem is a critical issue among anti-nuclear activists who argue that the endless and unlimited stockage of nuclear waste causes widespread radioactive contamination. Nuclear waste can be classified as high-, intermediate-, and low-level concentrations of nuclear pollution. Currently, highly concentrated waste, after glass solidification, is stored 445-490 meters underground at Bure, a rock laboratory in eastern France (see *Note 5-2*).

Note 5-1

Based on interviews with V. Dufour, General Director of EDF in Japan and Korea (June 11, 2021) and H. Machenaud, former director of EDF (October 4, 2021).

Note 5-2

The present writer actually visited ANDRA's site in Bure on February 28, 2022. Mr.

The *Agence Nationale pour la gestion des Déchet Radioactifs* (ANDRA), - the National Radioactive Waste Management Agency, - was established in France in 1991, based on the Waste Management Act, which was updated in 2006.⁶ In April 2019, ANDRA reported that France had 1.62million cubic meters of radioactive waste, of which 59% came from power generation, 28% from research, 9% from the military, 3% from industry, and 1% from medical uses.

The *Commission Nationale d’Evaluation* (CNE) - the National Scientific Assessment Committee - established following the enactment of the Waste Management Act in 2006, is responsible for assessing research and development (R&D) concerned with high- and intermediate-level waste: deep-geological disposal, separation and transmutation, and the storage of nuclear waste. Since 2007, CNE2, an expanded version of CNE has submitted CNE reports on the progress made in managing R&D waste across EdF, CEA, ANDRA, and the National Center for Scientific Research. Such inter-organizational annual reports contribute to the construction of public agreements related to the nuclear power industry.

In June 2006, the Nuclear Materials and Waste Management Program Act was passed, confirming the need for deep geological disposal of high-level and long-lived radioactive waste. This act affirmed the importance of reprocessing used fuel to reduce the final waste. Since 1992, ANDRA has run a disposal center in the Aube district, with one million cubic meters of stockage for low-level wastes and short-lived intermediate-level waste.

The core problems of nuclear waste disposal can be divided into two categories: the need to develop technology to decompose nuclear waste, and storage space limitations. First, although nuclear-waste decomposing technology will be a critical solution to the nuclear-waste problem once technological developments are advanced, Bure’s stockage site was constructed based on a reversible principle expecting technological development in the future; at present, there is scant evidence of such advances (see *Note 5-1*).

Second, in relation to waste stockage space, ANDRA’s geological surveys in four regions were halted by local opposition movements in 1990. After the 1991 Waste Management Act, ANDRA improved the survey and construction of underground storage sites in Bure, which will become available by 2025.

Two EDF directors noted that bedrock is not required for storing nuclear waste because the facilities are built of steel; for this reason, there are few limitations on nuclear-waste storage space.

Nuclear plant accident management

TARRIET presented and discussed ANDRA’s project and I observed the storage equipment space 490m underground with his guidance.

Presently, almost all French nuclear plants are constructed near rivers; they use river water to cool the reactors. As France experiences relatively few earthquakes, cooling system management is the primary plant-security issue. Indeed, anti-earthquake measures are implemented, including strengthening buildings and ensuring that reactors are stopped during tremors. However, the focus of this study is on investigating cooling system controls.

On December 27, 1999, the Blayais nuclear center on the Gironde River was flooded with river water after heavy rains. Three of the four active reactors were manually shut down for security reasons. Although the reactor cooling system was damaged by the flood, since PWRs have alternative electric power sources, designed to produce steam from pressed hot water, these were used to provide electric power to cool the reactors to a certain extent, resulting in a Level 2 accident that was estimated by responsible specialist members at the Blayais site.

This accident resembled the Fukushima accident caused by the flooding of the electric power sources that ran the cooling system. Fortunately, in the Blayais case, PWR was able to use a steam-producing electric power source to partially cool the reactors. In Fukushima, in contrast, the tsunami knocked out all electric power, causing a station black out (SBO). In 2000, the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) warned that several other riverside plants faced the same risk as the Blayais, as they did not have a sufficiently high foundation.

Following the Fukushima accident, the EDF improved the security of its reactor cooling systems and diversified its electric power sources. For example, large pools were constructed beneath the plants, and moats were added to protect plants from flooding. Underground pools can also cool stored river water during summer. In addition, alternative electric power sources were constructed in high places, such as the tops of hills and towers (see Note 5-1).

5.3. National consensus building

The next section summarizes the consensus-building process of the French nuclear power industry. One characteristic process involves balancing democratic and authoritative approaches to national decision-making. Fundamentally, there is a national consensus on the need for energy independence to ensure national sovereignty. Simultaneously, there is also an anti-nuclear movement in France, which this study investigates.

The process of balancing democracy and authority

According to Hayek, liberalism must maintain some discretion to determine the range and limit of democratic rule.⁵ In other words, liberalism must decide which themes can be voted democratically. Specialized subjects are not well suited for voting. For example, the subject of nuclear power generation necessitates a thorough explanation from experts before it can be discussed in an informed manner.

Hayek warned that simple voting supremacy would introduce democratic totalism, which is the opposite of liberalism. Members of the public cannot decide which option is better without explanations from specialists. However, specialists' decisions run the risk of introducing authoritative totalism. Thus, a democratic approach with authoritative means is required to maintain liberalism. This discussion is summarized in Table 1.

Table 1. The Liberal - Democratism Matrix
Oyama, Paradox between Ignorance and Civilization
Koyo-shobo Press 2017 p.113 Table 1.

	Liberalism	Totalism
Democratism	Democratic liberalism	Democratic totalism
Authoritarianism	Authoritative liberalism	Authoritative totalism

Liberalism guarantees every individual the right to question, request, and resist any decision. In contrast, totalism does not guarantee an individual any such right. Democratism guarantees the participation of all individuals. In contrast, authoritarianism permits only certain individuals with specialized knowledge and skills to participate in decision-making.

Thus, a free election system is a typical example of democratic liberalism. Democratic totalism never permits objection to a decision to be raised through democratic methods. Specifically, Hayek warned of the risk of democratic dogmatism. Authoritative liberalism is extremely important in specialized decision-making involving high-tech R&D and medical treatment. Informed consent during medical operations is a means of comparative decision making that blends authoritarianism and liberalism. Doctors explain the procedures in question to the patients and others concerned; they may question or refuse to accept the doctors' decisions.

As discussed in Chapter 5-1, the French government established a democratic approach that incorporates an authoritative mechanism through mutual interactions between national voting procedures and authoritative organizations, as follows:

In 1945, CEA established a nuclear R&D and policy organization, which was renamed the Commission on Atomic Energy and Alternative Energy (*Commissariat à l'énergie atomique et aux énergies alternatives* or - CEA) in 2009. OPECST, the Office parlementaire d'évaluation des choix scientifiques et technologiques, was established in 1983. In 2002, the Autorité de sûreté nucléaire was founded as a specialized authoritative organization.

France's first national energy debate took place in 2003, and its second national debate on energy transition, in 2012. These national debates were conducted using a democratic approach. However, in 2013, the authoritative organization OPECST argued, from a specialized point of view, that nuclear power generation should continue, rather than succumbing to conservative

public sentiment.

In addition, the French government and companies, including ANDRA, Areva, and Orano, have set up various Internet systems to communicate with people who have an interest in or questions about the nuclear power industry. The Internet is often used to build a national consensus in France, as it enables interactive decision processes and mass consulting to mediate between democratic and authoritative approaches.

The anti-nuclear movement

Although France generates over 70% of its electricity from nuclear power, there is an active anti-nuclear movement. After the Fukushima accident, anxieties about the risks associated with nuclear energy seem to have grown. Based on research interviews and corroborated by additional data, this study summarizes anti-nuclear views in France as follows (see Note 5-3).

First, the most serious risk concerns the harmful effects of radioactivity. In case of a nuclear accident that releases widespread radiation, as well as during usual operations, radioactivity has an influence on the health of nuclear plant workers, the consequences of which are not fully known. Second, nuclear waste cannot be decomposed now, or in the future. Building and continuing to store an unlimited quantity of high-level waste will inevitably spread radioactive contamination. Third, nuclear specialists and the government refrain from disclosing the complete truth or highlighting important points. Fourth, there is always the risk of human error involved when operating nuclear plants, with Chernobyl and Fukushima as two examples.

Anti-nuclear protesters do not trust the government, nuclear specialists, or nuclear policy. Although the government and companies provide well-constructed Internet communication systems, protesters argue that people are never informed about the most critical core problems. Anti-nuclear protesters insist that future technological R&D must focus on developing renewable energy sources instead of nuclear energy. They argue that nuclear energy is already a dead-end technology._

5.4. Conclusion

This chapter investigated the case of the French nuclear industry, focusing on its history, risks, and problems, and the consensus-building approach. Although certain specialized decisions in the nuclear power industry must be discussed among specialists, as in the case of medical

Note 5-3

Based on an interview with Catherine Cadou, a member of the anti-nuclear movement. (August 17, 2021)

treatment, concerned members of the public must have a guaranteed right to participate in a democratic society. According to Hayek, liberalism can incorporate specialized authoritative discussions alongside the democratic approach, creating a comparative system that allows concerned members of the public to participate freely. For example, informed consent in medical research is a typical authoritative liberalism decision-making system (see Table 1).

By investigating the history of French nuclear power policies, this study confirmed that the authoritative liberalism decision-making process has been achieved in France by several specialized organizations and two democratic national debates.

Authoritative specialized organizations discuss, analyze, and inform the public about the state of the nuclear power industry. People learn about problems associated with nuclear power from specialized information sources and construct their own opinions through dissemination of such information, common sense, and other impressions. Specialists analyze public opinion and explain the problems associated with nuclear power, sometimes persuading people to acquire a better understanding of nuclear policies.

These cooperative interactions among specialists, the public, and the government have the potential to achieve social consensus and a high rate of nuclear power generation, exceeding 70% in France. The public can continue to discuss nuclear policies with various governmental and industrial bodies via the Internet.

The present study further revealed through interviews, that EDF realized that the core problem at Fukushima was the loss of electricity needed to cool the reactors due to the flooding caused by the tsunami. Subsequently, EDF improved its own riverside flood protection, building moats and underground pools around its plants, and preparing alternative electricity sources in high places.

However, nuclear disposal remains a severe concern because the technology required to decompose radioactive materials cannot be developed without more advanced R&D. This serious problem contributes to the growth of anti-nuclear movements in France, Japan, and other countries. Resolving the disposal problem and easing radioactive anxiety are critical issues for the future.

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6. Future Energy Policy Based on a Comparison of France and Japan

This chapter will propose a rational future energy policy based on the previous chapters by specifically comparing France and Japan’s nuclear power politics and decision-making processes to construct a social consensus. Each country’s background influences its nuclear power decisions, and this comparative study focuses on political leadership and national consensus.

6.1. Political leadership

Scientific demonstration and political strategy

President E. Macron declared a technological innovation investment of 30 billion euros on October 12, 2021, with the budget allotted to nuclear power are 1 billion euros for the manufacturing of small-sized modular reactors (SMR), 1 billion euros for the increase in nuclear security and decrease in nuclear waste, and 0.5 billion euros for decomposing atomic nucleus innovation.¹

This declaration has several important implications. First, the French president announced a national decision to improve nuclear technology. Second, SMR is a type of dominant design for nuclear reactors because parts of the modular are standardized and can be mass-produced. The EPR mentioned in Chapter 5-3 is also a dominant design (see *Note 6-1*). The appearance of a safe and efficient nuclear reactor model means that the nuclear power industry is growing after the fluid and introduction stages. Moreover, as mentioned in Chapter 5-1, in mid-2015, Areva referred the significant (25%) cost reduction the new model of EPR, which indicated a competition was focusing to price from quality. That was a sign of nuclear power industry was coming to the growing stage (see Chapter 3-3). The industry will approach a maturation stage by improving reactor model standardization. Third, the French government is focusing on key technologies to resolve the nuclear waste problem, such as decomposing the atomic nucleus, FBRs, and MOX fuel.

Note 6-1

Auxence GROS-BOROT (Vallourec, Energy Transition Strategic Marketing Manager), a former member of AREVA recognizes EPR and SMR as standard reactor models. Moreover, he considered that a fundamental national consensus on energy independence exists in France. (Interview on December 19, 2021)

Comparatively, the Japanese government and politicians have not declared a concrete policy instead of announcing the continuing nuclear power industry. In 2018, five nuclear reactors remained active, nine passed, and 12 reactors were under examination by new regulations after the Fukushima accident in 2011.² These cases indicate Japan's active nuclear power industry. Although Japanese politicians declared the nuclear roadmap to reach 20% - 22% by 2030, they never concretely explained how to navigate the roadmap.³

Before the Fukushima accident, Japan maintained 20.3% of its primary energy self-sufficiency rate in 2010. After the accident, this decreased to 11.6% in 2011, 6.7% in 2012, and 6.6% in 2013, because nuclear power generation stopped. However, it increased by 9.7% in 2017 because of the partial removal of nuclear plants. Incidentally, France maintained 52.8% in 2017.⁴

In 2019, Japan produced a total of 1,000 TWh of energy in the following categories: natural gas 35.4%, coal 27.6%, other thermal power generation 9.3%, solar 8.5%, hydro 7.9%, nuclear 4.3%, biomass 3.2%, oil 2.0%, wind 0.9%, and geothermal 0.3%.⁵

The Japanese government employed incomparably stringent safety criteria for agricultural products such as 100 Bq/kg, whereas international standard is 1000 Bq/kg, 1250 Bq/kg in Europe, and 1200 Bq/kg in the U.S. Since 2017, no agricultural and livestock products and seafood in Fukushima have exceeded 100 Bq/kg.⁶ Although the Japanese government has tried to appeal to Fukushima's food security in the Olympic Village restaurant in 2021, there are several other promotional ways with concrete safety level announcements.

After six years of discussion, on April 13, 2021, the Japanese government decided to release tritiated water at the Fukushima Daiichi Nuclear Plant from 2023, already stocked 1,230,000 t, and increasing 140 t/day. The decontaminate treated by the Advanced Liquid Processing System (ALPS) will be diluted to 1/7 level of the WHO standard of drinking water from seawater before being released.⁷ Releasing tritiated water is a normal activity worldwide. Similar to the safety of agricultural products, there is much room for potential scientific demonstrations by the Japanese government. Moreover, the government has potential democratic approaches to reach consensus with fishermen's unions in Fukushima.

As mentioned in Chapter 4-3, Japanese leadership has not been effective enough to appeal to society, due to a weakness in discussions based on scientific logic. Leadership should have favored harmonizing various conflicts through sentiment. A fundamental strategy based on scientific logic must be designed through the cooperation of leaders and specialists.

6.2. National consensus

Authoritative liberalism approach

A national consensus is inevitable in democratic countries. However, every vote cannot necessarily result in a correct response, especially for specialized affairs. Hayek pointed out that

minority thoughts and concepts have brought triggered important innovations throughout human history. For example, democratism itself has never been the majority during long human history. Therefore, we must carefully determine the limits of democracy.⁸ An authoritative liberalism approach is needed to cope with specialized problems (see *Table 5-1*).

As mentioned in Chapter 5, the French government successfully combined a democratic approach and authoritative means through national energy debates and specialized organizational decision-making. National debates and voting are democratic approaches that guarantee people's participation rights. However, in highly specialized problems, the results of a democratic vote can be reconsidered by specialists. In the French case, the result of the national debate in 2013 certainly reflected the Energy Transition for Green Growth bill in 2014, which declared a 50% decrease in nuclear energy dependence by 2025. However, the 2025 target for reducing the share of nuclear power was postponed to 2035 through authoritative means.

The most important point is the manifestation of a national strategy by government leaders before the debate and discussion. In the case of Japan, leaders seem to be an irresolute cause of traditional characteristic leadership, avoiding controversy and intending to maintain ambiguous behavior without effectively utilizing both democratic and authoritative approaches. It seems that they are waiting for the anti-nuclear atmosphere to decrease while they investigate the active fault line that occurred one million years ago; nevertheless, the Fukushima accident was not caused by the explosion of an active fault line but was inundated by the tsunami.

Although nuclear specialists' organizations exist in Japan, specialized decisions are often denied by court judges as non-specialists of nuclear power. Specialist organizations do not debate with the opposition or appeal to their basis of the argument of safety to society. The government does not reveal its energy strategy and nuclear detail road map to the public or organizes national debates and votes on nuclear policy. In summary, the current Japanese nuclear decision-making process does not fully adopt either a democratic or authoritative approach.

6.3. Future energy policy

Energy portfolio

Energy portfolio selection among various alternatives, such as hydropower, thermal power, nuclear power, and renewable power generation, is important for designing future energy policies. As mentioned in Chapter 3-2, we can apply the PPM theory to select some types of energy in various life cycles.⁹ The original PPM theory proposes diversifying investment, which is comparable to a problem child product, at the introduction and fluid stage, a star product at a growing stage, a cash cow at a mature stage, and a dog product at a declining stage.

The PPM theory recommends investing in a problem child product from the revenue of a cash cow product to bring about a future star product, and to withdraw from a dog product to

avoid losses.

The energy policy will exclude hydropower in the future because of the dam shallowing and coast erosion problem, as mentioned in Chapter 3, and decreasing thermal power due to CO₂ and NO_x problems; thus, investment in nuclear and renewable energy will increase. However, renewable sources, such as solar energy and wind, are restricted by weather and seasons, such as energy sources in pre-industrialized civilizations. Furthermore, deforestation is the most serious problem arising from the construction of large-scale solar panels.

As mentioned above, nuclear energy is growing because of dominant designs and standardization, such as BWR, EPR, and SMR. In the growth stage, products can rapidly increase their security and efficiency by adding investments. Considering the Chernobyl accident, as a large-scale nuclear reactor is dangerous because of the long operational time lag, small reactors will be the dominant design in the near future.

Furthermore, a breakthrough has already emerged, in nuclear fusion reactors, creating tremendous energy from the fusion of deuterium and tritium, which are unlimited natural resources, without nuclear waste but with helium gas. In October 2007, the International Fusion Energy Organization was funded through an agreement in November of 2006. The International Thermonuclear Experimental Reactor (ITER) was constructed in Saint-Paul-lès-Durance, southern France (see *Note 6-2*).

International cooperation between France, Japan, the U.S., and others will drive forward extreme innovation in the future. Of course, there are risks associated with innovation, similar to other technological innovations. We must continue our efforts to overcome risks with a calm understanding of our human problem-solving history and a solid sense of mission for our future under our limited rationality and the uncertain environment.

Note 6-2

The present writer actually visited ITER in Saint-Paul Les Durance on February 25, 2022. After a presentation and discussion with the Chief Strategist - Deputy Head of ODG OMAE, I observed the construction site with a guide from ITER.

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