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Coordination Under Uncertain Conditions: An Analysis of the Fukushima Catastrophe

Masahiko Aoki and
Geoffrey Rothwell

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Masahiko Aoki is professor emeritus and senior fellow at Stanford University and visiting fellow at ADBI. Geoffrey Rothwell is a senior lecturer at the Department of Economics, Stanford University. We thank T. Amemiya, B. Carson, G. Coles, S. Deakin, R. Graber, T. Hatta, B. McDowell, B. Rasin, A. Seward, B. Smoter, K. Whattam, F. Wolak, and T. Wood for their comments and support. This work is being partially funded by the National Energy Policy Institute.

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Please contact the author(s) for information about this paper.

Email: aoki@stanford.edu; rothwell@stanford.edu

Asian Development Bank Institute
Kasumigaseki Building 8F
3-2-5 Kasumigaseki, Chiyoda-ku
Tokyo 100-6008, Japan

Tel: +81-3-3593-5500
Fax: +81-3-3593-5571
URL: www.adbi.org
E-mail: info@adbi.org

Abstract

This paper analyzes the impacts of the 11 March 2011 earthquake and tsunami at the Fukushima nuclear power plant in Japan, which were amplified by a failure of coordination across the plant, corporate, industrial, and regulatory levels, resulting in a nuclear catastrophe, comparable in cost to Chernobyl. It derives generic lessons for industrial structure and regulatory frame of the electric power industry by identifying the two shortcomings of a horizontal coordination mechanism: instability under large shock and the lack of "defense in depth." The suggested policy response is to harness the power of "open-interface-rule-based modularity" by creating an independent nuclear safety commission and an independent system operator owning the transmission grids in Japan. We propose a transitory price mechanism that can restrain price volatility while providing investment incentives.

JEL Classification: L22, L43, L94

Contents

1. THREE NUCLEAR POWER PLANT CRISES: THREE MILE ISLAND, CHERNOBYL, AND FUKUSHIMA

An earthquake of a magnitude of 9.0, the second largest in scientifically observed history, and the accompanying tsunami with a surge of more than 12 meters, hit Tohoku, Japan, on 11 March 2011. It triggered the immediate shutdown of nuclear reactors at the power plants owned by Tokyo Electric Power Company (TEPCO) at Fukushima (6 boiling water reactors, BWRs, at Fukushima No. 1, and 4 BWRs at Fukushima No. 2). However, hydrogen explosions and fuel core meltdowns at the No. 1 reactors occurred within a few days because there was no electricity to drive the pumps to cool them. This catastrophe has generated unknown public costs, symbolized by the emissions of Cesium 137, equivalent to 168 times of release from the detonation of the atomic bomb at Hiroshima, although without the immediate loss of life associated with the nuclear accident. (Most of the more than 20,000 deaths from the tsunami were from drowning.)

This nuclear catastrophe has not only generated a global public debate regarding the social costs and benefits of nuclear power generation, but also poses serious engineering and social scientific research questions. In this paper we are concerned with the question of whether the extent of the accident at Fukushima was an inevitable consequence of a natural disaster beyond the "conceivable hypothetical possibilities" ("*soteigai*"), as TEPCO claims; or whether there were inherent contradictions in the structure of Japan's nuclear power industry. What kinds of public policies are needed to deal with the economic and social costs of the catastrophe? How should this industry be restructured to be more robust to extreme shocks and to become more innovative?

Our theoretical framework is comparative so that our treatment is not only relevant to the Japanese situation, but also has relevance for public risk management, for the regulation of integrated monopolies, for innovation in alternative energy sources, etc. To motivate such a comparative approach, we first highlight briefly the causes and behavioral responses to the emergencies during three major nuclear crises: Three Mile Island, Chernobyl, and Fukushima.

On 28 March 1979, an equipment malfunction combined with miscommunication led to the melting of fuel in Unit 2, a light-water-moderated-and-cooled pressurized water reactor (PWR), of the Three Mile Island nuclear power plant that had begun commercial operation three months earlier. The reactor was brought under control within 100 hours without a hydrogen explosion. So when United States (US) President Jimmy Carter visited Three Mile Island on Sunday, 1 April 1979, he was there to raise hope for an anxious nation. He was not there to intervene, but as an ex-nuclear submarine officer, he wanted to show that there was nothing to fear. The interface rules between his function as the US president and the Three Mile Island manager had been promulgated by the US Nuclear Regulatory Commission (NRC) after its inception on 19 January 1975. Jimmy Carter did not involve himself with the decision making at Three Mile Island, or in the investigation of its causes or consequences.

On 26 April 1986, operators of Chernobyl's Unit 4, a graphite-moderated/light-water-cooled reactor (RBMK in Russian) that had been operating since March 1984, were testing the reactor's operating limits under low power. However, to conduct the test, some safety systems were disabled, and operators mistakenly reduced the power to 1%. At such low power, the reactor became unstable, leading to fluctuations in power up to 100 times above normal, causing a steam explosion that blew off the top of the reactor at 01:23:44 (GMT+2). When Mikhail Gorbachev, the last General Secretary of the

Communist Party of the Union of Soviet Socialist Republics (1985–1991), broke his 18-day silence, he was the head of a chain of command that determined on the morning of the accident to cover up information regarding the damages. This cover-up has continued with all leaders of the countries of the former Soviet Union with no accounting of the health of the 500,000 Soviet Army reservists who shoveled chunks of highly radioactive graphite off the Chernobyl site, or the residents of Chernobyl who spent 26 April 1986 absorbing that morning's explosive radioactive release.

In contrast to the previous two cases, the crisis at Fukushima, Japan, was first triggered by a natural disaster. On 11 March, following a magnitude 9.0 quake, TEPCO's boiling water reactors (BWRs) in Fukushima No. 1 Units 1, 2, 3, and 4 began their systematic shutdowns (Units 5 and 6 had already been shut down for refueling). In shutdown mode, cooling water should have reduced the reactors' remaining decay heat. However, it soon became clear that not only was electric power from the transmission grid unavailable because of quake damage, but also that the plant's backup generators had failed during the tsunami.

The imminent question was who had the ultimate authority and responsibility to decide what to do during these critical moments, but this was not clear. Prime Minister Naoto Kan inspected TEPCO's ten BWRs at both Fukushima sites (No. 1 and No. 2) with the plant manager, Mr. Masao Yoshida, giving him his first hands-on experience with nuclear power. (The prime minister had come to distrust TEPCO through his career experience in civic movements and because TEPCO had been caught lying about the quality of Fukushima No. 1 Unit 1's containment in 2002.) Two top managers, Chairman Katsumata and President Shimizu, were out of Tokyo and away from TEPCO headquarters for more than 20 hours after the quake. Between various stakeholders, including the prime minister and his advisors, the Nuclear and Industrial Safety Agency (NISA, see Figure 1), TEPCO headquarters, and Fukushima, there were continuous verbal exchanges, continuous mutual guessing of each others' intentions, and continuous hesitations to disclose unfavorable information or take decisive action; a situation that Mr. Kan described as a "language game" after his resignation as prime minister. During this period of indecision, fuel melted in Unit 1 (11 March, 19:30), hydrogen exploded in Unit 1 (12 March, 15:36), fuel melted in Unit 3 (13 March, 09:00), and fuel melted in Unit 2 (14 March, 20:50); see NEA (2011) and Wikipedia (2011) for chronologies.

On 15 March, during a meeting starting at 05:30, involving the prime minister, his staff, and TEPCO officials, dual hydrogen explosions damaged the containment and roof of Unit 2 (06:10) and in the reactor building of Unit 4 (06:14). It is unclear what TEPCO officials might have known about the state of their melted reactors at the start of the meeting, but with televised explosions during the meeting, the prime minister became furious and sent the minister of the Ministry of Economy, Trade, and Industry (METI) to TEPCO's headquarters to co-chair the committee supervising crisis management with TEPCO's president. While information sharing among stakeholders improved after the meeting on 15 March, the usual method of making decisions in Japan failed in March, and the prime minister resigned in September 2011 under mounting public criticism of his failure to effectively mobilize and coordinate resources to respond and contain the impacts of the disaster.[1]

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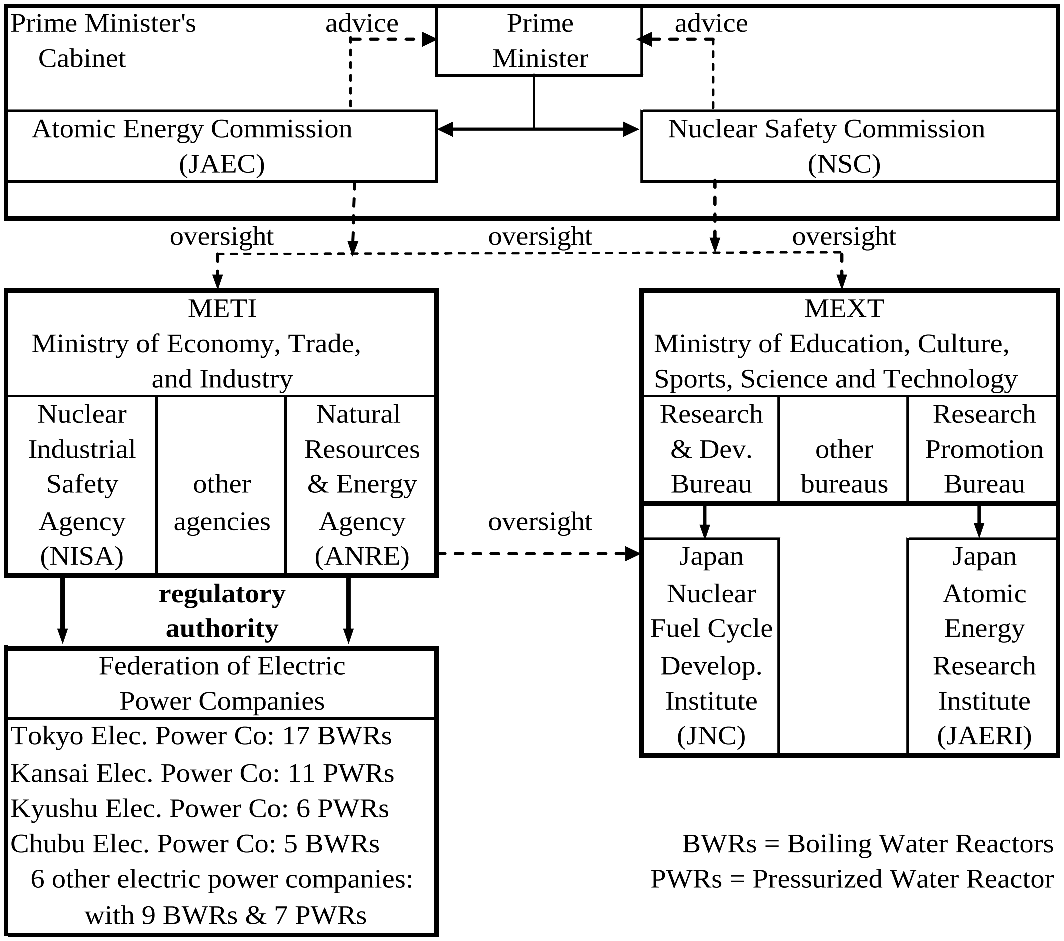
[1] What happened at the Fukushima nuclear plants during the quake and tsunami, as well as the ensuing human errors, are being examined by the "Investigation Committee on the Accident at the Fukushima Nuclear Power Stations" appointed by the Kan government. The committee is headed by a university

Figure 1: Japan's Nuclear Industrial Complex Organizational Chart



Source: www-pub.iaea.org/MTCD/Publications/PDF/CNPP2011_CD/countryprofiles/Japan/Japan2011.htm

2. THREE PROTOTYPICAL ORGANIZATION ARCHITECTURES

These three episodes may be regarded as unique events in extraordinary circumstances, but each of them is indicative of a particular built-in information architecture in and around the respective nuclear power plants, and the associated mode of response to an extraordinary event. To understand their distinct features, imagine a system composed of many units designed for specific tasks or functions with distinct modes of interconnectedness among them. We can identify three modes of system architecture: (1) the "open interface-rule-based modular" mode, (2) the "top-down" or "vertical control" mode, and (3) the "horizontal coordination" mode.

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professor specialized in crisis management, and its members include lawyers, engineers, geologists, and other specialists, who do not have any financial interest in the industry or positions in the government.

In its generic form, the first, modular mode is a system composed of units; each specialized in a particular function and connected through in advance agreed upon interface rules. As long as it is following the rules, each unit can “encapsulate” its function without intervention by other units. The information systemic properties of this mode have been theoretically analyzed by Cremer (1990) and Aoki (2001, Chapter 4), and applied to an interpretation of the post-IBM industrial organization of the information and communications industry by Baldwin and Clark (2000). The idea of modularity can be applied to various levels: the engineering design of a plant, organizational architecture, and industrial organization. At the level of nuclear power plant design, a pressurized water reactor (PWR) can be considered as a set of equipment modules inserted into a nuclear-grade concrete structure. These modules are (1) the reactor, (2) the steam generator, (3) the turbine-generator-condenser, (4) the transformer and electrical equipment, and (5) the cooling and plumbing systems. In recent designs of Small Modular Reactors, based on naval reactors, the reactor and steam generator are being integrated into a single module, which can be installed in increments (45-200 MWe) to more closely match local demand conditions, see Rothwell (2011).

One of the known advantages of the modular mode is its ability to self-organize innovation. Baldwin and Clark (2000) explain how multiple modules pursuing the same function can lead to the selection of the best performing module through evolutionary competition. In environments where uncertainty is very high, a mechanism allowing for duplication, substitution, splitting, and the addition of modules according to open interface rules can create higher option values in spite of the costs of duplication. It is analogous to the gains from multiple experiments when possible experimental outcomes are highly uncertain. An analogy to this is the defense-in-depth in the design of the nuclear plants where multiple backup devices to correct engineering failures are built into the structure, and their operation are successively triggered according to advance design rules. Below, we apply the concept of modularity at the company and industrial levels, and discuss its importance to the safety and efficiency of nuclear power generation.

The second, the “vertical control mode,” is the one most familiar to economists and organizational theorists. It is conceptualized as a system in which constituent units are arranged in a tree structure, and (command and report) information flows only along vertical lines, and rarely across horizontal levels. It is known that such a mode performs relatively well when there is a low degree of uncertainty because scarce information processing capacities are held at the top of the chain of command. However, as can be seen after the Chernobyl explosion, rigorous applications of this mode may not be conducive to dealing with a crisis when speedy use of on-site information is critical, which we will discuss further below.

The third, the “horizontal coordination mode,” at the most generic level is one in which information about evolving environments is shared among constituent units engaged in complementary functions, and decisions on respective outputs are continually adjusted and negotiated among them. The theoretical properties of such mechanisms has been analytically studied by Aoki (1986), Cremer (1990), Alonso, Dessein, and Matouschek (2008), and others. It is known to perform better than the vertical control mode if the environment changes continually, but not drastically and if functions of modules are technologically complementary. Aoki (1990) wrote (emphasis added), “On the other hand, if environments are *extremely volatile or uncertain,* [horizontal coordination mode] adaptation to environmental changes may *yield highly unstable results*.”

Rothwell (1996) empirically tested the relative performance of the horizontal coordination versus vertical control at the level of a nuclear plant and found that the hazard rate of outage is indeed lower for horizontal coordination. Because plants are running a higher percentage of the total time, the horizontal mode is generally superior in the absence of crisis. Rothwell analyzes data on operation and outages from 49 nuclear power *plants* (with most of the nuclear power *units* in the US) between January 1976 and December 1985, and constructs an index of hierarchy based on nuclear power plant organization charts in Olson et al. (1984) from the Final Safety Analysis Reports (FSARs) required by the US NRC. Rothwell estimated parameters that support the proposition that the horizontal mode is associated with longer periods of operation and that the hierarchical mode is associated with shorter periods of outage.

3. THE 3-2011 FAILURE OF THE JAPANESE HORIZONTAL COORDINATION MODE AT FUKUSHIMA

TEPCO is a regional integrated monopoly that supplied 29% of the power supply of Japan in 2010 to 24 million households and more than 2 million businesses in the Tokyo metropolitan area. They own 17 nuclear power units at Fukushima and Kashiwazaki-Kariwa, thermal plants, and the transmission and distribution grids. There was "seamless" horizontal coordination among various power generating plants, transmission, and distribution systems to meet electric power demand under regulated pricing. As a consequence, TEPCO boasted of its "quality of power supply," i.e., the extremely low probability of power outage in response to seasonally fluctuating demand. However, inside the integrated system, we find that the lengths of voluntary and involuntary outages at TEPCO's nuclear power plants have been high, for example, following the earthquake at Kashiwazaki-Kariwa on 16 July 2007, which damaged the plant in ways extremely similar to the quake damages at Fukushima on 11 March.[2] This suggests the existence of ample slack in capacity to sustain the claimed quality of supply. After dozens of nuclear power units were shut down following the 11 March crisis due to breakdowns, precautionary suspensions of operation, and regular maintenance, the total power supply capacity of TEPCO was cut by 25%. The expected power shortage during the summer of 2011 did not occur, and capacity use barely exceeded 90% (which was due to the collective sacrifice of millions of Japanese).

In spite of its apparent performance in the normal state of affairs, however, aspects of the horizontal coordination mode at the corporate and industrial levels that manifested themselves in response to the natural disaster clearly failed to contain its impacts to a more reasonable level. The ambiguity in the decision-making locus and the failure of continuous-negotiation among stakeholders can be most clearly exemplified in the decision to cool reactors with seawater. The New York Times (13 June 2011: A1) published:

[2] Damages at Kashiwazaki-Kariwa, the world's largest nuclear power plant, included water leaks in the reactor buildings; water seal leaks in the reactor core cooling system; oil leaks in the reactor core cooling system pumps; oil leaks in the transformer facility; fires in the transformer facility; loss of power to and from the transformer facility; water leaks in the backup diesel generator facility; loss of power to the liquid waste disposal system; cracks in the cooling water intake system; radioactive contaminated water leaks; and uneven liquefaction under the reactor site. Only two of the seven units at Kashiwazaki-Kariwa have operated since 16 July 2007.

"On the evening of March 12, the Fukushima Dai-ichi nuclear plant's oldest reactor had suffered a hydrogen explosion and risked a complete meltdown. Prime Minister Naoto Kan asked aides to weigh the risks of injecting seawater into the reactor to cool it down. At this crucial moment, it became clear that a prime minister who had built his career on suspicion of the collusive ties between Japan's industry and bureaucracy was acting nearly in the dark…. Based on a guess of the mood at the prime minister's office, the company ordered the plant manager to stop [injecting sea water]. But the manager [Masao Yoshida] did something unthinkable in corporate Japan: he disobeyed the order and secretly continued using seawater; a decision that experts say almost certainly prevented a more serious meltdown and has made him an unlikely hero…. Last week, TEPCO gave Mr. Yoshida its lightest punishment of a verbal reprimand for defying the order."

In responding to unexpected external shocks at nuclear plants, correct and timely human actions at the site are "essential." To make the general definition of human-asset essentiality, due to Hart (1995, see also Aoki 2010, Chapter 2) more specific, human resources at the nuclear plant site are "essential" (or "indispensable") in the event of a sudden, major shock, if the (marginal) effectiveness of top management direction cannot be enhanced only with the hierarchical control of physical assets without complementary inputs of local human resources. If this condition holds so that human resources at the top management and plant level are reciprocally essential, the specific tasks of information processing and decision-making of each level in the event of a sudden shock should be made distinct and their interactive mode should be clearly specified in advance. In this way, expertise at the corporate and plant level are best used in coordinating with each for coping with a crisis without delay and mutual interventions in others' expertise. This is essentially the power of modularity in a highly complex system subject to high uncertainty. But this is possible, provided that the top management is capable of designing required interface rules, on the one hand, and essential expertise is available at the plant level, one the other. The impact of the 11 March disaster was amplified by ad hoc negotiations among multiple stakeholders in the midst of an emergent crisis, some of whom lacked professional knowledge of nuclear engineering or valuable on-site information.

Horizontal coordination may be superior in terms of "just-in-time" coordination in the normal state of affairs, but not in terms of "just-in-case" preparation. Would it be possible then to implement horizontal coordination (with continual information sharing and negotiation among multiple units) in the normal state of affairs, but switch to the modular mode of coordination with the emergence of a large shock? This is unlikely, because actions of constituent units of corporate organizations are normally taken on the basis of their shared beliefs about others' expectations and actions in the normal state of affairs (see Aoki 2010, Chapter 2, on "corporate culture" as a common framework for intra-corporate games). Such a matrix of expectations is not malleable in response to a sudden shock. As chaotic exchanges escalated among the stakeholders after the 11 March catastrophe, they tended to behave as they had been in the normal course of events. If so, how can aspects of the modular mode of coordination in a crisis situation be incorporated into the Japanese power industry in spite of its path-dependent reliance on horizontal coordination within the context of an integrated monopoly? It can be done only through a fundamental institutional innovation made possible by applying the principle of modularity in a broader context of industrial organization and regulation.

4. UN-BUNDLING THE THREE FUNCTIONS OF THE INTEGRATED REGIONAL ELECTRICITY MONOPOLIES

Modularity can be applied to the Japanese electric power industry by splitting the integrated regional monopolies into separate corporate entities based on their functions: generation, transmission, and retail distribution. More concretely, the Independent System Operator (ISO) who owns the transmission grid may be created as a crucial infrastructure, to which potential electric power suppliers, as well as retailers and large corporate customers-cum-independent generators, are to be assured equal accesses under rules that the ISO sets and implements. To avoid problems like those of the 2000−2001 California power crisis, as well as to provide incentives for investments (possibly, including investments in safer nuclear plants), rules for the matching and safety monitoring needs to be carefully designed and implemented by the ISO with the support on information technology (IT), on which we will touch on shortly. We first suggest the way by which a transition to such industrial restructuring may be possible. There were some discussions within the government and METI between the late 1990s and the early 2000s as regards to the possibility of separating generation and transmission. However, it was not materialized by the strong political resistance of TEPCO who argued it being detrimental to the “quality supply of power.” The situation has changed dramatically in the aftermath of the 11 March catastrophe. TEPCO will certainly be short of cash in meeting all the accumulating Fukushima liabilities and the costs of decommissioning the Units 1–4 at Fukushima No. 1, and in the worst case scenario its net assets will become negative.[3] However, coping with this situation through formal bankruptcy procedures will be costly in terms of the public welfare associated with secure electric power supplies and the stability of financial markets (TEPCO is one of the largest corporate bond issuers in Japan, with its outstanding long-term debt of ¥11.3 trillion against its net value of ¥1.6 trillion as of 31 March 2011). Thus, an infusion of public funds into TEPCO is inevitable, for which purpose the “Nuclear Damage Support Organization” was established in September 2011. It is expected that this organization may expend as much as ¥5 trillion.

However, public expenditure on TEPCO need not, and should not, be made to bail TEPCO out of its potential insolvency with its corporate form intact. The Japanese government could purchase (a part of) TEPCO’s transmission grid, and place their ownership and operations in a new corporate entity acting as an Independent System Operator (ISO).[4] As in many European countries, Japan could create a publicly-owned, equal-access transmission system. Public-ownership is based primarily on the

[3] The “Commission for Investigating the Management and Financial State of TEPCO” set up by the Kan administration made public its final Report on 3 October 2011. It estimates the cost of decommission of Fukushima reactors 1–4 at ¥1.081 trillion and one-time costs of compensation for damages at ¥2.61 trillion in 2011, followed by annual compensations estimated at ¥1.24 trillion for fiscal year 2011 and ¥900 billion thereafter. (The cost of decommissioning was estimated by multiplying the cost of decommissioning Three Mile Island by 4 units, plus the extra costs associated with decontaminating the cooling water, etc. On the cost of decommissioning Three Mile Island, see Pasqualetti and Rothwell, 1991). According to a simulation study by its Task Force, the net asset of TEPCO could become negative in 2013 without the operation of the nuclear plants and an increase of retail tariffs. The function of this Commission was absorbed into the “Nuclear Damage Support Organization,” chartered in September 2011.

[4] TEPCO is one of nine regional monopolies in Japan. An ISO may be first created within the domain of TEPCO and, contingent on its success, other regions may follow the suit.

experience in electricity deregulation that the transmission grid is a natural monopoly, unlike generation. See Rothwell and Gomez (2003). Generators of varied types (possibly including existing nuclear plants that will have passed stress tests), as well as regional retail suppliers, may also be independently incorporated. Supplies and demands may be matched through the spot market operated by the ISO. However, to avoid problems like those of the 2000–2001 California power crisis, and to provide incentives for investment in power generating assets, spot markets can be augmented with the following three measures. First, retail distributors and large consumers can be engaged in long-term fixed-cost contracts with supplies to restrain the potential exercise of “short-term” market power by suppliers. In the power industry, suppliers may be able to create monopoly power by creating artificial shortages of supply by deliberately shutting own their plants for unscheduled maintenance, if only the spot markets are to be used (Bornstein 2002; Wolak 2003b).[5]

Second, on the consumer side, consumers can contract for power supply for a specified quantity limit under a fixed price, and pay a current spot market price (e.g., a day ahead price) beyond the limit, while rolling over unused quantities, as in cellphone service (Bushnell, Hobbs, and Wolak 2009). Such dynamic pricing mechanisms can be supported with the introduction of Internet-friendly smart meters. It will certainly motivate consumers’ behavior to respond to changing supply conditions. In the present situation, TEPCO is obligated to meet forthcoming demand under regulated prices to consumers and is being forced to maintain extra productive capacity to avoid power blackouts.

These contractual measures on the supply and demand sides determine an initial position of each player in the market, because consumers in long position can release a part of contractual quantities at spot markets, while supplies in long positions have some commitments. Third, given these positions, competition in electricity supply can be accomplished by first introducing “cost-based dispatch” (Wolak 2003a). In a market with cost-based dispatch modular generating, companies submit their start-up, no-load, and variable costs, or supply schedules contingent on spot market prices, to the ISO. The ISO then requests power per hour from the generating companies’ assets to minimize cost and maximize reliability in meeting electricity demand. The ISO thus facilitates the way to trade energy in the spot market based on marginal cost of generators. Consequently, generators compete based on their cost of production. The clearing price in the spot market is equal to the cost of production of the last generating unit dispatched. For an application of cost-based dispatch in Latin America, see Falconett and Nagasaka (2009). Given the state of information and communication technology, the operation of such smart grids ought to be feasible in Japan.

Further, a disintegrated, modular structure can be innovation and environment friendly. With an electric and information transmission system as an infrastructure of natural monopoly, various power generators, including nuclear, thermal, hydro, solar, wind, geothermal, and other renewables, can be connected as mutually autonomous modules (i.e., as independent corporate entities) and compete for investor attention on a level-playing field. The system as a whole can then self-organize its innovation through

[5] One of the important factors of the 2000–2001 California electricity crisis was the creation of an artificial short supply, engineered primarily by Enron before it declared bankruptcy in September 2001, to aggravate the impact of a shortage of hydroelectricity from the Pacific Northwest due to draught. This caused an 800% price spike in wholesale electricity prices in 2000. See Wolak, Nordhaus, and Shapiro (2000). Simultaneously, a cap was imposed on retail electricity tariffs. As a result, huge losses were incurred by the three regional electricity monopolists in the wholesale market, operated by the California Independent System Operator, and one of them, Pacific Gas & Electric, owner and operator of the Diablo Canyon nuclear power plant, declared bankruptcy in April 2001.

evolutionary selection from among those modules rather than through advanced planning by a corporate headquarters. As Baldwin and Clark (2000) argued, such modular competition in innovation can create option values not possible under a hierarchical corporate control of innovation. Further, modular competition has favorable incentive impacts on each module not available under the integrated corporate system, because the extra innovative effort increases the marginal probability of finding the best technology (Aoki and Takizawa, 2002). Readers can observe that the remarkable speed of innovation in the information and communications industries, as well as in the pharmaceutical industry, in the last several decades is largely owed to the development of modular industrial organizations (e.g., Powell et al., 2005). By competitively linking suppliers and customers through a Japanese electric and information transmission system there will be high-powered incentives for energy conservation, on the one hand, and the development of alternative energy sources and power storage, on the other. Various companies outside the traditional electric power sector may become active players, e.g., members of industries in IT, plug-in automobiles, architectural design and construction, new generations of batteries and electric equipment, etc. The definition of Schumpeterian innovation is "creative destruction and recombination." Unbundling the integrated Japanese electricity generation, transmission, and distribution system of private, regional monopolies, and re-combining human and physical resources in these modules into a system of self-regulating markets with an electric and information transmission system would be institutional innovation in this sense.

From this perspective, one may say that the public debate regarding nuclear energy in Japan in the framework of an all or nothing choice is misplaced, because there could also be a middle way to apply the power of modularity for more effective monitoring of nuclear energy generation and development. A group of nuclear energy plants (or groups of thermal plants) can be modularized as autonomous corporate entities that internalize highly-qualified human resources, subject to transparent rules stipulated by an autonomous regulatory agency. The modular system is thus conducive to shock-resistance, operational efficiency, and innovation at the plant, corporate, and industrial levels, with possible complementarities among them. However, the potential benefits of modularity will not be realized unless it is applied to the regulatory level as well.

In the Japanese scheme of integrated regional monopolies, nuclear plants are placed under a two-tier control by corporate managers and regulators. The TEPCO CEO has never been anyone having primary expertise in nuclear engineering, but someone skilled in government relations, business procurements, etc. TEPCO exercised enormous market power not only as a regulated monopoly in the supply of electric power, but also in terms of enormous purchases in wide-ranging markets, such as industrial equipment, fuel, financial services, real estate, and advertising. They are able to shift cost burdens to regulated tariffs, resulting in electric power prices in Japan that are 50% higher than in the US and the Republic of Korea. The primary concern of the top management of TEPCO has been to secure its position as a regional monopolist, and accumulate monopoly profits. On the other hand, the government safety regulator, the Nuclear and Industrial Safety Agency (NISA), is a division of METI, which promotes nuclear energy development; see Figure 1. NISA cannot autonomously monitor the safety of nuclear power generation and encourage nuclear energy development. There has been implicit and explicit collusion between the regulator and the regulated, entrenching both in a self-promoting "nuclear-industrial complex," as portrayed in Figure 1.

We have suggested that one important factor to control the crisis risk at nuclear plants is to prepare a defense-in-depth, that is, to install modular devices in advance from among which one can be successively mobilized after another fails. One of the human factors that aggravated the impact of the 11 March natural disaster was the failure of this precautionary mechanism, as symbolized by the failure of a backup generator installed close to sea level despite the possible risk of tsunami. Subsequent to the 11 March catastrophe, TEPCO insisted that the size of the tsunami had been beyond any hypothetical possibility ("*souteigai*"). However, warnings of a possible disaster of that magnitude have been published. A historical document, *Nihon Sandai Jitsuroku* (*Japan's Three Emperors' Historical Records*), compiled in 901, recorded a tsunami disaster of similar scale in Tohoku in 895, known now as the Jyokan-Sanriku quake. (It documented that more than 1,000 people died in the disaster; the population of Japan around the year 1000 was about 7 million.) This and other historical data were dismissed by the Japanese government and industry officials as an exaggeration typical of historical narratives. Recent geo-physical research confirmed that tsunamis caused by quakes greater than magnitude 8.0 took place six times in Tohoku during the last 6,000 years.

On the basis of such historical and scientific research, concerns over the inadequacy of defense against a tsunami were expressed by a scientist at official meetings at METI that discussed the safety regulation of Fukushima nuclear plants ("*sogo shigen enerughi chosakai*," in June and July 2009). The warning was not effectively reflected in TEPCO's interim report. According to a recent finding of the Japanese government-appointed committee for investigating the cause of the disaster, TEPCO did a simulation study of the possible impacts of tsunamis with 10–15 meter surges on the Fukushima plant, and reported its results to NISA five days before the 11 March catastrophe. This report and its implications for TEPCO's credibility have not yet been made public.

The defect of placing the regulatory agency under the umbrella of METI has become generally accepted in Japan after the crisis. The government's proposal (to be discussed in the Diet in late 2011) stipulates that a new regulatory agency would be placed under the Ministry of Environmental Protection, absorbing the functions of NISA and some of those in MEXT (see Figure 1). However, it is still problematic to place a regulatory agency under a government ministry, in which the head of the agency reports to a minister. This is so because the safety regulator's decisions could be influenced by interest-group politics, but also because it would be difficult to recruit professional regulators versed in nuclear engineering under the closed personnel rules and practices of the Japanese administration. Japan needs a truly independent regulatory commission without pressure of interest groups, including TEPCO. Without such modularization of regulatory function, safe, reliable nuclear energy development in Japan will be nearly impossible.

5. SUMMARY: TWO MAJOR FACTORS

We have described some of the basic human factors that exacerbated the natural disaster at TEPCO's Fukushima nuclear power plant, transforming it into a catastrophe. There were two major factors: One was the delay of action, such as the opening of vents to release pressure in the reactors to prevent hydrogen explosions, and another was the failure of the reactor cooling systems, leading to reactor nuclear fuel melting. Confused and unstructured information exchanges and negotiations among the various stakeholders, lacking professional knowledge, on-site information, and clear decision-making authority, were responsible for the delay of action. The failure of the cooling systems was caused by mistakes in the risk assessment of possible natural disasters and the consequential failure of defense-in-depth against a massive tsunami. For this, the compromise of public safety to maximize profit by the regional monopoly entrenched within the Japanese nuclear industrial complex was ultimately responsible.

The essence of these problems can be said to stem from an aspect of the coordination mechanism inherent in the Japanese industrial organization, that is, the horizontal coordination mode. In this mechanism, stakeholders or constituent system units, either at the plant, corporate, industrial, or regulatory level, tend to share information relevant to their complementary stakes and be engaged in continual negotiations over them. Such a mechanism may function relatively smoothly and well by fine-tuning reaction to continually and mildly changing environments. However, as theoretical analysis has made clearer, and events such as the Fukushima catastrophe empirically revealed, the horizontal coordination mode may fail in the event of a sudden, major shock. An aspect of an alternative coordination mode may be referred to as the modular mode. In this, modules specialized in specific functions may be interconnected under advance designed interface rules. We discuss reasons why such a mode may perform better in terms of (1) defense-in-depth, (2) response to sudden, massive local shocks, (3) efficient industrial organization in the network industries of electric power and IT, and (4) self-organization of innovation.

We question whether the Japan power industry can be reformed in a direction incorporating some aspects of the modular mode into its traditional horizontal coordination mode. We argue that a solution to the financial difficulties of TEPCO caused by the natural accidents and human errors is to introduce modularity in the electric power industry, beginning with the TEPCO's sale of its transmission assets to the Japanese government. The natural monopoly of transmission grids in public ownership can serve as an infrastructure for introducing and developing aspects of the modular mode of industrial organization to make the Japanese power industry safer, more efficient, more innovative, and more environmentally friendly. In conjunction with such industrial reform, the regulatory mechanism should be reframed by making the regulatory agency truly independent and professional. This is another application of modularity, in this case at the level of public policy.

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