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The Japanese Electricity System 15 months After March 11th 2011

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Keywords **Public Policy; Nuclear Power; Energy Conservation**

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The Japanese Electricity System 15 months after March 11th 2011

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Abstract

The Great East Japan earthquake and tsunami on March 11th 2011 caused mass destruction, significant loss-of-life and a large displacement of people. It also placed significant strain of Japan's electricity-generating infrastructure. There was a significant reduction in capacity due to the damage in thermal generation and gradual closure of Japan's nuclear power plants; the ability for load-balancing across the Japanese grid was compromised due to limited interconnections between the different utilities that comprise the Japanese electricity system. This paper looks at the first fifteen months following the earthquake and tsunami: outlining the supply reduction and consequent attempts to manage the demand. In turn it highlights the foibles of Japan's vertically-integrated monopolistic structures and the evolution of governmental and utilities response that went from decisions made "on-the-fly" to a more developed policy for peak-demand electricity savings. The findings from this paper should serve as a useful set of examples to aid decision makers in contingency planning for disruptive large-scale reduction in electricity-generating capacity.

Keywords chosen from ICE Publishing list

Public Policy; Nuclear Power; Energy Conservation

List of notation

ANRE: Agency for Natural Resources and Energy
FEPC: Federation of Electric Power Companies
IEEJ: Institute of Energy Economics Japan
JAPC: Japan Atomic Power Company
METI: Ministry of Economy, Trade and Industry
NPAJ: National Policy Agency of Japan
OECD: Organization for Economic Co-operation and Development
RBA: Reserve Bank of Australia
RITE: Research Institute of Energy Technology for the Earth
TEPCO: Tokyo Electric Power Company
TMG: Tokyo Metropolitan Government

1. Introduction

At 14:46 JST on Friday March 11th, a magnitude 9.0 earthquake occurred off the coast of Japan. It was the most powerful earthquake ever to have hit Japan and one of the five most powerful anywhere since modern records began in 1900. A powerful tsunami was triggered that rose 40.5 metres and in places along the eastern Japanese coast travelled 10 km inland. A recent (2014) World Bank publication notes the earthquake yielded an estimated 18,571 deaths, with 2,651 missing; with an estimated economic cost of ~US$210 billion [1], it is one of the most expensive natural disasters in history.

For various reasons March 11th precipitated an immediate crisis of electricity supply, requiring the Government and utilities to manage an adjustment of demand and scrape together additional supply sources. In the aftermath, policy decisions that were made in response to the crisis may have significant long-term implications. From the first days after the catastrophe in March 2011 until the unprecedented bailout of TEPCO in the spring of 2012, the crisis has breached the 50-year-old utility-government nexus, and further damaged the public's confidence in Japan's “nuclear village”.

This paper highlights the immediate challenges that faced following the Great East Japan Earthquake and summarises the main events that took place from March 2011 to May 2012. Section 2 details the supply-side of the Japanese electricity industry; it exposes the singularities of the electricity grid, quantifies the capacity shortage following “The Great Earthquake” and addresses the supply-side recovery and the challenges that faced the summer of 2012 for the power sector. Sections 3 and 4 address the demand management and demand reduction measures, respectively, that lead to the Japanese Electricity System being able to cope with the summers of 2011 and 2012. How these measures described in this work have affected Japan’s long-term energy policy has been explored in detail in the subsequent work of Grimston et al. [2].

2. The Japanese Electricity System Prior to March 11th 2011

Figure 1 provides a schematic overview of Japan’s electricity infrastructure before March 11th 2011. It comprised (and still comprises in 2014) separate Eastern and Western grids operating at different frequencies: East Japan, including Tokyo, operates at 50 Hz whereas West Japan (i.e. Osaka) operates at 60 Hz. This unusual division of the electric grid is a pure product of history: in the 19th century, Tokyo’s electrical entrepreneurs installed 50 Hz generation equipment mainly from Germany while their counterparts in Western Japan bought 60 Hz equipment from the United States [3]. Furthermore, the power exchanges between the two grids are limited by the capacity of the existing interconnections. Prior to 2011, only three frequency converter facilities were in operation with a total conversion capacity of 1,130 MW [4].

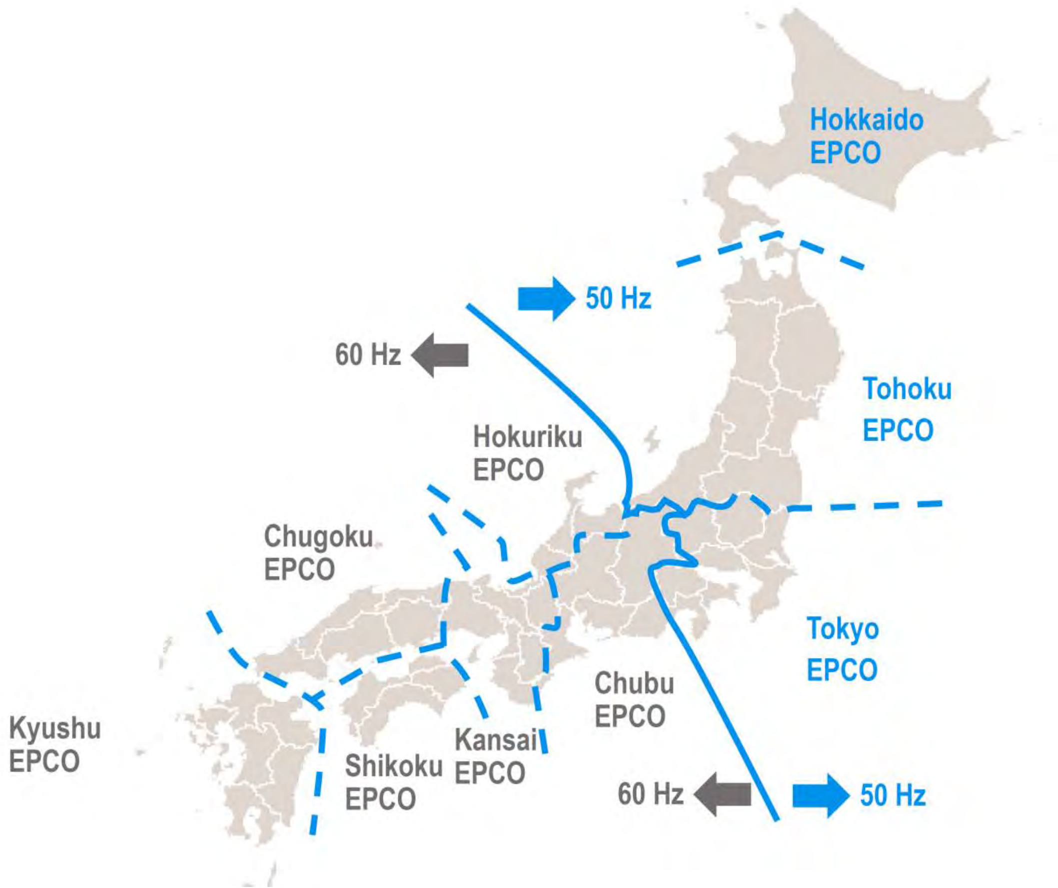

Figure 1: Japan's Electric Companies (Excluding Okinawa EPCO). Figure Adapted from Ref. [5].

In addition to the divide between Eastern and Western grids, Japan's electricity system is further divided regionally. Ten privately-owned electric power companies, also called General Electricity Utilities, were (and in 2014 still are) in charge of regional power supply services. Each utility was structured as a vertically-integrated regional monopoly, responsible for supplying electricity from power generation to transmission and distribution to their consumers in their respective service areas [6]. The ten utilities controlled 97% of the market for electricity generation and transmission [7] and, in FY 2009, sold 858.5 TWh of electricity [4]. TEPCO, which includes Tokyo in its region of supply, served ~29 million customers and was the world's largest privately owned electric utility in 2011. In FY 2009, its total sales of electricity amounted to 280.1 TWh [8]. Furthermore, wholesale electric utilities, i.e. businesses having supply capacity of 2 GW and above (mainly J-Power and JAPC), also supplied electricity to these utilities and in some areas operated their own transmission infrastructure [9].

For a long time, the utilities had total monopoly control in their respective service areas. However, the 1995 revision of the Electric Utilities Industry Law (along with two later revisions) introduced the liberalisation of power generation and partial liberalisation of retail sales [9]. These changes in the regulatory environment resulted in wholesale suppliers and power producers and suppliers (PPS) entering the market. Wholesale suppliers, like independent power producers (IPP), supply electricity to the General Electric Utilities, contracting with them for the supply either 1 GW or more for at least ten years or 100 GW for at least five years. PPS act as brokers, buying electricity (mostly from manufacturers that generate their own) and selling it to commercial customers. They nevertheless depend on utilities' power line networks [10]. The relation of Japanese electric power businesses to each other are presented in Figure 2.

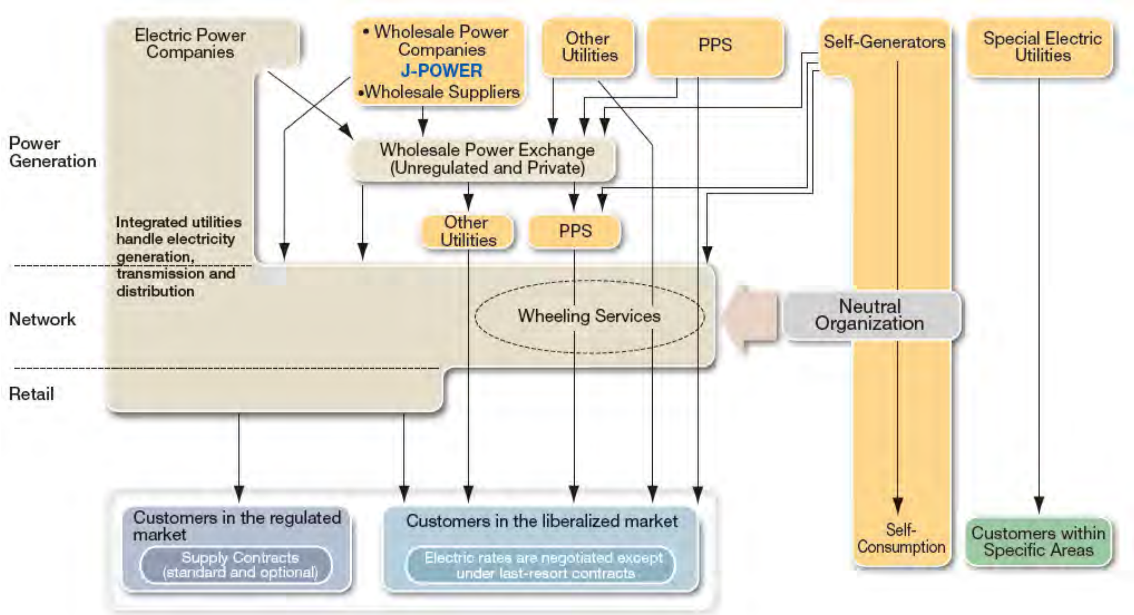

Figure 2: Japan's Electric Power Infrastructure (from April 1 2005). Figure Adapted from Ref. [11].

Even with liberalisation, the utilities remained very powerful. TEPCO was the most powerful and has had great influence on the country's affairs, notably through its direct links to METI, other government regulatory bodies, and influence within the Keidanren, a business lobby representing the voice of large Japanese corporations [12]. TEPCO also had a great deal of political power, see e.g. [13].

Table 1 shows the power generation by energy source for the country and each EPCO for 2010. Before the earthquake Japan was dependent on imports for 96% of its primary energy supply, or 82% if nuclear is classed as 'domestic' energy [4]. Therefore, Japan's energy supply structure is vulnerable to volatility in the global market even though it is today the country with the lowest primary energy consumption by unit of GDP [14]. As highlighted in Table 1, the mix of energy sources can vary significantly between the different utilities. Prior to March 11th 2011, Japan had a total installed generating capacity of 223.6 GW (including the ten EPCOs, J-Power and JAPC) with the capacity margins for each EPCO ranging from 0% to 30%. In FY 2009, TEPCO had a third of the production capacity of the country with 64.5 GW installed – i.e. equivalent to Italy's capacity, and operated 160 hydropower stations (9.0 GW), 26 thermal power stations (38.2 GW) and seventeen nuclear reactors in three nuclear plants (17.3 GW) [8]. In addition to its own capacity, in 2010, TEPCO bought 13.1 GW from wholesale electric utilities and IPPs, setting its total power sales at 77.6 GW [8].

Table 1: The Generation Mix, Supply Capacity and Peak Demand for Japan, its Ten EPCOs for FY2010 and Two Wholesale Producers [11,15,16].

Electric Power Company	LNG	Nuclear	Coal	Hydro	Oil	Renewables	Total Capacity (GW)	Peak Demand (GW)
Hokkaido	0%	44%	31%	15%	8%	2%	7.4	5.7
Tohoku	22%	26%	34%	13%	3%	2%	17.2	15.6
Tokyo	45%	28%	10%	6%	10%	1%	65.0	60.0
Chubu	48%	13%	26%	9%	3%	1%	32.8	27.1
Hokuriku	0%	28%	44%	24%	3%	1%	8.1	5.7
Kansai	20%	44%	21%	10%	5%	1%	34.9	31.0
Chugoku	19%	3%	58%	6%	13%	1%	12.0	12.0
Shikoku	5%	43%	36%	9%	6%	1%	7.0	6.0
Kyushu	19%	39%	27%	5%	7%	3%	20.3	17.5
Okinawa	0%	0%	77%	0%	21%	2%	1.9	1.5
10× EPCO total	30%	29%	24%	9%	7%	1%	206.6	177.8

Wholesale Power Company	LNG	Nuclear	Coal	Hydro	Oil	Renewables	Total Capacity (GW)	Peak Demand (GW)
JAPC	0.0%	100%	0.0%	0.0%	0.0%	0.0%	2.6	
J-Power	0.0%	0.0%	49.5%	50.4%	0.0%	0.1%	17.0	
Others (PPS, etc.)							13.6	

2.1 The Great East Japan Earthquake and its Impact on Japan's Electricity Infrastructure

From a power generation perspective, the earthquake and tsunami mainly affected TEPCO, Tohoku EPCO, and the independent producer Japan Atomic Power. Contrary to common belief, the capacity loss following the March 11th 2011 natural disaster affected not only nuclear capacity but also thermal capacity [17] as shown in Table 2.

Table 2: Generating Capacity Affected by the Great East Japan Earthquake [17].

	Tohoku EPCO	TEPCO
Affected by earthquake		
Thermal capacity	6.1 GW	8.4 GW
Nuclear capacity	2.2 GW	10.2 GW
Seriously damaged		
Thermal capacity	3.4 GW	2.6 GW
Nuclear capacity	—	4.7 GW

Overall, five thermal power stations were damaged and eleven out of fifteen nuclear reactors in the region were immediately shut down, with the other four already being offline for maintenance [17]. Eight of them were safely brought to cold stop conditions but a series of incidents occurred at Fukushima Daiichi No. 1–3, leading to the subsequent nuclear accident. At the time of the earthquake, TEPCO's generating capacity was 52.0 GW [18]. The earthquake and following tsunami affected 18.5 GW of the generating capacity (i.e. 29% of its total capacity of 64.5 GW), of which 7.3 GW (11.3%) were destroyed or seriously damaged [17]. Similarly, of the 21.2 GW generating capacity of Tohoku EPCO, 8.3 GW (39.3%) were affected by the natural disaster and 3.4 GW (16.0%) were seriously damaged. Overall, 10.7 GW (i.e. 5.2% of Japanese utilities' capacity) would be lost indefinitely. In addition to the generating capacity, six oil refineries in the region were affected by the earthquake and tsunami along with the Sendai LNG receiving and regasification terminal [17].

Further to the physical damage caused by the Earthquake, two external factors added to the loss of installed capacity: (1) the nuclear power plants struggled to immediately resume operation (as detailed below), and (2) there was limited exchange of electricity due to lack of electricity interconnections between the 50 and 60 Hz grids — according to an executive within Mitsubishi Electric Power Products, the Western utilities could have covered TEPCO's peak demand but, owing to the lack of interconnections, they could only supply up to 1 GW [19].

On May 6th 2011, Prime Minister Naoto Kan requested the suspension of the Hamaoka nuclear plant operated by Chubu EPCO [20]. The plant was believed to be vulnerable due to its location in a particularly seismically active area. Chubu EPCO accepted the request and closed the plant on May 15th. Although Prime Minister Kan specified that Hamaoka was an exceptional case, many nuclear reactors were already off-line for maintenance at the time of the earthquake or for planned maintenance afterwards — i.e. every thirteen months of operations, plants stop for refuelling and maintenance for two months. The closure of Hamaoka plant snowballed into a freezing of plant restarts throughout the country as local ("prefectural") governments exercised their veto power due to heightened and politicized safety concerns [20]. In Japan, authority over nuclear policy is highly fractured. Provincial governors have veto power regarding proposals for construction of nuclear plants, alteration and operation [21]. Local governments used their power to voice anxiety fuelled by the uncertainty around the Fukushima Daiichi nuclear accident and the rationale of shutting down Hamaoka at the time. Therefore, the number of reactors in operations began decreasing. In May 2011, only 22 nuclear reactors out of 54 were still operating and the number was down to sixteen reactors by July 2011. In particular, TEPCO was left with slightly less than 5 GW in view of the summer peak compared with its 2010 total nuclear capacity of 17.3 GW. Figure 3 shows the steady decline in the number of nuclear reactors in operations. The last reactor still operating was shut down on May 5th 2012 [22]. Whilst Ohi 3 and 4 briefly resumed operation, Japan has not restarted any of its nuclear power plants since May 2012, as detailed in [2].

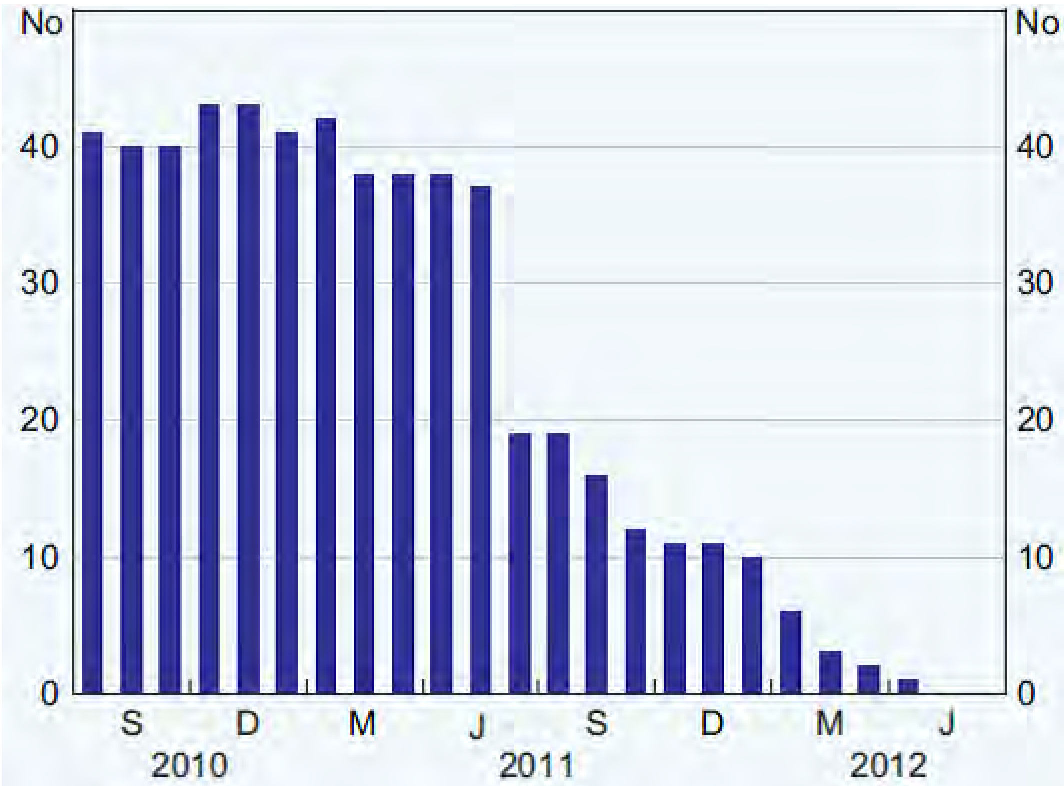

Figure 3: Japanese Nuclear Reactors Online as of May 2012 [23].

2.2 Planned Supply Recovery in View of the Summer 2011 Peak

As Japan's peak demand of electricity occurs during the summer, TEPCO and the government devised an action plan for supply recovery during the spring of 2011 in order to recover the maximum generating capacity before the summer peak.

2.2.1 Measures taken by TEPCO

In order to recover the maximum generation capacity before the summer peak, TEPCO undertook four main measures:

(1) Restoring three thermal power stations at Hirono, Hitachinaka and Kashima that were severely affected by the earthquake [24]. Hitachinaka (coal plant, total output 1 GW) and Kashima (heavy and crude oil, 4.4 GW) resumed operations by mid-May 2011. All units at the Hirono power plant (heavy oil, crude oil and coal, total generating capacity of 3.8 GW) had resumed operations by mid-July 2011. Overall, this allowed TEPCO to recover 9.2 GW by July.

(2) Restarting Yokosuka thermal power station which had undergone a long-term suspension since April 2010. This allowed TEPCO to add ~0.9 GW of capacity [24].

(3) Installing emergency power supplies in the form of gas turbines and diesel generators on the premises of existing thermal plants [24]. On May 13th 2011, TEPCO was confident that it could install 1.5 GW by August 2011 [25]. New power supply facilities were procured not only in Japan but also overseas and then urgently installed wherever possible in existing thermal stations.

(4) Intensive use of existing thermal plants and in particular LNG and oil-fired thermal plants [23]. Figure 4 shows the average utilization rate of thermal power plants (usually used as middle to peak load supply) increased by ~150% by February 2012.

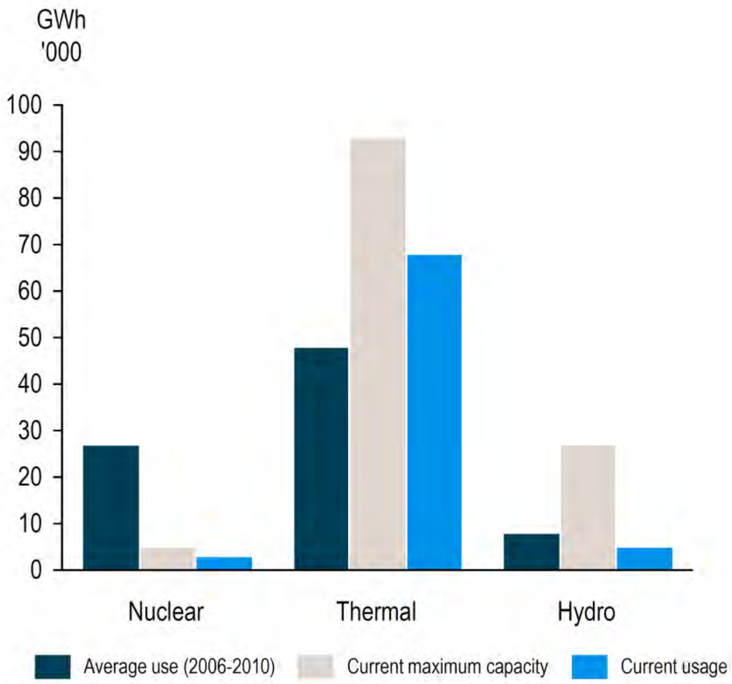

Figure 4: Usage of Power Plants One Year after the Great East Japan Earthquake. Figure Adapted from Ref. [23].

Measures (1)–(3) enabled TEPCO to recover ~11 GW by mid-July 2011, restoring its generating capacity to 55.6 GW. However, measure (4) turned out to be the most important factor to support the supply recovery.

These actions were to some extent made possible by the structure of the Japanese electric power business. Indeed, as a monopoly with limited interconnections, TEPCO required its own reserve capacity, explaining why such capacity could rapidly ramp up their production.

2.2.2 Measures taken by the government

The government also undertook different legal actions to support TEPCO in its supply recovery efforts.

(1): the Japanese government relaxed two main pieces of regulation: (a) the application of the Environmental Impact Assessment Act to additional emergency thermal power supply facilities was waived [26] — that is to say that the environmental impact was not a necessary consideration in the design phase of these emergency facilities; and (b) the postponement for up to one year of periodic inspections of thermal plants under the Electricity Business Act. This prevented additional plants from going off-line for maintenance and inspection during the summer peak [26].

(2) METI requested companies with private power generation capacity to sell their electricity directly to TEPCO. In addition, the promotion of private power generation provided grants to cover the installation of generating equipment and the fuel costs [26]. As a result, TEPCO received 1.6 GW of additional electricity from the 10 GW of installed private capacity in its service area (and Tohoku EPCO received 0.2 GW from the 4 GW installed). However, some critics have argued that measures taken to source private power generation capacity destroyed competition. Private generators were unable to take advantage of TEPCO's capacity shortage to gain market shares as they had to sell their electricity to TEPCO, evidencing the influence of TEPCO. Some companies like Ennet even had to sell at a lower price than what it charged its own customers, leading to monthly losses of $130,000 [10].

2.3 Power supply outlook in view of 2011 summer peak

During spring 2011, TEPCO published monthly press releases presenting its actions taken to recover supply and the estimation of its supply capacity for the summer 2011. Hence, on April 8th, it estimated it would have re-established its generating capacity at 46.5 GW. By mid- May, it re-estimated its summer capacity at 55.2 GW [18]. Taking into account the 1.4 GW power transfer to the Tohoku region which contained many disaster-stricken areas, TEPCO's predicted supply capacity in view of the summer was of 53.8 GW and was the basis of its policy package to reduce electricity demand.

With the shutdown of nuclear plants, the installation of new thermal power supplies and the more intensive use of existing thermal plants, Japan's LNG imports increased by 13.5% from 2010 to 2012, and overall fossil fuel requirements for electricity generation increased by 45% [27], which matched mid-2011 predictions detailed in Figure 5. Japan managed to secure extra supplies of fossil fuels, notably LNG, thanks to the immediate offers of foreign governments and LNG sellers of countries including Qatar, Russia, Australia and Indonesia [28]. Qatar delivered nearly 12 million tons (~150% increase from the previous year), accounting for the largest portion of the increase in Japan's LNG imports [27]. Simultaneously, Japanese companies including Tokyo Gas, Osaka Gas, Chubu Electric and Chukogu Electric, as well as Korea's KOGAS diverted their LNG cargoes to TEPCO [28]. At the end of 2011, total power production in Japan stood at 188.8 GWh of which hydropower represented 6.3% (cf. 6.2% in 2010), thermal 83.1% (cf. 57.7% in 2010) and nuclear 10.3% (cf. 35.7% in 2010), meaning a significant shift to fossil fuels.

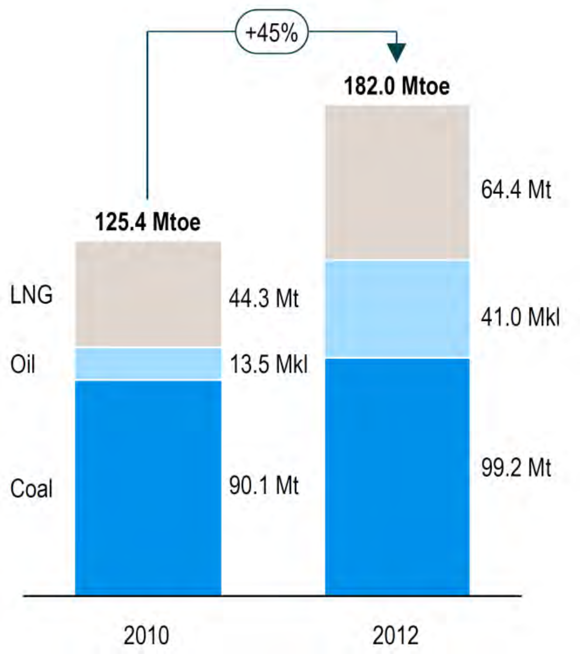

Figure 5: Mid-2011 Predictions of Increased Fossil Fuel Requirements for Electricity Generation for 2012. Figure Adapted from Ref. [29].

It was posited that if the Japanese nuclear plants did not resume operations while the yen depreciates as observed recently, the value of Japan's LNG imports would increase by +86% from ¥3.5 trillion (€35 billion) in 2010 to ¥6.5 trillion (€65 billion) in 2012 [27]. To cover the higher cost of thermal generation, which added ¥830 billion to its electricity bill, TEPCO announced on January 17th 2012 that the electricity price for large commercial users would increase by 17% as of April 2012. During 2011–2012, TEPCO were expected to apply for regulatory permission to increase rates for residential users (permission that is not required for the larger users) [30].

Even with the increase in fossil-fuel generation over 2011, power shortages were expected for five utilities for Summer 2012, as detailed in Table 3; although as detailed in Ref. [2] these shortages were successfully circumvented.

Table 3: Original Estimates for the Predicted Shortfall of Electricity Supplies in Summer 2012 [31].

	Estimated Capacity (GW)	Estimated Demand (GW)	Nuclear Share	Shortfall Margin
Hokkaido	4.7	4.8	34.1%	-2.1%
Tohoku	14.9	14.2	21.6%	4.7%
Tokyo	51.9	57.4	27.9%	-11.0%
Chubu	27.5	26.5	13.3%	3.6%
Hokuriku	5.7	5.3	35.0%	7.0%
Kansai	25.3	29.6	45.1%	-17.0%
Chugoku	12.3	11.5	14.6%	14.0%
Shikoku	5.3	5.7	40.6%	-7.5%
Kyushu	15.3	17.1	41.6%	-11.8%
9× EPCO total	163.0	172.3	29.2%	-5.7%

3. Japanese Government's Demand Management

Beginning with the immediate fortnight after March 11th 2011, there is a sharp contrast between the chaotic first ten days of electricity supply management and the systematic planning for a comprehensive and effective policy package to cut demand for summer 2011. From March 11th to 24th, the Japanese government committed to the recovery of the damage-stricken region of eastern Japan. The quick fossil-fuel ramp-up proved the existence of well-designed contingency plans for power plants. However, the Government struggled to set up a crisis management plan for the drop in electricity generation capacity. Had this contingency plan been ready in advance, the Government and TEPCO would have been saved a substantial amount of time and embarrassment.

The decision-making bodies were initially overwhelmed by the scale and complexity of the crisis during the first two days. Whilst the loss in capacity would have put any government into an emergency state, the power generation capacity loss was a minute concern compared to the loss of life and infrastructure magnitude of damage caused by the earthquake and tsunami that overwhelmed the government. Furthermore, TEPCO's top executives were away from their offices when the utility was stricken by the catastrophe — at a time when leadership was most needed. In fact, the firm's top two executives did not arrive at the Tokyo headquarters until roughly 20 hours after the earthquake [32]. As a result of these combined factors the whole area of northern Tokyo was subject to unplanned blackouts. TEPCO and Tohoku Electric Power (TEP) reported that a combined seven million homes were without electricity at the height of the event, including at least four million in and around the greater Tokyo metropolitan area [33]. According to official figures, this represented approximately 19 million people without power (almost 15% of the Japanese population).

On March 14th 2011, the Government and TEPCO met to plan rolling power outages. Although these outages were necessary, their design reveals the technical unpreparedness of TEPCO, and added electrical chaos to the already catastrophic situation. In order to lower the social cost of the power outages, METI announced a plan for rolling power outages on Sunday March 13th just after midnight- without providing any explanation to the public for the rationale of such an announcement [34]. These outages were implemented as follows: consumers in TEPCO's jurisdiction were divided into five groups that corresponded to existing cells of the network. The electricity supply was stopped in one group after another according to a predetermined schedule (the period from 06:20 to 22:00 was divided into five zones and blackouts were conducted for three hours at most) [34].

The government asked TEPCO not to implement shortages in the central Tokyo grid cell because of the presence of central Government offices and many company headquarters; however, no distinction was made within other cells and critical facilities were deprived of electricity [35]. On March 14th, the Ministry of Health declared that small clinics might be compromised by the blackouts; disruption was also expected for railway and traffic management services [36,37]. Hence, TEPCO had the ability to control the implementation of blackouts at the grid-cell level but not at the sub grid-cell level. It took them two additional weeks to refine their outage planning so as to spare areas of industrial interest [38]. Once again these distinctions could have been made earlier had TEPCO devised a capacity drop contingency plan.

The consequences of this unpreparedness were combined with a lack of appropriate communication. First, the government failed to explain the situation to the population and justify the implementation of blackouts. Two weeks afterwards on March 24th, the first official meeting of the government about the electricity crisis took place [38] where the Government declared that they had “no other reliable means to curb electricity demand” because power consumption had to be restricted at the peak only and it did not have the power to force households and small retailers to cut their demand [39]. Second, as it was learning how to manage the crisis in real time, it gradually appeared to METI that the population needed further information as to how the blackouts were to be implemented.

Had METI and TEPCO prepared an emergency procedure to setup power outages, these measures could have been implemented from day one, and would have limited the negative reputational cost. From hereafter, the PM cabinet seconded by METI, took control of the situation. METI implemented a survival power outage scheme, which prevented the whole region from diving into the dark again following those first few days. Since the electricity supply and demand crisis was just a minute part of the picture, it is understandable that a polished communication plan on blackouts was neither the priority of the Government nor TEPCO. But had the stakeholders already devised a capacity drop emergency plan, exceptions could have been set up more expeditiously and fairly, and the population would have been much better informed. On March 24th, the Government met and decided that there should be two more weeks of outages (with improved planning on the grid sub-cell level) and was forced to acknowledge that the country was about to face an unprecedented challenge of surviving the summer demand peak without power outages.

On March 25th, 14 days after the catastrophe, METI held a meeting about TEPCO's capacity recovery and established the Electricity Supply-Demand Emergency Response Headquarters (ESDERH) led by the Chief Cabinet Secretary, including the Agency for Natural Resources and Energy (ANRE), the National Public Safety Commission and TEPCO experts. The ESDERH mission was to devise a policy package by the end of April 2011 to drastically change the electricity demand structure so as to avoid power outage enforcement during the summer [39].

3.1 Mobilisation for Summer 2011

As a result of the 2011 crisis, the IEA updated its series of guidelines for policy makers to achieve large-scale demand-side electricity savings as quickly as possible [37]. Although the policy package devised in Japan was reasonably in-line with the best practices recommended by the IEA, better communication of data between stakeholders could have improved the process.

The first step of these guidelines involves determining of the cause and duration of the shortage. In this case, the Tohoku earthquake caused a capacity shortage (as opposed to an energy shortage when demand exceeds energy input available for electricity generation). The recommended response is a focus on load shifting, that is, a reduction of the electricity consumption only during peak hours, when the supply-demand balance is jeopardized. Initially, this was what the Government attempted to do but a more substantial plan was needed for the longer-term management of the system. The second step involves identifying opportunities for electricity savings. The Japanese Government encountered two major difficulties: (1) sector-specific data was not immediately available and so the energy saving campaign could have been implemented much faster [37]. To address this problem of limited sector-specific data, the government convened periodic meetings with groups of outside researchers, government energy officials, and TEPCO staff to estimate load curves, predict energy-savings potential for each sector and develop specific recommendations for saving electricity. (2) Japan was already an energy efficient country with the lowest energy supply per unit of GDP, about 20% lower than the OECD average [40]. METI was thus facing a tough challenge.

The IEA proposed a series of five tools for governments to save electricity, some of which were used by the Japanese Government:

1: Price signals (time-of-use pricing, real-time pricing, and critical-peak pricing). Only the biggest electricity customers had access to the requisite metering technologies therefore the Government chose not to implement this measure.

2: Behaviour change campaigns. The Japanese Government made extensive use of various behavioural campaigns as detailed in Section 4.2.

3: Market mechanisms (such as consumption rationing and credit trading). The Japanese Government did not use these schemes that might have enabled companies to sell low-value consumption credits to others.

4: Rationing (both targeted and/or general). The Japanese Government considered these measures as a safety net only — as although some rationing strategies are less disruptive than others, it is a less desirable of a tool than others.

5: Technology replacement (generally for long-term savings). Japanese LED-lighting sales reached 40% of market share, double the pre-crisis share, and for the first time surpassed incandescent lamp sales [37].

By Mid-May — much behind the expected schedule — METI came out with the definitive forecast shown in Figure 6. In Tokyo, the expected supply and demand gap was -10.3% compared to 2011. Rolling blackouts were considered the worst possible outcome [39], therefore any demand reduction needed to ensure a 5% safety buffer. Overall, it meant that demand reduction had to be 15% for the whole country.

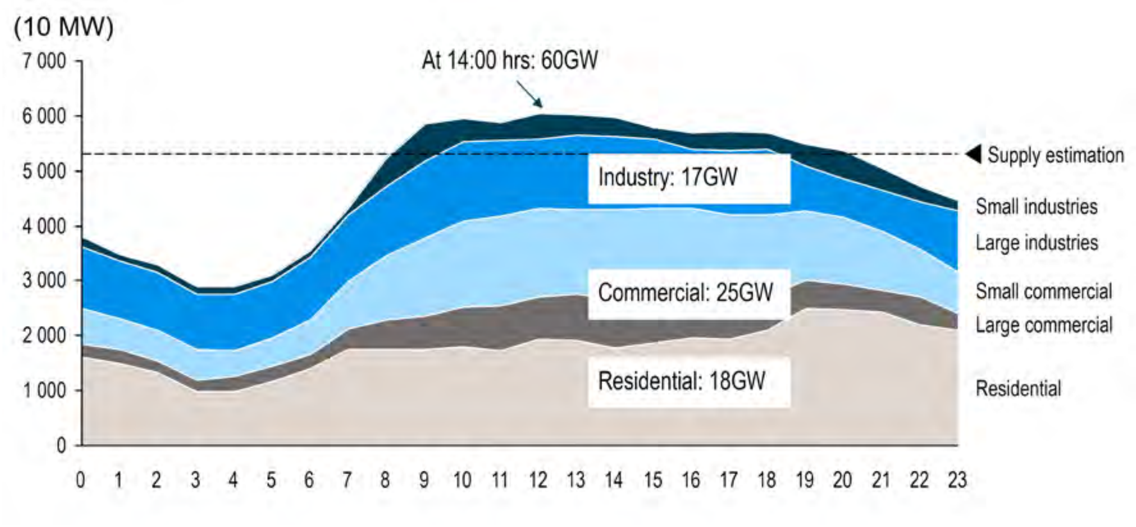

Figure 6: Estimation for Electricity Supply and Forecasted Demand in the TEPCO Service Area for Summer 2011. Figure Adapted from Ref. [37].

3.2 The Policy Package

As a result of TEPCO's huge efforts to recover supply capacity, the reduction target was eventually set to 15% from July 1st to September 22nd on business days from 09:00 to 20:00 [41]. Albeit necessary, the target was overly ambitious because the Government hardly had the legal means to enforce it beyond large electricity consumers.

In Japan, there is a legal difference between the different types of electricity customers. According to Article 27 of the 1964 Electricity Business Act [42], only large electricity contractors (>500kW) can be legally required to reduce their consumption. In cases where the target is not met, the Government sets a fine of more than ¥1 million (£7,600) per hour. There were exceptions such as disaster stricken zones and specific industries [28]; a lower reduction target (5–10%) was proposed for particular end-users such as hospitals, nursing homes, public transport and water utilities [37]. For smaller electricity contractors (<500kW), METI only played an educating role and targets were not mandatory [43]. METI also held educational workshops in small business offices. Finally, the government promoted casual and cooler clothing through the ‘Super Coolbiz’ campaign which aimed at reducing energy consumption of air conditioning systems by asking office workers to change their fashion habits [44]. For the domestic sector, the Government prepared a “Menu for households to save electricity” [26] and launched a public information campaign including newspaper, TV and internet advertisements. It even asked households to commit to a “Home Electricity Saving Declaration” featuring ten measures to achieve the 15% reduction that could be taken concerning different appliances commonly found in Japanese homes: air conditioning, refrigerators, lighting, television, toilet seats with warmers and water spray functions, and rice cookers [45]. A power-saving contest in the residential sector was also created, rewarding customers for meeting their energy-saving targets [37].

4. The Process of Electricity Demand Reduction

A maximal demand of 60 GW was observed on July 19 2010. TEPCO forecasted that its supply for summer 2011 would be 53.8 GW (a -10.3% capacity margin). As shown in Section 3.2, the Japanese authorities decided to aim at a 15% demand reduction during summer 2011, dividing demand into three main categories: large consumers (15% mandatory reduction), small businesses, and households (15% reduction requested for both). Figure 7 shows the peak electricity demand in 2011 cf. 2010, and the important reductions observed in the Tokyo and Tohoku regions.

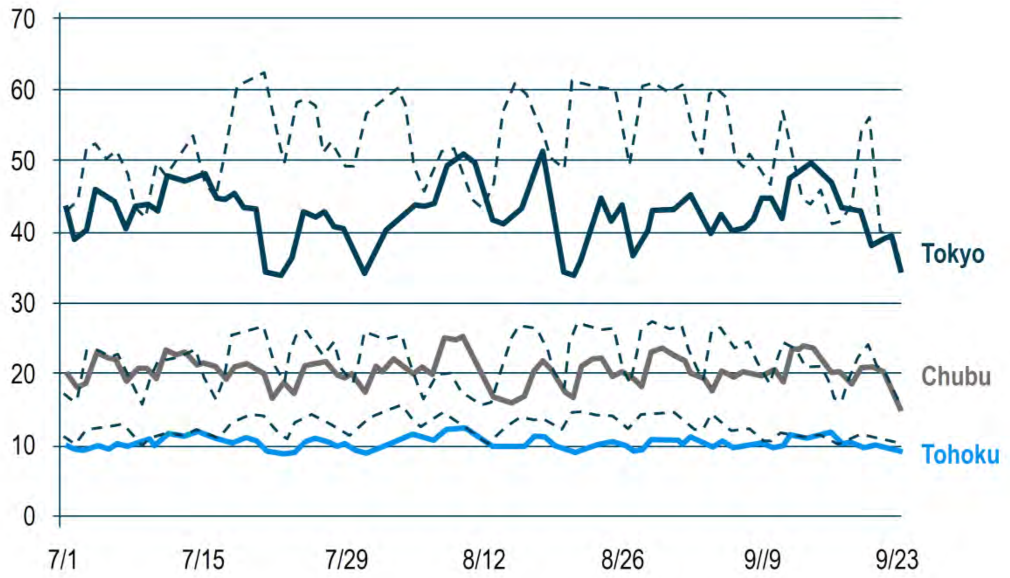

Figure 7: 2011 Peak Electricity Demand (GW), Compared with 2010 Peak Demand (dotted). Figure Adapted from Ref. [46].

Overall, the actions taken by the government were successful as the initial 15% reduction target was achieved. With that said, the summer of 2011 was colder than the summer of 2010. Therefore, it is difficult to determine precisely the effectiveness of Japanese users' efforts to lower their electricity consumption because air-conditioning accounts for an important part of electricity consumption. In that perspective, Nagatomi, a researcher at IEEJ, has estimated the net electricity saving rates based on an analysis that corrects for the differences in temperature in the Tokyo and Tohoku regions [27]. The results are presented in Figure 8, which shows that the temperature had a strong impact in August 2011, since it accounted for ~25% of demand reduction. In June and July, though, it still helped to reduce consumption and the temperature's share in total reduction was lower. The achieved demand reductions vary from one sector to another: household reductions ranged from 6–11% (cf. 15% target); Small businesses achieved with a 19% reduction (cf. 15% target); large consumers achieved a 27–29%, albeit partly due to the legally binding target. Again, the reduction in consumption in all sectors was due in part to a colder summer.

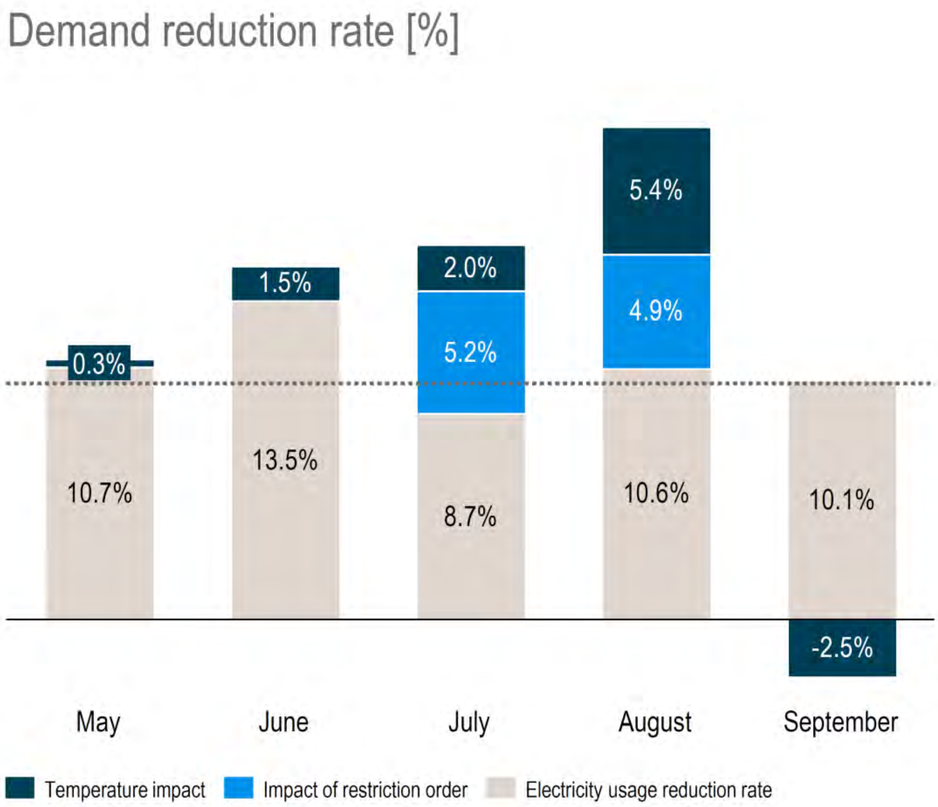

Figure 8: Breakdown of the Factors Explaining the Electricity Demand Reduction in the TEPCO Area. Figure Adapted from Ref. [47].

4.1 Implementation of an Electricity-Saving Strategy

Considering the 10.3% electricity supply gap described previously, the Government announced its summer electricity-saving strategy, which aimed at a conservative 15% demand reduction target for the whole country. It is worth noting that a lower target (5–10%) was proposed for particular end-users such as hospitals, nursing homes, public transport, and water utilities [37]. Whereas specific requirements from the Japanese authorities have been presented earlier, the Tokyo Metropolitan Government (TMG) enforced its own emergency power-saving program on May 27th 2011. It was devised to complement the National Government's measures and aimed at “freeing [Japanese] society from its excessive dependence on electricity” [48]. In that perspective, complementary efforts were emphasized to aid each sector with achieving their 15% reduction target. In order to help large electricity consumers, emergency power conservation seminars were organized and attended by approximately 2,000 businesses. The city also helped small consumers by coordinating power-saving measures, publishing reports and organizing workshops. A primary action proposed to these users was to reduce lighting (i.e. switching off lights, removing lights, and in some cases using low-power bulbs). With regard to the residential sector, energy conservation advisors visited more than 300,000 households from mid-June to the end of September 2011. The city also promoted the ‘Electricity Action Month’, which was held at public elementary schools and high schools and encouraged 1 million children to save electricity. Additionally, a subsidy program was implemented to foster home power generation through photovoltaic and gas cogeneration systems. Finally, efforts were carried out at TMG facilities: a 29% reduction from the previous summer was achieved at TMG main buildings. Interestingly, the city had already listed measures that could be taken to lower electricity consumption before the Great Earthquake, with the objective of lowering carbon emissions. Therefore, actions were taken in all TMG-related facilities, with emissions reduction measures already in place.

4.2 Customers' Reaction

Whereas it is clear that many actions have been taken to lower electricity consumption, a share of the reduction is arguably the result of lower production caused by disrupted supply chains. However, according to the Fujitsu Research Institute, the recovery of supply chain operations in Japan was very quick, with 90% recovery by the end of July 2011 [49]. Therefore, the government policy package was likely more effective than the destruction of supply chains in the industry's electricity consumption reduction.

4.2.1 Large consumers

Overall, large industrial consumers executed a 27–29% reduction in power demand, compared to summer 2010. The strategies of companies from two different industries are analysed below [26]. (1) For the electronics manufacturers, a reduction of (20–34%) in power consumption was achieved by: purchasing and leasing private power generation, shifting of work to holidays and night-time, production adjustment, and lowering air-conditioning and lighting. Costs incurred by the company amounted to ¥4 billion (€40 million) mostly due to private power generation, fuel and labour costs after shift changes. Moreover, sales plans had to be modified and led to lower sales results, which incurred further costs for the company. Also production decreased by 10–15% whilst private power generation equipment was being installed. (2) For iron and steel companies, a 26% reduction in power consumption was achieved by shifting work hours, relocating production to the West, implementing private power generation and electricity-saving activities, and increasing the efficiency of their facilities. Costs were estimated to be nearly ¥8.6

billion (€86 million) and were caused by additional fuel for private power generation, labour costs from shifting work schedules, increased inventories, decreased production, and opportunity cost due to non-use of contracted electricity.

4.2.2 Small businesses

The 15% target was achieved with a 19% reduction observed for small consumers across the Tokyo area. According to a questionnaire from the Japan Chamber of Commerce and Industry [26], 26% of small customers claimed to have carried out reductions greater than 20%. Several approaches to reducing electricity consumption were implemented: shifting of work hours, demand response monitoring equipment, private power generation, heat insulation, energy saving training workshops for employees, reduction in air-conditioning use and lighting systems. Moreover, when electricity was supplied jointly to industrial complexes which multiple tenants, the site was treated as a large user and small and medium enterprises in the cooperative implemented rolling operation shutdowns. While many companies recognised the merits to energy savings measures, such as improved electricity usage, many pointed out cost increases, decreased production volumes and increased workload for employees.

4.2.3 Households

Residential electricity consumption accounted for ~30% of electricity demand in Tokyo in 2010. The breakdown of this consumption is shown in Figure 9.

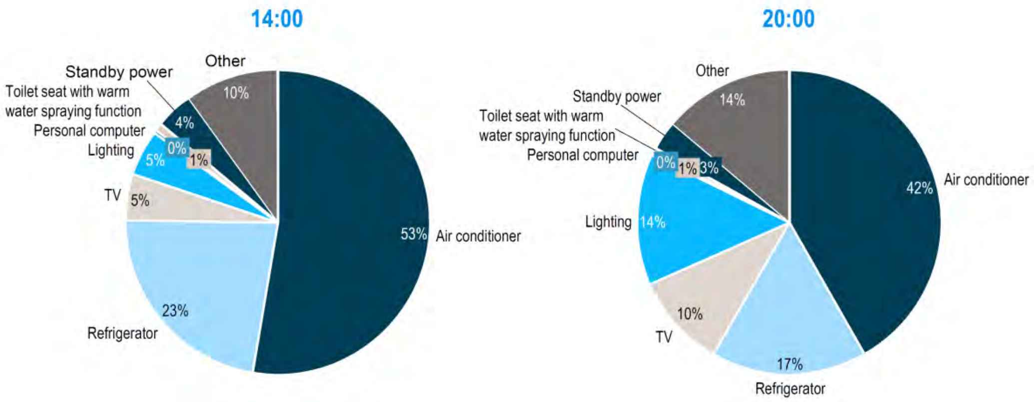

Figure 9: Breakdown of Electricity Consumption for a Household in Tokyo Area before the Crisis. Figure Adapted from Ref. [45].

The Agency of Natural Resources and Energy published nine energy-saving recommendations for the residential sector, with the expected power saving effects. The latter has been advertised by means of various media such as Internet and television. A study was conducted to analyse these electricity-savings measures of the residential sector in Tokyo during summer 2011 [50]. Interviews were performed along with questionnaires in order to assess strategies employed by households to decrease their electricity consumption. According to the authors, 10% savings were achieved on average after the weather normalization adjustment. In addition, it was estimated that approximately 40% of electricity were achieved from lowering the use of air conditioning. Figure 10 presents the main electricity conservation measures and their effects. When implemented, reducing the number of refrigerators in use decreased the volume of electricity used by a household by roughly 11%. Switching to energy-efficient refrigerators was also efficient since it produced a 10% decrease in power consumption. On the other hand, adjusting the consumption levels of appliances such as television brightness and refrigerator temperature had negligible effects. Reducing the time of use of air-conditioning systems was had the greatest impact, and adjusting air-conditioner temperature settings was ranked as the second greatest savings measure in terms of overall effect, emphasizing again the importance of air-conditioning in lowering household demand.

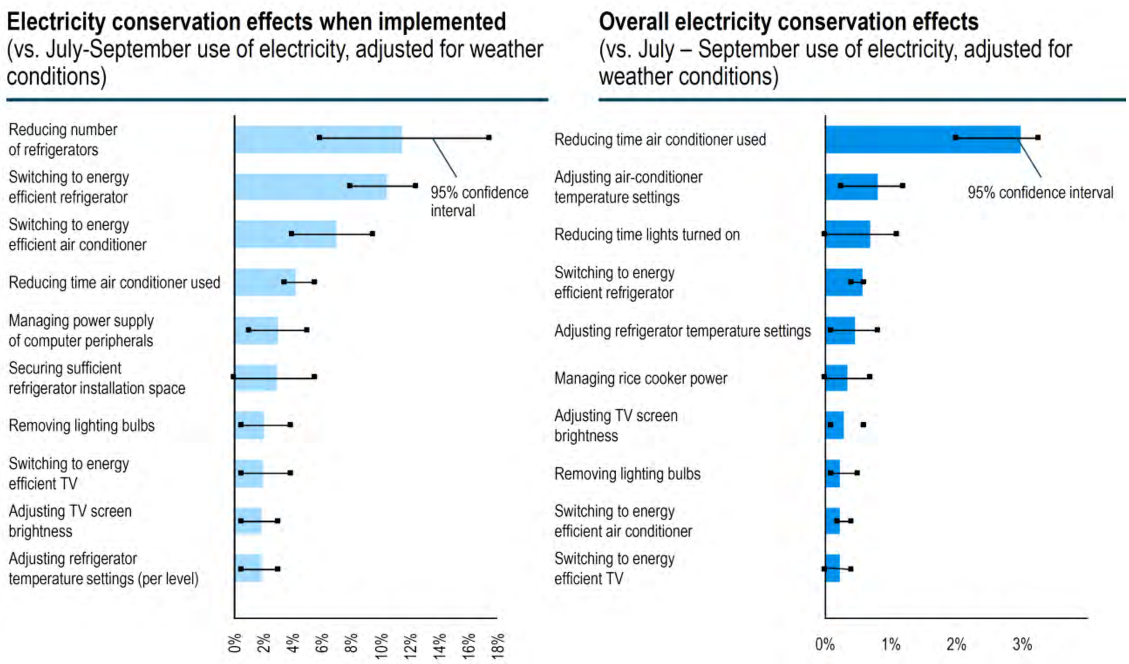

Figure 10: Assessment of the Main Measures Implemented by Households. Figure Adapted from Ref. [50].

The study also analysed what the electricity conservation motives were for households. Three reoccurring responses seem to explain why people chose to lower their power consumption. First, households wanted to contribute to the resolution of the electricity shortage crisis. Second, respondents were not aware of electricity reduction methods used until, they learned of them through the tips provided by the government in information campaigns. Third, households were recognizing opportunities to lower their electricity bills.

Interestingly, the results of the household survey showed that only 5.8% of households felt it had been difficult for them to save electricity, while most stated that they were able to save electricity without difficulty [26]. With regard to long-term effects, over 90% of households affirmed that they would continue electricity savings in the future. Specifically, over 60% of them contended that they wanted to continue reducing their consumption by 10% or more. While ANRE's survey results are in concordance with Nishio and Ofuji's study, their calculations also show that many households have carried out lighting reductions. 81% of the respondents used reductions in lighting to reduce their consumption, while a shift from air-conditioning usage to electric fans and/or modification of air-conditioner settings were used by 77% and 73% of the sampled population respectively.

5. Conclusions

The Great East Japan earthquake heralded a significant reduction in capacity due to the damage in thermal generation and that gradual closure of Japan’s nuclear power plants. The reduction in capacity was exacerbated by limited interconnections and the vertically-integrated monopolistic structures that comprised the Japanese electricity system. The subsequent response comprised a significant drive to bring replacement fossil-fired capacity online coupled with demand-side reductions that were developed on the fly. All-in-all, the targets for reducing consumption, and avoiding rolling blackouts, in 2011 were achieved. An interesting question is how these short-term, hastily-enacted emergency measures will impact future Japanese energy policy, and is investigated further in the work of Grimston et al. [2].

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