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# Disruption, disaster and transition: analysis of electricity usage in Japan from 2005 to 2016

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**ABSTRACT**

This research analyses changes to electricity generation and demand in Japan following both the Global Financial Crisis and Disasters of March 2011. Monthly electricity data for all regions of Japan from April 2005 to March 2016 were reviewed to identify differences in disruption-response between categories of electricity users. We apply inferential statistics to identify underlying trends, which are dominated by differences in user scale response. Higher capacity users reduced demand in response to the Global Financial Crisis, whereas smaller domestic scale users reduced electricity demand after the Disaster. Analysis reveals that regions within the 50Hz grid that were directly impacted by the Fukushima event and resulting load restrictions showed a statistically significant sustained reduction in monthly electricity demand post-disaster. However, Kansai and Shikoku, regions that are both outside the area directly impacted by the Fukushima event, also showed the same sorts of sustained significant reductions. By considering two disruptions to the same sociotechnical system, we can draw conclusions that add to the discourse of electricity use behaviors, which informs both disaster response planning and policy for the broader issues of electricity demand reduction for climate stabilisation.

***Keywords***

Energy Transition;
Electricity Market Disruption;
Energy Austerity;
Demand-Side Electricity Management

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## 1. Introduction

A dominant factor in anthropogenic climate change is unsustainable energy usage. The theme of a 'fundamental shift to our energy paradigm' is often repeated in both energy and climate literature to validate research or reinforce policy initiatives. This narrative implies that not only are the fragmented approaches of gradual advances which dominant modern policy initiatives entirely inadequate, but the scale of change required is unfamiliar to our existing systems. Historically, shifts of comparable novelty and scale have been defined as 'transition events'.

System disruption is one pathway to transition, and it has been argued that shortfalls have been more effective in producing efficiency gains than traditional conservation programs, even providing "insights into the upper bounds of what may be achievable" [1 p. 448]. However, to date, sudden disruptions to energy systems have been relegated to a simple supply and demand problem, with emphasis on bolstering and rapid recovery of the supply side, with little consideration given to fostering ongoing behavioral change. This emphasis is highlighted by statements such as: "savings need only be temporary, that is, electricity use can return to traditional levels at the end of the shortfall" [2].

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The Japanese scenario is unique in that electrical shortfalls form part of a wider and more complex experience, and are neither small-scale nor within a minor geographical range, making scaling and relevance to a wider international audience applicable. In addition, the disaster occurred in the period subsequent to the Global Financial Crisis (GFC), meaning lower economic resilience may have complicated decision-making; and also occurred in the midst of a liberalization program to modernize a traditionally vertically integrated and geographically monopolized structure.

This series of events provides an opportunity to better understand the interaction of disruptions on an established sociotechnical system and provides potential insights into management of energy conservation initiatives to achieve demand-side mitigation. The aim of this study is to quantify the impacts of those interactions on electricity demand, with a view to identify common factors and variables that may therefore influence changes to consumer energy-use behavior.

This study is singular in that it addresses all regions, user-scales and electricity tariffs in Japan over an extended timeframe. Further, this study goes beyond a single event, undertaking a statistical consideration of both the GFC and the Fukushima disaster as potential disruption triggers for multiple cohorts of energy consumers. This approach allows for an expanded investigation and discussion of the outcomes from each event.

The application of these findings are pertinent to a wide-range of policy and management scenarios. Better understanding of energy behavior decision making and motivations can inform targeting and customization of interventions to promote behavioral-change, to system preparation and resilience-building, to direction and focus of further research projects. We document that electricity savings need not only be ‘temporary’ in the case of shortfall, but if well managed and directed, can in fact provide valuable and long-lasting system transformation.

The paper is structured as follows. Section 2 presents the Case Study, along with a summary of existing related scholarship. Section 3 provides the methodology for the data collection and analysis phases of the work, with the results making up Section 4. Section 5 reviews and discusses the results and the implications of the findings. A brief conclusion is offered in Section 6. Supporting information including definitions, calculation syntax and detailed statistical results are included in the Appendix.

## 2. Background and Literature Review

The Great Tohoku Earthquake (11 March 2011) was a magnitude 9.0 event centered off the northeast coast of Japan’s main island. The resulting tsunami was observed at over 9m, causing significant impact to both Fukushima and Miyagi Prefecture (Tohoku Region) [3]. The tsunami triggered automatic shutdowns of 10 nuclear powered reactors across three different plants. Of these, Fukushima Daini and Onagawa were contained, however the immediate damage to the Fukushima Daiichi plant resulted in loss of emergency cooling systems which resulted in uncontrolled release of radioactive material [4].

Between March 2011 and May 2012, Japan gradually shut down each of its 50 remaining nuclear reactors, largely in response to safety concerns resulting from the incident at the Fukushima Daiichi reactor. In total, approximately 30% of Japan’s electricity generation capacity, or over 44,300 MW, was rendered unavailable. This resulted in marked changes to both the make-up, and total generation output in Japan.

This disruption was managed through a combination of demand-side controls for peak loading and augmenting generation with under-utilized capacity [5]. The nuclear decommissioning following the disaster occurred over a 14-month period, with the resultant electricity supply shortages encompassing the whole country [6]. The make-up and generation output for Japan between April 2005 and March 2016 is shown in Figure 1.

The combination of a lack of generation capacity, and to a much greater degree, the inability to transfer power between western and eastern (Japanese) grid systems was the cause of power supply interruptions post-disaster. This ‘bottleneck’ of supply, coupled with an inability to retrieve and analyze real-time data to better target load-shedding activities, limited the capacity of the administration to minimise the impacts of energy system changes [9].

Several policy measures were employed to manage the supply-demand ‘gap’; forecast at between 15-20% for summer peak-loading, as summarized in Table 1 [10]. In the summer following the disaster, energy austerity measures resulted in 12% lower energy consumption, and an 18% reduction in peak-load compared to 2010 for large users in the Tokyo (Kanto) and Tohoku regions [11, 12]. Existing thermal power stations increased output by over 20% to cover the nuclear-shortfall [8].

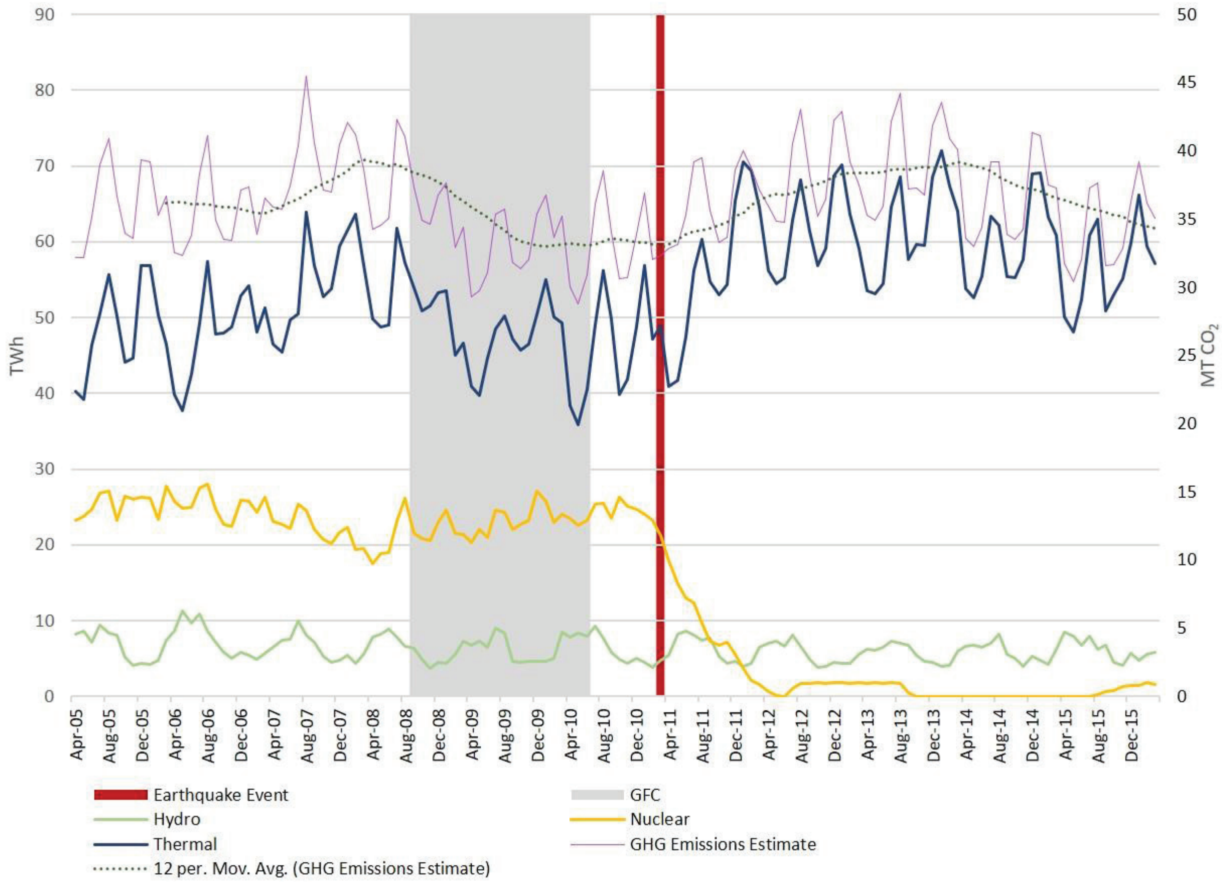


Figure 1 - Electricity generation in Japan by source between April 2005 and March 2016 with corresponding national greenhouse gas emissions for the same period. Electricity data from [7], Emission intensity values from [8].

Generation data sourced from the Japanese Ministry of Economy, Trade and Industry (METI) shows gradual re-commissioning of Japan's nuclear reactors commenced in August 2015. Even so, nuclear power contributed less than 4% of Japan's total generation compared to 30% pre-disaster [7].

The March 2011 tragedy is not the only disruptive event to impact the Japanese electricity industry. The impact of the GFC must also be considered as a potential driver of change through both direct economic pressure (reducing electricity consumption for cost savings) and productivity impacts (e.g., reduced operational requirements with lower output or sales). The latter is likely to be a major impact given the industrial 'collapse' in Japan from late 2008 to early 2009, attributed to the dominance of 'income-elastic' components and durable equipment (capital goods) for export markets [13].

Running parallel to these disruptions was the planned liberalization of the Japanese electricity market. Compartmentalizing of system management along historically fostered regional boundaries resulted in a monopoly of nine (and later 10 with the addition of Okinawa) vertically integrated generation, transmission, distribution and retail corporations [14].

The northern part of the country operates on the European standard of 50Hz, and the southern on the American, 60Hz; meaning that frequency converter facilities were critical as the network matured to connect the Eastern and Western Japan networks. However, the capacity of these interconnectors (1.2 GW) was insufficient to allow full exploitation of excess generation capacity across the zones or 'buffering' of high demand events.

Deregulation of the Japanese electricity system began in 1995 with allowed entry of Independent Power Producers (IPPs), and Specified Utilities (private generation, transmission and distribution services covering only retail customers in their specified areas).

Extra-high voltage customers (such as office towers, large factories, and department stores) drawing over 2MW at 20,000 volts or higher have been contestable since March 2000.

In April 2004 this contestability was expanded to include high-voltage customers drawing 500kW or more and expanded again the following year for the balance of high-voltage customers (≥50kW). This coincided with the first electricity trading services through the new Japan Electric Power Exchange (JPEX).

No further actions were planned to enable retail competition at the domestic low-voltage scale. Additional reform was only pursued when the disaster highlighted systematic failures in the development and management of the nation's electricity systems. In 2015, cross-regional coordination of transmission services and an independent regulator were established allowing for improved balance of supply across the transmission barrier and scheduling of load to maintain stability.

Full retail contestability was introduced for domestic-scale customers at the beginning of the 2016 Japanese Financial Year, along with a mechanism for trading beginning one hour ahead of demand. Legal separation of retail, transmission, distribution and retail responsibilities, hedging, a full-service spot market and market rate liberalization are in place or imminent [15, 16].

Analysis of quantitative changes in electricity consumption in Japan in light of the disaster are limited. The most complete review of electricity consumption regarding the impacts of the Fukushima event (in English) was undertaken by Wakiyama, Zusman [17].

They collate monthly demand data from January 2008 to December 2012 for both small (>50kW) and large (>500kW) users, with specific attention given to the Kanto and Kansai regions. Econometric analysis of temporal, spatial and scale-based electricity demand using Autoregressive Moving Average models were investigated along with policy and environmental (temperature) influences. The authors found a statistically significant national reduction which was "significant, sudden, and sustained" [17, p. 655].

It was documented that proximity to the earthquake resulted in greater reductions, but the sustainability of that reduction was varied. Large users generally had larger reductions, but these rebounded in time. Similar ongoing reduction in Summer (but not winter) peaks were identified by Murakoshi, Nakagami [18], who found a correlation between peak electricity usage and temperature before, but not after the disaster.

In depth analysis was also undertaken by Daggy, Wakiyama [19], who provide electricity analysis for 18 Japanese cities from 2007 to 2012 as part of a larger transition narrative. The researchers state a clear, traceable hypothesis relating to the influencing factors and test individually using a random effects panel time series model [19, p. 150]. They identify higher reductions for households adopting energy saving reforms and link those reductions to the presence of non-profit organizations.

Hayashi and Hughes [20] provide an analysis and discussion of policy responses and potential future actions following the disaster. In support of this, a disruption narrative, including regional installed capacity, customer numbers and generation are presented, but no in-depth quantitative analysis is offered. Additional time series information for 2009-2011 generation and fuel inputs (in Mtoe) and price are provided to illustrate post-disaster outcomes, with the conclusion that a radical shift away from nuclear remains unlikely due to energy security, cost and environmental drivers.

A larger group of authors offer limited high-level outlines of post-disaster outcomes as part of preambles or baseline investigations for future policy or scenario exploration (rather than quantitative examination). For example, Portugal-Pereira and Esteban [9] present historical (1989 to 2012) supply and demand data as part of a wider set of indicators of future energy security.

High level generation data is also provided by Komiyama and Fujii [6] from 2008 to 2014, showing step change in energy mix, and an increased use of LNG and coal (to make up for the nuclear short fall) as a preamble to complex modelling of future fuel mix scenarios.

A group of researchers also examined the quantification of energy-use behavioral change during and following the disaster. Investigation of actions taken post-disaster by Fujimi and Chang [1]; Fujimi, Kajitani [21]; Kimura and Nishio [22]; Murakoshi, Nakagami [18]; Tanaka and Ida [23] had largely consistent results, with limitation of air conditioning usage (both length of time and temperature), and refrigeration (lowering temperature) dominating results. Other findings include replacement of lighting with energy efficient versions and turning off devices in stand-by mode.

While not based on consumption data, Abe [24] reviewed editorial articles of the major national newspapers in Japan after the event and finds differing views regarding de-nuclearization along a 'nationalistic' vs 'democratic' social value divide. The author draws linkages between the nuclear power debate and a wider discussion of social direction and highlight that power saving and public distrust were among the major themes identified across articles.

Energy system disruptions have also been studied overseas. A combination of drought and transmission limitations in Brazil caused electricity shortages in 2001-02 in the North and South-East. The restriction of hydroelectric plants in this region (making up over 80% of installed capacity), and inability to utilize power from the unaffected Southern region led to anticipated shortfalls of around 20%.

Like Japan, this shortfall was persistent and widespread, leading to a range of government interventions covering conservation requests, personalized reduction quotas, economic instruments (fines and rewards, tax reductions and increases on relevant goods depending on their ability to reduce or increase electricity consumption), and even disconnection threats for ongoing non-compliance.

Gerard [25] examines 15 years of utility reporting and monthly billing data from three million households in Brazil to study demand response trends using a variety of statistical methods. Reductions (from an already small baseline) of around 34% in affected systems, and interestingly, 9% in the unaffected South - far in excess of what can be attributed to the established incentives. The author therefore attributes a 25% reduction to the conservation requests alone. This result shows a surprisingly high demand elasticity for the study area, supported by ongoing reductions of around 12% post-crisis.

Domestic consumption in Alaska following the destruction of a critical transmission line was studied by Leighty and Meier [26]. The Alaskan example is unique as supply was replaced with back up diesel generation, so while baseline demand would have been met, sudden price shock (a five-fold increase) and potential environmental concerns, were key to triggering behavioral changes. Residents reduced consumption by a quarter, and again, a persistent 8% reduction over baseline continued after resolution. A repeat of the event within 12 months observed only a 12% reduction over baseline, but an increase in residual savings of 10%.

In summary, previous research has documented regional or city-specific changes to electricity usage reduction behaviors (and the actions taken to produce those reductions) and addressed the immediate tactical and policy response to each disaster, appropriate to their timing and focus. This paper is distinct and novel in its inclusion of all regions, user-scales and tariffs associated with electricity demand in Japan over an extended timespan.

This paper advances evaluation of impact variables beyond a single event, undertaking a statistical consideration of both the GFC and Fukushima disaster as potential disruption triggers for multiple cohorts. This approach allows for an expanded analysis and discussion of the findings from each event, which may be relevant to both disaster management and wider energy policy scenarios.

## 3. Method

Monthly reporting of both generation (by source) and demand (by customer type and region) was extracted (aggregated by Japanese financial year) provided by the Japanese Ministry of Economy, Trade and Industry (METI)'s Agency for Natural Resources and Energy [7].

Following extraction, this data was flattened into pivot style for compatibility with Power-BI analysis.

Data prior to March 2005 and Post March 2016 was excluded due to inconsistencies in the scope and reporting (specifically with changes to division of demand between categories coinciding with policy or legislative changes, making analysis unreliable between user groups). This allowed for the largest consistent data set to provide the widest scope of assessment available. A description of the available input data and summary of the applied functions has been provided as Tables 4 and 5 [10].

A number of culturally specific and technical definitions were sourced from formal translations of relevant legislation and industry contracts and have been provided in the supplementary information.

Each individual data division (array) was assessed for normality using descriptive statistics, skew and kurtosis (limit of +/– 2). A statistical F-test was performed for equality of variances between the arrays. Following this, a single tailed T-test (for either equal or unequal variances as determined previously) was performed for four separate data pairs.

Test one included comparison of data before and after March 2011 (pre- and post-disaster). Test two compared data before and after January 2009 (pre- and post-GFC). Test three compared pre-GFC data to post-GFC up until March 2011, and test four compared post-GFC up until March 2011 with post-disaster data.

These iterations were designed to clarify changes to average monthly electricity generation and/or demand between the two event drivers. A sustained GFC triggered reduction would show a statistically significant reduction in both tests two and three (and potentially test one), but not test four. A sustained disaster-catalyst reduction would show a statistically significant reduction in both tests one and four (and possibly test two) but not test three.

A 95% confidence interval was selected for all applicable tests. While generally preferred for independent population samples, T-test comparison of means have been applied in this scenario as no trend analysis or predictive modelling was completed, and the high number of observations allows for averaging of seasonal variations over time.

The limitations of this approach need to be acknowledged. This study explores the quantitative relationships between changes in electricity generation and demand associated with the GFC and Fukushima disaster in Japan. While some conclusions can be inferred from the commonalities identified, it cannot in isolation confirm the supporting mechanisms behind the identified changes. The exclusion of other quantitative system variables, such as ambient temperature or pricing structures, also constrains the analysis.

Statistical significance with a 95% confidence interval has been used in the analysis to indicate a difference in electricity generation or demand between the tested groups. This approach allows a 95% confidence that the averages observed are not part of normal variation of the data sets. There is therefore a 5% change remaining that this was not the case.

The core data set itself has been retrieved from a reliable source, and therefore is assumed to be without meaningful errors. The timeline used has been intentionally selected for consistent data categorization. Notwithstanding, some minor discrepancies were managed on a case-by-case basis. While minimal, these remain limitations to a definitive analysis, and center on the use of wholesale, privately-contracted and self-consumption electricity (by both private companies and utilities). These loads cannot be reliably assigned regionally or to a specific user-scale, and have been largely excluded. The total contribution of this additional load is approximately 2% of the large user category.

## 4. Results

The results are divided into generation, demand and user scale, while the discussion section focusses on policy implications drawn from these results. Detailed statistical results are provided in Tables 8 through 27 [10].

### 4.1. Generation

Total generation is typically expected to be in the region of 10% higher than demand to allow for network (transmission and distribution) losses, fluctuating with load and ambient temperature. When compared to reported generation, demand data showed a reporting lag, with a growing trend (post April 2010) for reported demand outstripping reported generation.

This discrepancy is likely due to changes in the reporting scope related to the expiry of transitional supplier-approvals in March 2010, and definition of these participants as wholesale supply companies thereafter. An ongoing reduction in total generation can therefore be at least partially attributed to changes in data scoping and is consequently not as reliable as demand-based metrics.

Biomass and waste generation are similarly limited by scoping, as they are recorded separately from March 2010 only, and cannot be examined for GFC-centric testing.

Overall, as nuclear generation reduced, thermal generation, wind and solar increased to compensate. There was also an ongoing reduction in geothermal generation which could not be linked to a single catalytic event. It is also notable that the IEA calculated emissions intensity [8] for this period shows an increase following the disaster. When this data is used along with monthly generation totals, a sharp departure from the total generation trend is observed following the earthquake, reinforcing the transformative nature of the overall change in energy mix.

General Utilities (the sum of the geographically aligned retailers) experienced a reduction statistically related to the disaster, while the wholesale bodies experienced more variable results complicated by changes in reporting structures and scoping implemented in April 2010. The Japan Atomic Power Company provided nuclear power to commercial scale clients from two facilities which ceased generation following the nuclear shutdowns, while J-Power shows post-earthquake growth from its coal and hydroelectric facilities, likely due to increasing thermal output to compensate for lost nuclear capacity.

Specific scale (out of geographic range) generation showed consistent growth, while private contracts and special arrangements showed inconsistent responses to the tested disruptions.

### 4.2. Total demand

Analysis of the aggregated electricity demand data (Figure 2) shows an initial increasing trend, followed by

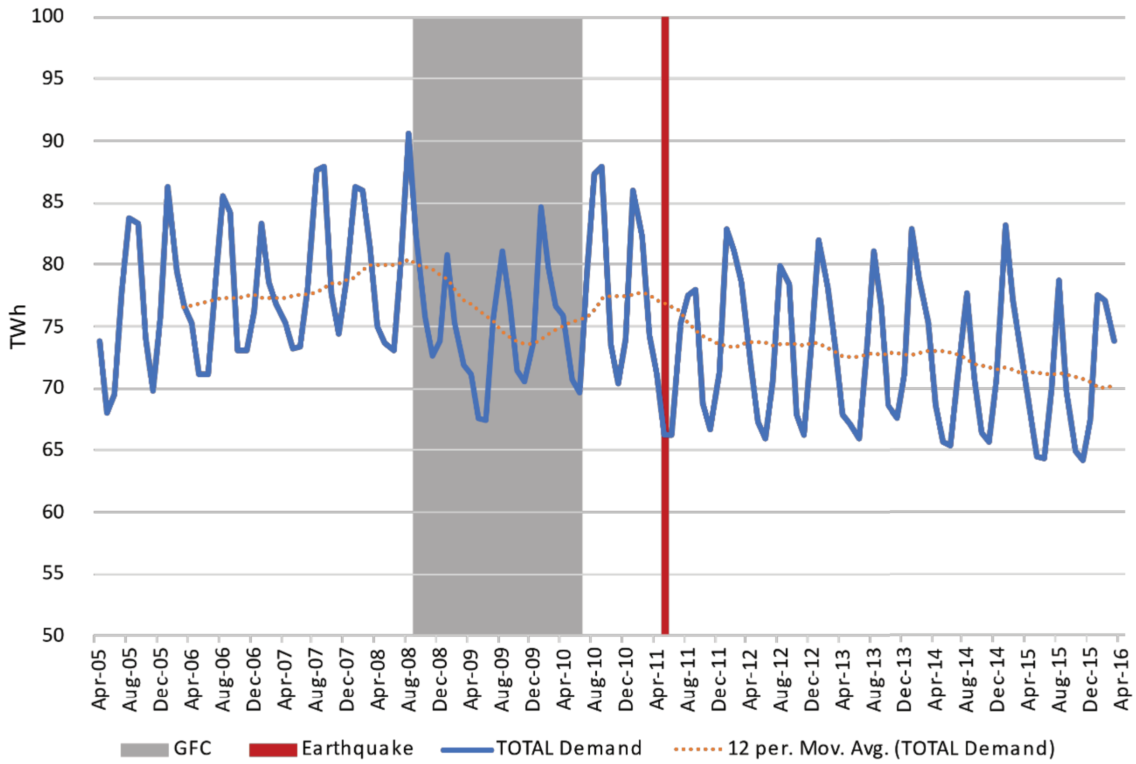

Figure 2 - Total Monthly Electricity Demand in Japan April 2005 to March 2016. Data from [7].

a clear drop in monthly electricity usage during the GFC. Partial recovery of this decline can be seen starting in late 2009, interrupted by the disaster, with a subsequent and sustained reduction to March 2016.

While post-2011 energy use was statistically lower than pre-event numbers, this was also true for the GFC meaning that results may be linked to economic factors. By identifying that there was no statistically significant difference between the pre and post GFC cohorts but a statistically significant difference between post GFC and post-disaster arrays, it is suggested that the 2011 event triggered a decline in monthly MWh demand across Japan.

### 4.3. Demand by electrical frequency

The primary impact of the earthquake, tsunami and resultant nuclear disaster was concentrated in the north of country, within the 50Hz region. While the 50/60Hz distinction isn't precisely aligned along regional boundaries, it sits generally between Tokyo and Chubu; and between Tohoku and Hokuriku.

There was a significant reduction in monthly electricity demand in the 50Hz region for tests one, two and four, indicating the reduction was due to the disaster (these results hold true for total usage, and specifically for months April through July and October to December).

The 60Hz cohort showed statistically significant reductions for both the disaster and GFC tests, meaning a single triggering event could not be isolated (in total, and for months June through October; only November showed causality with the disaster). These outcomes hold with analysis of the monthly data (Figure 3), where a clear decline for all months can be seen in 2009 for both groups, however the 50Hz region also shows a noticeable dip in 2011 with a general reduction trend thereafter. For the 60Hz region this pattern is also identifiable, but less distinct.

### 4.4. Demand by geographical region

A summary of the electricity demand results for the geographic distribution regions of Japan is provided as Table 6 [10].

Causality of demand reduction based on the disaster can be inferred for Hokkaido, Kansai, Kyushu, Shikoku, Tohoku and Tokyo. Chubu alone shows a statistically significant reduction based on the impacts of the GFC. A statistically significant reduction in Chugoku could

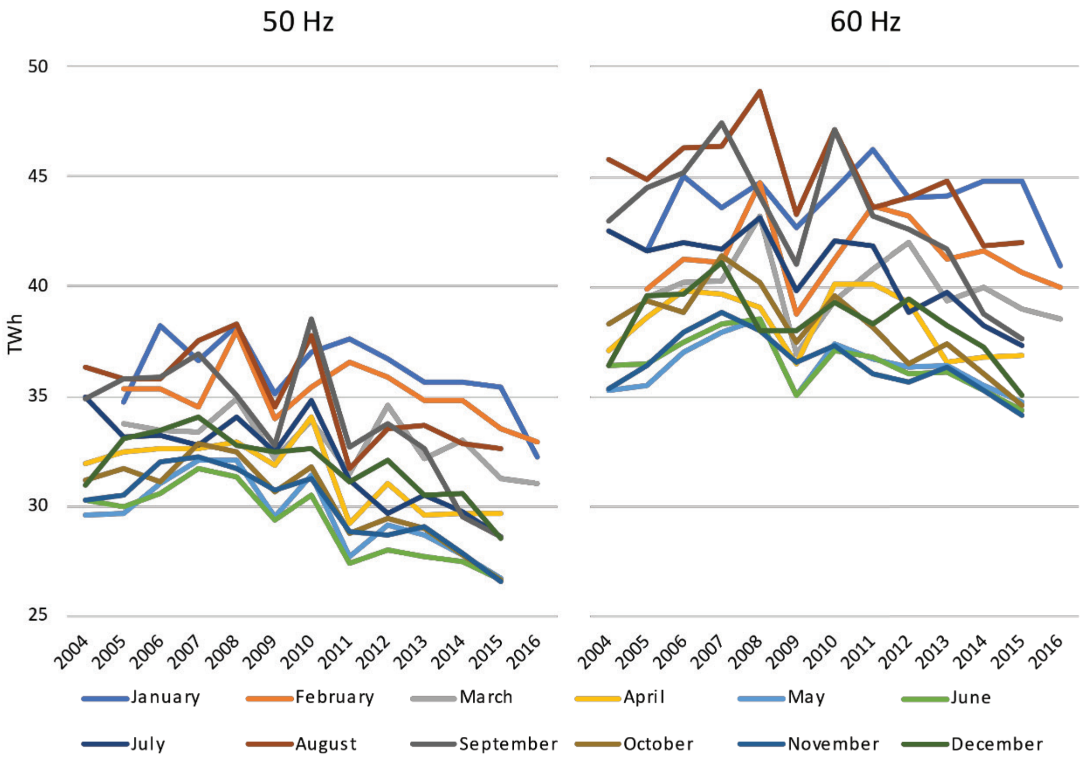


Figure 3 - Pre and Post Event Average Monthly Electricity Demand in 50Hz and 60Hz Frequency Areas. Data from [7].

not be attributed to a single catalyst, and no impact could be identified in Hokuriku.

The non-geographical cohorts (contestable demand and private contracts) are subject to additional influences, leading to no conclusions being drawn. For example, growth of contestable demand could be related to recategorization or sideways movement of consumption, rather than net decline. The outcome of all location-based monthly electricity demand testing is provided in Figure 4.

**4.5. Scale-based demand**

In addition to geographically based demand, electricity consumption data can also be classified according to the scale or category of the users (the amount of electricity used in total or instantaneously, as well at the tariff). This broadly categorizes users as being either small (<50kW demand) or large (>50kW) scale. Tariffs further allow grouping of users as domestic or other, with further clarification on specific usage type within these sets.

Demand reductions considered at the user scale show the dominance of small users following the disaster, at a rate high enough to produce an overall statistically significant reduction nationally. This is contrasted against an inconclusive or GFC triggered reduction at the large-user scale, both are summarized in Figure 5.

**4.6. Large users**

Approximately 60% of electricity demand in Japan over the analyzed period was potentially contestable or ‘Specified Scale’; meaning that users have the option to contract supply from outside their geographic area. Uptake of liberalized contracts however remains low at under 10% of sales; meaning that regional assessment of this demand is still possible with caution. This load is drawn by users contracted at 2,000kW (defined in the source data as special high-voltage) and 50kW or more (defined as high-voltage) [27].

METI provides an additional level of ‘large user’ demand; being those consumers who draw 500kW or more. Manipulation of this data can therefore provide three separate categories of large-scale users as detailed in Figure 6.

Analysis of the data shows a clear ‘dip’ in the over 2MW and 500kW user network-demand in 2009, coin-

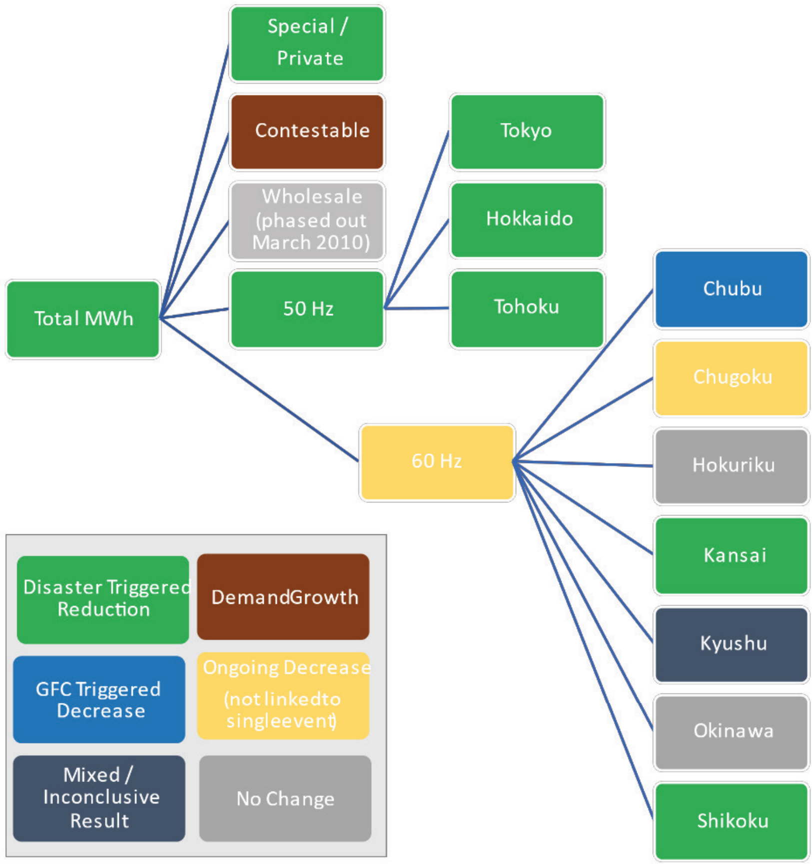


Figure 4 – Summary of Changes to Monthly Electricity Demand in Japan 2005-2016 by Location

ciding with the impacts of the GFC (meaning reductions may be linked to general economic conditions). In contrast little immediate impact is evident following the disaster.

A statistically significant decrease was found for all users, with the exclusion of 499-50kW draw, which saw an increase after the GFC. The largest users (over 2 MWh draw) show a demand reduction aligned with the GFC. A decrease in demand for all other cohorts was seen in each scenario between arrays; so, while monthly large user electricity use has declined, this cannot be stated to be a result of the disaster alone. A future review of production intensity would provide additional clarity on this issue.

It should be noted that while no ongoing reduction in network demand was identified in the study, data from the Japan Institute of Energy Economics documents a reduction in peak power demand of almost 30% for the sector, with only 300 of 19,000 large customers not meeting the mandated targets [28, p.6].

### 4.7. Small users

The remainder of Japanese electricity is consumed by users with a draw of under 50kW, typically domestic users. The balance of this small-scale demand is lighting and power for building sites, temporary constructions, agriculture, street lighting, other businesses (using specific tariffs) and small commercial operations.

Smaller scale tariffs (as summarized in Table 2 [25]) are not necessarily mutually exclusive of connection point (meaning a user could have multiple tariffs for the same location) and these can include a range of time-of-use variation [29, 30].

Optional agreements or selection agreements are used where standard retail contracts do not suite the end user and are often limited by time of use (TOU) or season, such as for snow melting, peak shift lighting or night only operations.

Similarly, low voltage or low-pressure contracts for users needing under 50kW based on nameplate rating of equipment or switchgear. These users are difficult to assign

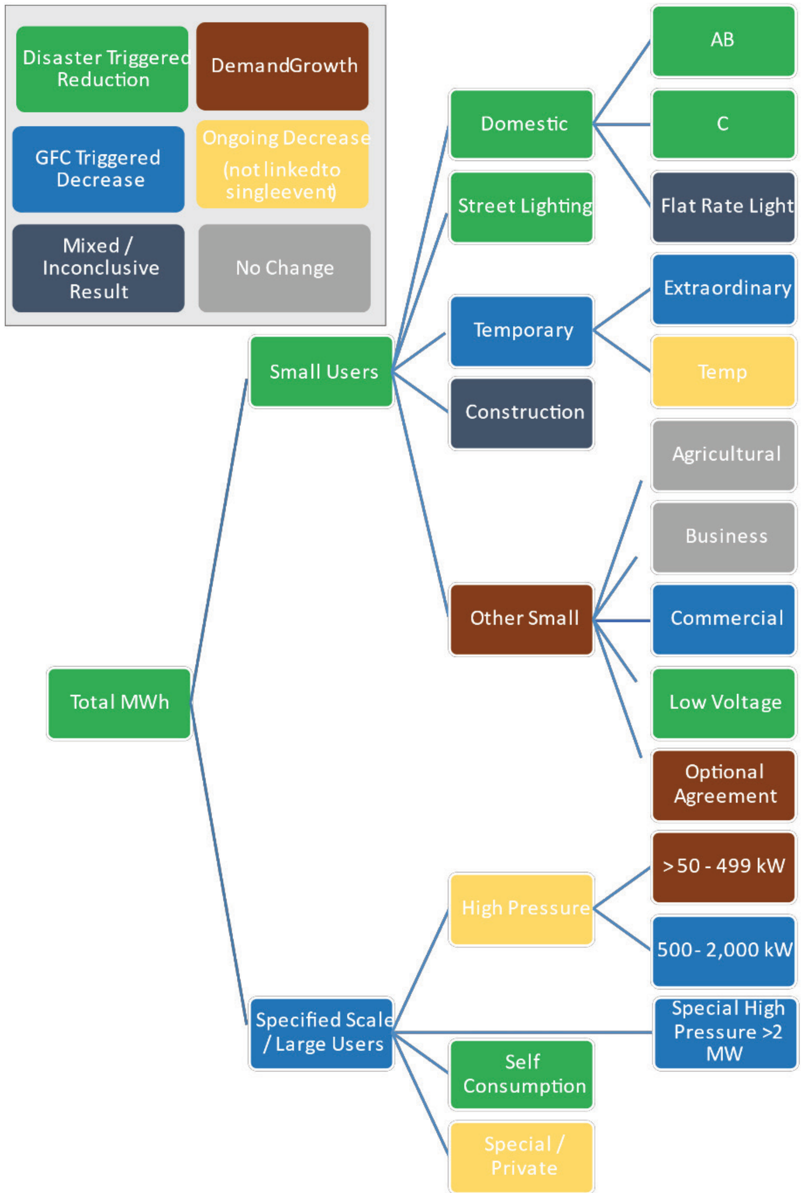


Figure 5 - Summary of Changes to Monthly Electricity Demand in Japan 2005-2016 by User Scale and Type. Tariffs are detailed in Table 2 [10].

a category to due to the variety of optional agreement tariff contracts available; and likely fall within the agriculture / commercial / industrial categories (and have therefore been binned as a single user group for this analysis).

While domestic users showed a general ongoing decline in demand, non-domestic users increased their usage over the assessed period. It is possible that some non-domestic growth is lateral movement of customers downsizing from higher demand tariffs (through either productivity reduction or energy efficiency), or reductions in network demand with micro-generation (solar PV for example). However, statistical testing showed greater variability in this cohort, suggesting influences are not uniform.

Reductions can be attributed to the disaster for tariffs A, B and C, along with aggregated domestic demand. The non-discretionary (connection based) flat-rate light tariff had variable outcomes, with a post-GFC reduction followed by an increase after the disaster.

Street lighting showed a statistically significant decline in MWh demand following the disaster in all regions except Hokuriku. Other small users (excepting

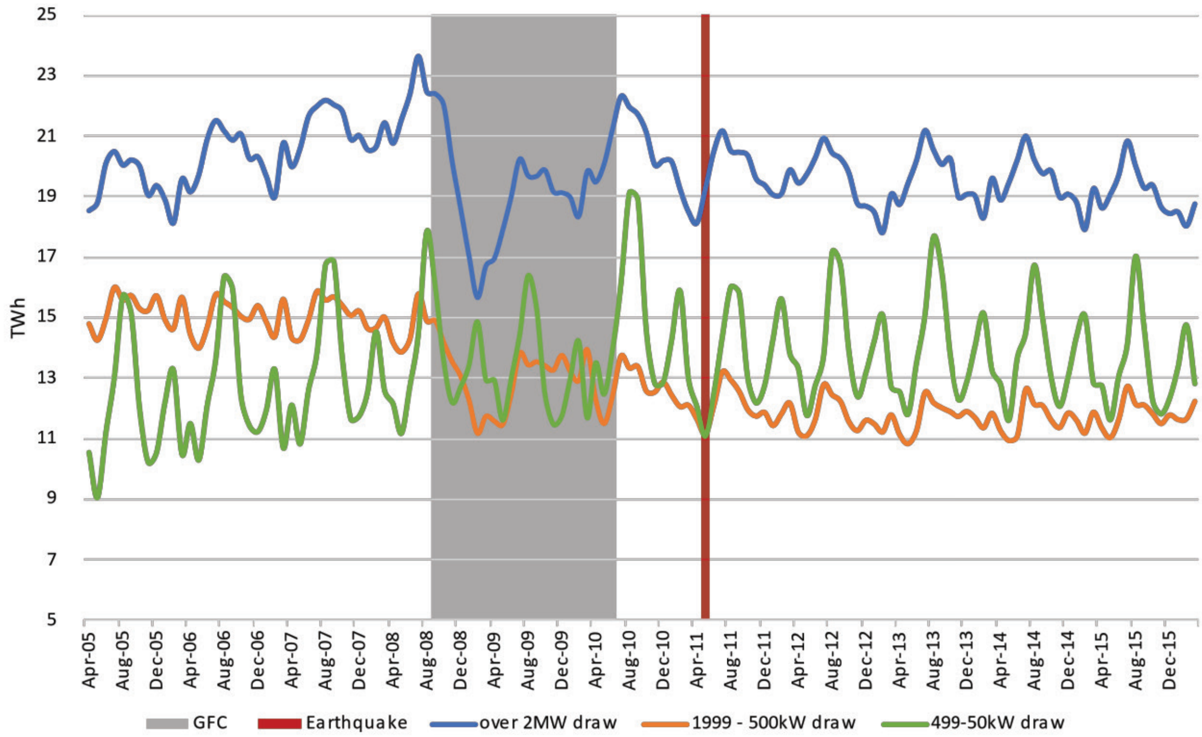

Figure 6 - Large User Monthly MWh Demand Japan April 2005 to March 2016. Data from [7].

Okinawa) showed a GFC triggered increase in demand, with a paired decrease in special arrangement consumption.

These mismatched results may be linked to impacted businesses moving off higher use tariffs due to productivity reductions or efficiency or may be a reflection of the diversity of small business types (corner stores, restaurants, small farms) leading to a certain resilience for the cohort overall.

In total, this user scale showed a statistically significant reduction for the post-GFC period compared to post-disaster. Supplementary information addressing tariff, scale and geographic location has been provided as Table 7 [25] for greater granularity and trend identification.

## 5. Discussion

This section will review the core research findings, and consider these results within the context of previous relevant scholarship.

### 5.1. Summary

Prior to the disaster, Japan held nuclear generation at the center of its energy policy [5], with nuclear technology development and implementation dominating over 60% of research and development budgets [8]. While Japan certainly did not de-carbonize as a result of the disaster, it unquestionably did trigger a complete re-evaluation of its electricity systems to integrate a new risk paradigm incorporating both the direct potential threat of nuclear energy, and the loss of domestic energy security and independence.

The data analysis confirms a statistically significant reduction in consumer demand, and changes in generation profiles, following disruption of the electricity system due to the March 2011 disaster. While not uniform, these reductions were also not necessarily dependent on direct exposure to the disaster and varied with user scale and category.

Overall, statistically significant reductions were found pre vs. post disaster in the regions serviced by the Tokyo (Kanto), Hokkaido, Tohoku, Kansai and Shikoku supply areas, with a borderline result in Kyushu. While all regions were encouraged to reduce electricity demand for 2012 summer peaks, more targeted requests (both binding and non-binding) were issued for these specific regions. While binding requests applied to peak loading only, the impact of these communications on total demand appears significant.

Interestingly, demand at the smaller scale (consumers on domestic tariffs) showed a statistically significant reduction outside of these areas, for all regions except for Okinawa. These results suggest that structurally, in additional to national trends, the changes in electricity demand may also be considered as individual regional transition events. Localized (geographically bounded, sub-national) transition events have been recognised as being dependent on elements relevant to the case study, such as participant ownership, multi-advantageous solutions and situative governance [31].

Mid-range users (50 to 1,999kW draw) showed reductions in Hokkaido and Kyushu, with highest tier users (over 2MW) having no identifiable geographically linked reductions following the disaster. The GFC was identified as the triggering event for demand reduction for mid-range users in Hokuriku, and highest tier users in Chugoku, Hokuriku and Shikoku (as well as for sector total).

A number of other regions showed an unassignable but ongoing reduction pattern, especially for mid-range users (in Chugoku, Kansai, Tohoku, Tokyo and for sector total). Highest tier users in Tohoku and Tokyo followed a similar pattern. This may indicate that both the GFC and disaster prompted separate electricity reduction measures, that the disaster interrupted financially driven savings already underway, or that a third, untested catalyst is responsible.

While it is possible that a portion of reductions in these higher demand groupings was sideways movement (for example, from geographically linked to liberalized contracts), or between mid and high-range tariffs with business growth or shrinkage, the total reductions seen for groupings would suggest this is not a dominant factor, with a move away from network demand through either self-generation, efficiency measures or even production decreases more likely. A complementary review of relevant economic factors may offer some clarification in this regard.

The data indicates that agricultural customers were not impacted by either of the events tested, meaning that this sector may be buffered from the analyzed events. Street lighting showed an across-the-board decrease following the disaster event, which indicates government leadership in demand-side energy saving initiatives, and prioritization and acceleration of existing policy goals in this area.

### 5.2. Policy and institutional response

The history and analysis of the political climate surrounding Japanese energy policy has been documented thoroughly from both historical [32], and modern perspectives [33, 34]. Here we focus on the impact of these policies on the results identified.

The Japanese "Strategic Energy Plan" was first released in 2007 and focused on the delivery of a stable and secure energy supply, environmental adaptation and economic efficiency (often referred to as the '3E' goals) [35].

A review in 2010 (i.e. post-GFC) added economic growth and structural (energy) industry reform to these goals [35]. These changes may be reflective of the challenges faced by energy users preceding the review, suggesting a strong economic element to the decrease in demand observed for large users.

Under the Strategic Energy Plan, a number of more specific strategies and projects designed to fulfil the Plan's policy objectives exist. A suite of energy efficiency and demand-side programs including reporting and performance obligations form part of a wider policy implementation environment, including provision of innovation support and Energy Services (ESCO) [36]. However, the impact and effectiveness of these early programs is unclear. Efficiency improvements for domestic goods (such as TV's, refrigerators and air conditioning) resulting from the 'Top-Runner Program' while predating this policy, also contributed to its outcomes [36].

An additional review of the Strategic Plan was triggered by the disasters of March 2011. The review focused on a decrease in nuclear dependence, and increased safety considerations, engendering the '3E+S' (i.e. Safety) goals. A national discourse and agreement on energy mix was emphasised, with the goal of further utilising distributed generation (typically smaller electricity generation facilities that connect directly to the distribution system rather than the higher capacity transmission system) without causing an increase in costs or triggering generation shortfalls [37].

A greater engagement of smaller energy users as a result of the policy review process may reflect the dominance of small energy users in our results. A focus on distributed energy increases the resilience of the grid as a whole and lowers the impact of future transmission bottlenecks. However, our results also suggest that the monopolisation of vertically integrated generation, distribution and retail corporations may have previously hindered innovation in this regard, reflected in the finding of a lack of longer-term response post-disaster for large energy users.

The 'Sunshine Project' (1979-2005) supported solar innovation and made Japan a world leader in PV manufacturing [33]. Subsidies for residential PV and fuel cell systems are also notable [36]. However, it may be argued that Feed in Tariff (FIT) programs enacted in November 2011 (the "Special Law to Promote Renewable Energy"), along with distributed energy relaxation policies were more successful in allowing small energy users to take greater control of their energy management, resulting in a decrease in small user network demand [33].

Similar impacts could not be identified for larger scale users, for whom average monthly self-generated electricity increased post-GFC, but counterintuitively decreased in the years following the earthquake.

It is also possible that the disaster provided additional motivation for action under this existing program framework. For the streetlight example noted previously, the 2010 Strategic Energy Plan had a goal to use LEDs exclusively for new lighting by 2020, with all existing stock to be upgraded by 2030 [35]. However, detailed economic modelling and technical considerations for LEDs (including the high intensity discharge required by streetlights) was only pursued following the disaster [38].

The influence of local governments in electricity demand response is also notable. Kameyama [34] documents the leadership of the Tokyo Metropolitan Government (TMG) in facilitating decreases in energy consumption from 2001 onwards. A culture of environmental awareness and sustainability leadership is also notable in Fukui (Chubu region), Kitakyushu (Kyushu), Kyoto (Kansai) and Yokohama (Tokyo / Kanto Region) [34]. This could explain some of the 'outliers' presented in our results, as well as the ongoing reductions identified in the 50Hz-region.

As system operators, the electricity utilities also participate in (direct and indirect) policy implementation. TEPCO public reporting highlights the promotion of efficient infrastructure for commercial and industrial customers, suggesting that existing lines of communication and partnerships occurred at the time of both the GFC and the disaster [39, 40]. Following the disaster, these relationships may have been key in reducing peak demand loading across industries. Cognisant of the increased generation-based emission intensity post disaster, the FEPC extolled the emission reduction benefits of collaboration and consultation with customers in their 2013 Environmental Action Plan [41].

### 5.3. Behavior change pathways

The role of small consumers in reducing electricity demand in Japan is noteworthy, and the pathways and mechanics of these changes, if identified, could inform energy and environmental policy in other locations.

Work by Frederiks, Stenner [42] outlines the largely 'irrational choice model' of decision making by households concerning energy consumption and conservation from a behavioral economics and psychological perspective. These barriers include things like inertia / status quo bias, risk aversion, temporal discounting, lack of incentive, social norm performance and bare minimum (good enough) patterns as obstacles to sustainable energy decision making.

Analysis of the monthly electricity consumption in Japan both before and after the disaster suggests there is the potential for a disaster to short-circuit this model and allow for more sustainable energy choices to become embedded.

Importantly, evidence shows proximity to the disaster may not be critical for behavioral change (such as was the case for Kansai), nor specific targeting of government conservation requests (such as with Chubu and Chugoku). The exclusion of Okinawa from both cohorts provides an additional opportunity for comparison of behavior change motivation moving forward.

The research findings are also relevant to transition planning and visioning as positioned by Verbruggen et al., [43]. The Japan case study highlights the validity of a socio-political model of transition as an alternative to the traditional engineering-economics approach. This example illustrates that adaptation and alteration of core electricity supply and demand paradigms is possible under select circumstances.

Studies of specific actions taken by households to save electricity have been previously published by Fujimi and Chang [1], Fujimi, Kajitani [19], Kimura and Nishio [20], Murakoshi, Nakagami [16] and Tanaka and Ida [21] with largely consistent results. Specific actions taken by users in reducing electricity consumption centered around limitation of air conditioner usage (both length of time and temperature), and refrigeration (lowering temperature), with replacement of lighting with more efficient versions and some stand-by load reduction.

Consistent finding are documented in overseas examples, like those presented for Brazil by Gerard [23] and in Alaska by Leighty and Meier [24], who also found the dominance of lighting, temperature control and refrigeration in domestic energy conservation actions. Research into the underlying motivations for these actions remains very limited.

Our analysis suggests that successful motivators and electricity saving techniques for domestic-scale clients were not effective for larger users, especially those at industrial scales. For these customers it seems the GFC was an equally or more impactful event, but again this was scale dependent, and possibly elastic. Understanding these dynamics better may help shape more user-specific and targeted energy conservation policy and as an extension, inform energy transition management.

For larger electricity users, self-reported actions were centered around behavioral adaptations such as lighting and air-conditioner usage and settings were more common than hardware, scheduling or load shifting initiatives [1, 44]. This builds on commercial insights by Kimura and Nishio [20] who surveyed commercial energy users in summer 2011 to find lighting and air-conditioning limitation were the most popular demand reduction techniques. This was complemented by an increase in self-generation and adjustment of operation hours, which would lower peak grid demand, but does not provide net energy savings.

While these actions aren't clearly reflected in our analysis, they are not inconsistent with the analytical findings. While the commercial and industrial scale data did not show a statistically significant reduction following the disaster, this was likely impacted by a lower post-GFC baseline, and a focus on peak reductions rather than aggregated savings.

Work by Fujimi and Chang [1] suggests that economic considerations were dominant for this group, in that minimal (or no) evidence was found for changes that affected the businesses financially, such as a reduction of production or business hours, decreases in output or capital investment were not voluntarily pursued (with the exception of LED lighting).

This supports the finding that the impact of the GFC was of greater significance or importance to these organizations. As investigated by Guerra-Mota et al, [45], the GFC manifested changes in environmental, social and financial business performance in European electricity utilities. It is probable that similar pressures may have impacted the Japanese experience from a top-down perspective.

The reasons for the differences between cohorts are not well understood. Surveys by Kimura and Nishio [44] of Tokyo and Kansai based participants from 2011 to 2014, (including domestic, commercial and industrial users) show that domestic reductions were driven by a mixture of normative, informational and economic incentives. Commercial and industrial scale energy savings were reported to be initially motivated by corporate responsibility and a desire to reduce regional supply shortages, however this reduced over time to be a cost-saving activity.

A further survey of industrial energy users in Hyogo by Liu et al., [46] found reduction actions were largely independent, siloed decisions; with additional opportunities associated with connection of industries and policy integration not available to users, suggesting a potential informational or network-based difference between user groups may have influenced decision making.

The scale of the user has also been found to influence the perception of 'adverse' impacts of energy saving. Very large industrial clients found conservation activities more burdensome than large commercial or domestic participants, and while normative drivers increased willingness to accept this inconvenience in the short term, this impact was not persistent.

Learning about energy conservation was also found to provide greater long-term engagement of survey participants [44]. Internationally, this is echoed by work in the US showing framing of energy conservation requests influenced response rates, with greater persistence of savings with inclusion of health and environmental messaging over pure economic benefits [47]. The investigation of the role of narrative and scale-applicable education between user groups may also therefore play a role in explaining the different outcomes between user scales.

## 6. Conclusions

This paper details a review of electricity demand and generation data from Japan covering the period of 2005 to 2016, and how the GFC and Fukushima disaster altered those patterns depending on the location, scale and application of energy. It was identified that overwhelmingly, domestic energy users produced demand reductions following the disaster, with higher-draw commercial and industrial customers tending to be impacted to a greater degree by the GFC.

Further, these post-disaster reductions where predominantly (but not exclusively) in the directly impacted 50Hz grid system, with Kansai and Shikoku being notable outliers. The existing sustainability positioning and influence of local governments in supporting energy users in reducing demand may have contributed to these results.

The regional specific reductions were found to coincide with the specific 10-15% conservation request areas, suggesting that compliance with authoritative communication was essential for public action. It is also noteworthy that smaller users of energy were shown to have a longer-term altruistic response (whether deliberate or passive), when compared to larger scale energy users. For this later cohort, electricity demand trends indicate these behaviors are reactive to financial or other market queues only.

This suggests that a combination of both economic incentivization and philanthropical messaging may be positively leveraged in sustaining and enhancing the response of all users to the need for energy use reduction in times of disaster, and for engendering low-carbon energy transitions. However, ultimately additional research is required to better develop the understanding of the decision-making mechanisms to properly apply incentives and advocate for net-reduction electricity saving behaviors.

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