Systems Analysis of the Impacts of the Great East Japan Earthquake and Tsunami on Energy Supply System in Kamaishi-City

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ABSTRACT

The Great East Japan earthquake and tsunami hit coastal cities in Iwate, Miyagi and Fukushima Prefectures of Tohoku Region devastating the energy supply system in the region. Electricity and fuel shortages caused severe problems in the city of Kamaishi varying from lack of mobility, communication, heating to reduced health conditions.

This paper, aims to analyze the impacts of the earthquake and the tsunami on local energy supply system in Kamaishi City by; i) clarifying what energy services were in need when there was a shortage in energy supply right after the disasters by performing semi-structured interviews; and ii) identifying and analyzing causes and effects of the energy supply shortage at local level when the disasters occurred by applying systems thinking approach and causal loop diagramming methodology. Suggested alternative potential measures in tackling energy supply shortages and in preparing future disaster risk reduction plans are expected to be use of policy makers

Key Words: *Earthquake, Tsunami, Natural Disaster, Energy system, systems thinking, Systems analysis, Causal Loop Diagrams*

Introduction

An earthquake of magnitude 9.0 generating a massive tsunami hit north-eastern Japan on 11th March, 2011 (Hosomi 2011, 415). Coastal cities in Iwate, Miyagi and Fukushima Prefectures of Tohoku Region were devastated by this natural disaster with 15,854 people died and 3,155 missing (as of 14th March, 2012) (National Police Agency of Japan 2012).

The earthquake and tsunami unveiled the vulnerability of the current energy supply system that all the affected cities relied upon. Energy supply was insufficient in the affected areas after the disasters due to electricity outage and shortages in fuel supply especially heating oil and gasoline (METI 2011). About 30% of the population in the affected areas is over 65 years old and many of those who could flee from the tsunami battled for survival in the condition with insufficient heating in the severe cold weather in Tohoku region (McCurry 2011). The electricity loss was a vital problem for patients in the hospitals as they needed it for medical devices (Sasahara 2011). It was also critical that communication lines were stopped, which made it difficult to access to vital information (Nohara 2011).

Overall aim of this study is to analyze the impacts of the earthquake and the tsunami on local energy supply system in Kamaishi City in Iwate Prefecture.

More specifically the study aims;

1. to clarify what energy services were in need when there was a shortage in energy supply right after the disasters by performing semi-structured interviews;
2. to identify and analyze causes and effects of the energy supply shortage at local level when the disasters occurred by applying systems thinking approach and causal loop diagramming methodology;
3. to suggest alternative potential measures in tackling energy supply shortages and in preparing future disaster risk reduction plans, which could be use of policy makers.

Research Methods

Empirical data were collected partly from literature, but mainly by conducting semi-structured interviews in the City of Kmaishi, which is one of the coastal cities severely damaged by the tsunami. In November, 2011, About 930 people of total population (approximately 39,000) died or are missing (Kamaishi City 2011) although the city was prepared for tsunami disasters with the world deepest seawall (Hosomi 2011,415)

Semi-structured interview enables the interviewer to vary the sequence of questions and to ask further questions in response to significant replies in interview (Bryman 2008,699).

Table 1 summarizes interviewees and the collected data in the interviews. The interviews were performed among the 97 residents of Kamaishi City, as well as in the Steel Memorial Hospital and Kamaishi Works of Nippon Steel Corporation in order to gather information concerning the significant impacts of electricity outage and shortage of other fuels on individuals' life, medical services and the coal-thermal plant. The data of semi-structured interview with the 97 residents were converted to quantitative data set to create statistical graphs. Yurtec Corporation, a company in charge of maintaining electricity supply network, was interviewed also to study the causalities and impacts of the disasters on the network, as well as the restoration process of the network.

Table 1: Interviewees and collected data

Interviewee	Collected Data
97 Residents	Impacts on individual's life, Place to evacuate, Age group
Steel Memorial Hospital	Impacts on medical services and patients, Measures taken to minimize problems
Kamaishi Works (Nippon Steel Corp.)	Impacts on the coal-thermal plant, Roles of the plant in electricity supply when natural disasters occur
Yurtec Corporation, Kamaishi Branch	impacts on the supply network and process of restoring electricity outage

The research takes systems approach, in which causal-loop diagrams (CLD) were developed to analyze the causalities, impacts and feedbacks of the energy supply shortage in a holistic manner. CLD is a useful tool to quickly and concisely communicate the essential components and interactions in a system (Richardson 1986,158). The intention with the application of causal loop diagramming methodology in this study was to provide a better understanding of how the disaster affected energy supply system had an impact on the quality of life in Kamaishi City. Such an understanding would help all stakeholders (i.e. from residents to local/regional level decision makers) in preparation for disaster risk management and policy making.

3. Results and Discussions

3.1 Results from literature survey (destruction, causalities etc.)

The three severely affected districts (Unosumai-cho, Tenjin-cho, Toni-cho), circled with blue line in Figure 1, were selected for semi-structured interview with 97 residents. The rational of choosing those areas is that the level of damage and geographic features are different amongst those areas, and it was assumed that these as well as other social factors might affect the impacts of energy supply shortage.

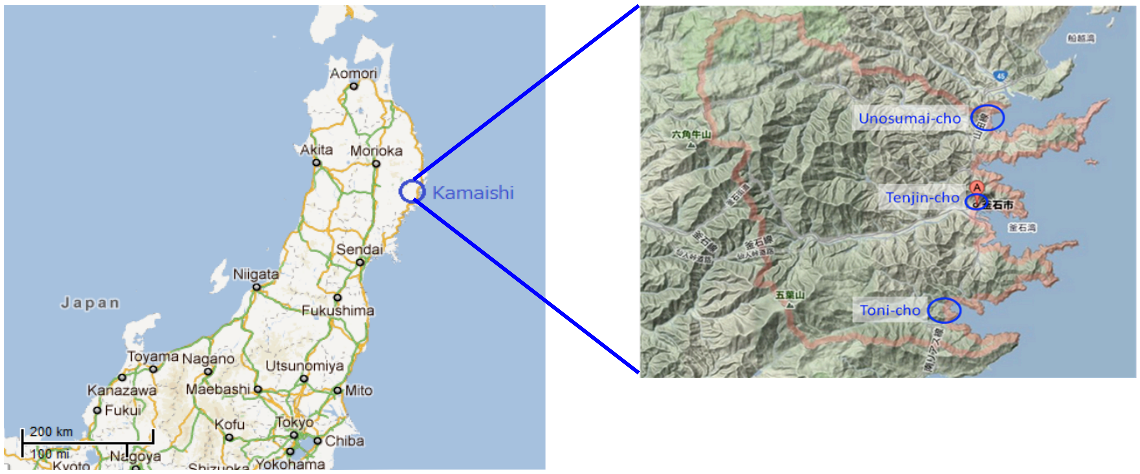


Figure 1: Three areas where semi-structured interviews were conducted (Google Map)

As Figure 1 shows, the entire coastal areas of Kamaishi are shaped with narrow inlets and steep terrains, which tend to increase the amplitude of tsunami. Unosumai-cho in Unosumai District is located in the north in Kamaishi, right next to another municipality of Otsuchi, where there had the most severe damage in Kamaishi (Table 2). Tenjin-cho is one of the areas Kamaishi District, which is the downtown of Kamaishi, with many residential and commercial buildings. The district also had the second largest damage after Unosumai District (Table 2). Toni-cho in Toni District is a fishing village located in the south in Kamaishi. Many private residences were built at high point as the topography of the area becomes steep right near the port. The level of damage as well as number of death or missing persons is relatively smaller than other districts (Table 2).

Table 2: Damage situation in Kamaishi (November, 2011) (Adapted from Kamaishi City 2011)

District	# of Destroyed houses*	% of destroyed houses	# of Deaths or missing persons	% of deaths or missin people
Unosumai District	1,515	51.3	583	62.6
Kamaishi District	1,005	34.0	229	24.6
Toni District	254	8.6	21	2.3
Other Districts	180	6.1	98	10.5
Total in Kamaishi	2,954	100.0	931	100.0

*Number of destroyed houses does not count houses partially destroyed

3.2 Results from the Interviews

3.2.1 Residents' answers

During the interviews, the residents including those who stay in emergency housing units (houses built for people who lost their home by the tsunami) were randomly visited and interviewed one by one. The number of interviewees is 28 in Unosumai-cho (of which 14 in emergency housing), 34 in Tenjin-cho (of all in emergency housing) and 35 in Toni-cho (of which 18 persons in emergency housing). In many cases, residents preferred to stay at the emergency housing close to their home location simply because of staying close to neighbors within the same community.

In each interview, the following three core questions were asked:

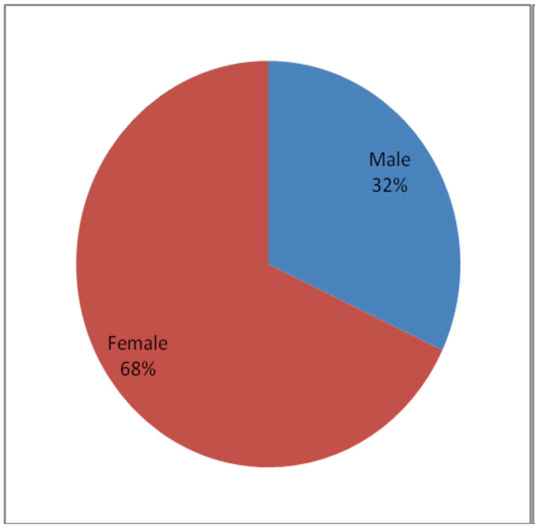
1) *If you do not mind, what is your age range?*
2) *When the supply of electricity, oil and gas were stopped because of the disasters, what were the most significant effects on your life? For example, no communication, no lights, etc…*
3) *Where did you stay right after the disasters?*

Further questions were asked depending on the context of responses. For instance, in case of receiving more general answers (i.e "everything was lacking"), further specific questions were asked to get more detailed answers (i.e. "what were particularly necessary when you did not have such as electricity and heating oil?" etc.)

Quantitative data shown in the following graphs are based on the interview data with 97 residents in the three different areas in Kamaishi, which help understanding tendency of needed energy services and place to evacuate, and differences between those three areas.

3.2.1.1 Demographical figures

Of all the interviewees, 66 were female where as 31 were male. In terms of age group, 68% of all the interviewees were over 60 years old (one interviewee did not answer the question about age group) (Figure 2). The reasons why the majority of interviewees were female and elder people can be twofold: Firstly, most of the interviews were conducted during daytime and weekdays when it is very likely that male and younger generations were working. Secondly, the demography of entire Kamaishi is rather old (Kamaishi City, 2009).



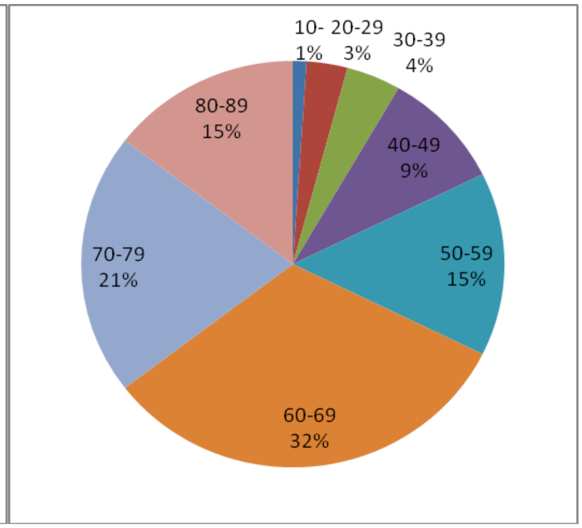


Figure 2: Gender (left) and age group (right) distribution of 97 interviewees

3.2.1.2 Impacts of the Earthquake and Tsunami on Life in Terms of Energy Service

Figure 3, 4 and 5 are the graphs based on the data collected by semi-structured interview with 97 residents. For the question 2), energy services that were needed and lacked were counted based on the following criterion.

1) *Suffered without energy service and no alternative. If there was an alternative way that enables providing a similar energy service (i.e. oil stove heating instead of electricity heating), no count.*
2) *Candle as alternative lighting is counted because its brightness is too little. But lantern is not counted.*
3) *Electric heating and stove heating are counted together as 'heating'.*
4) *Cooking with electricity and cooking with gas are counted together as 'cooking'.*
5) *Use of wood for heating fire and cooking is counted.*
6) *'Saving electricity or other fuels is not counted as it can be understood as 'managed'*

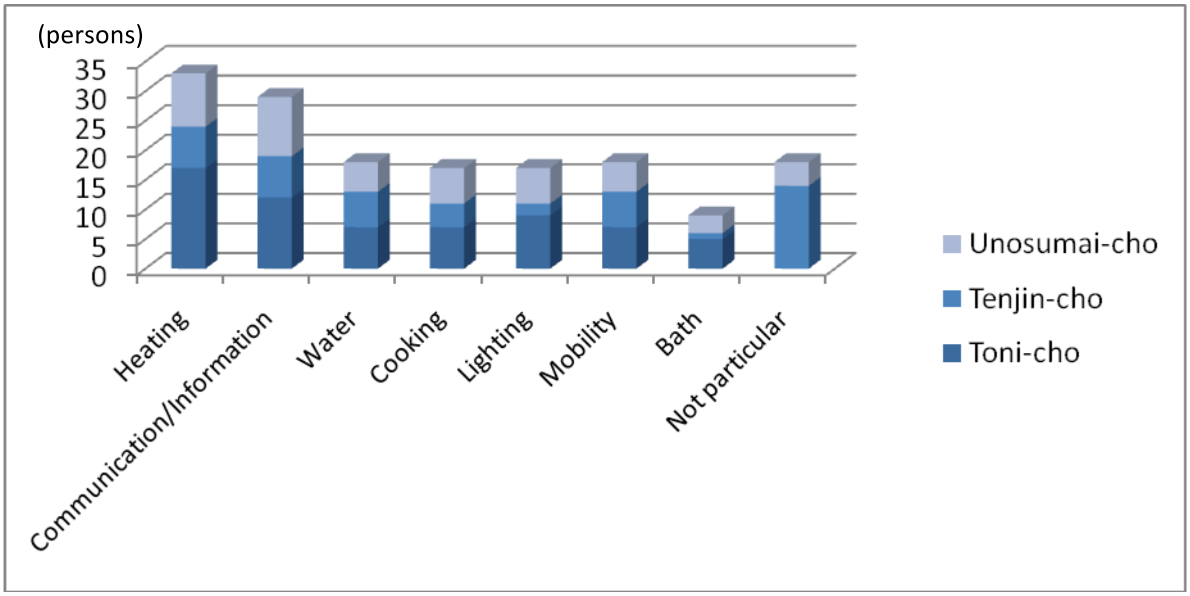


Figure 3: Energy service needed in the three areas in Kamaishi

Figure 3 is the graph that shows energy services, which the residents needed but could not use right after the disasters due to energy supply shortage such as electricity outage and stopped fuel logistics. The interviewees were allowed to answer over one energy service; therefore, the sum of the total number of persons for each type of energy service is over the total number of interviewees. It does not mean that a particular type of energy service, which one did not mention in interview was not necessary, but means less priority compared to what s/he mentioned.

The graph shows that 'Heating' (34% of the total interviewees) and 'Communication/Information' (30%) were particularly necessary, but were not available because of blackout and other types of fuels were in shortage. 'Communication/Information' means there was no or little ways to communicate with others by telephone, mobile and e-mail, and to access information by TV, radio and the internet. 19% of the total interviewees raised 'Water', of which the 72% said that they were in trouble without flushing toilet that needs relatively a large amount of water compared to cooking or drinking. The rest mentioned drinking water. 18% chose 'Cooking', especially those who used electric cooking system had no alternative way of heating water and foods. 18% chose lighting and they used candles instead, of which only 11% chose this in Tenjin-cho. 19% chose 'Mobility' as it was vital for some residents because they needed to bring their family, who were injured by the tsunami, to a hospital. Needless to say, public transportation systems were stopped as well. 'Bathing' (9%) is a daily-custom for Japanese people, but they could not bathe because water could not be heated. 19% chose 'Not particular', of which 74% are interviewees in Tenjin-cho and nobody in Toni-cho.

3.2.1.3 Place to Evacuate in the First Three Days from the Disasters

Figure 4 shows where the residents were evacuated to during the first 3 days after the 11th March, 2011. The intension of this section is to see correlations between areas of interview (meaning places where the interviewees lived when the disasters occurred) and place to evacuate, and eventually to compare with needed energy services. As it takes a few days until people affected get relief supplies such as foods, water and fuels, it is considered that the first 3 days are the most vital for evacuees to survive with self-reliance in this paper. Some interviewees answered that they stayed over one place (i.e. 1 day at home, 2 days at shelter). A place they stayed for a longer period is counted for such a case. But in case an answer is not clear how many days they stayed one place, the first place they evacuated is counted. One interviewee did not answer to the question 3; the sum of the answers is 96.

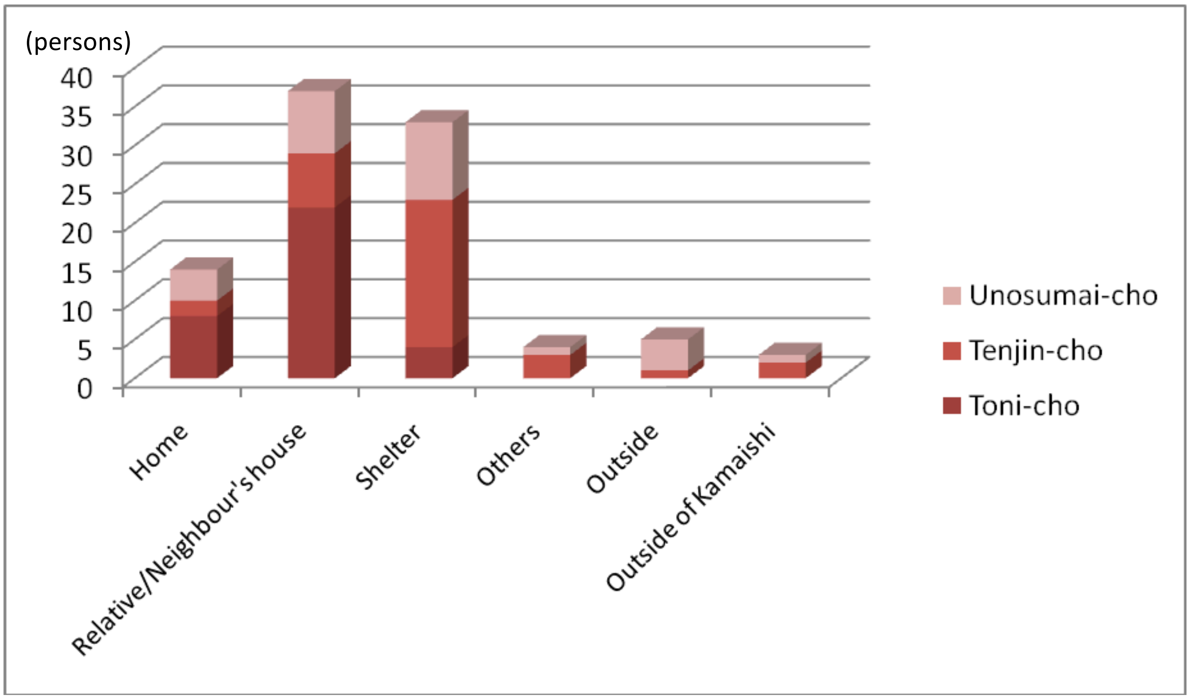


Figure 4: Place to evacuate right after the disasters (First 3 days)

Figure 4 shows the clear difference amongst the three areas. While 24% of the interviewees in Toni-cho stayed at their home and 65% stayed in their relative/neighbor's home (mostly, in Toni-cho), 56% in Tenjin-cho and 34% in Unosumai-cho stayed in shelter such as school or hospital in the downtown or more inland areas in Kamaishi. This difference implies the next two points. Firstly, the social network within community could be relatively stronger in Toni-cho than other two areas. Many residents had their relatives lived in the same area, and they knew well and could help each other. Secondly, in Toni-cho, although many houses near the port were destroyed, those located at high point were safe while many buildings were destroyed on the flat area and close to the sea in the downtown and Unosumai-cho as Table 2 shows. Therefore, it might be difficult for evacuees in Tenjin-cho and Unosumai-cho to find a home nearby to stay although they might have relatives in the same area, thus public buildings played important roles. It is also important to note that 4 % in Unosumai-cho stayed outside (in a mountain) for the first three days.

3.2.1.4 What Energy Service was needed Depending on Place?

Figure 5 shows energy services needed depending on place where the residents evacuated. 34% of the interviews who stayed in their ‘Relative/Neighbor’s home’ chose ‘Mobility’. One possible reason is that they might need to drive to buy foods as they might share limited foods with many persons. But it does not seem that there is a strong correlation between staying in ‘Relative/Neighbor’s home’ and needing mobility because 56% of the interviewees who raised ‘Mobility’, needed to drive to find missing people or for other reasons rather than buying foods. What is important in this graph is 42% of those who stayed in shelter chose ‘Not particular’ and many of them were interviewees in Tenjin-cho. This result implies that , compared to other places to evacuate, there is tendency that those who were in shelter had fewer troubles in terms of energy service as some of them answered there were a power generator and oil heating stoves.

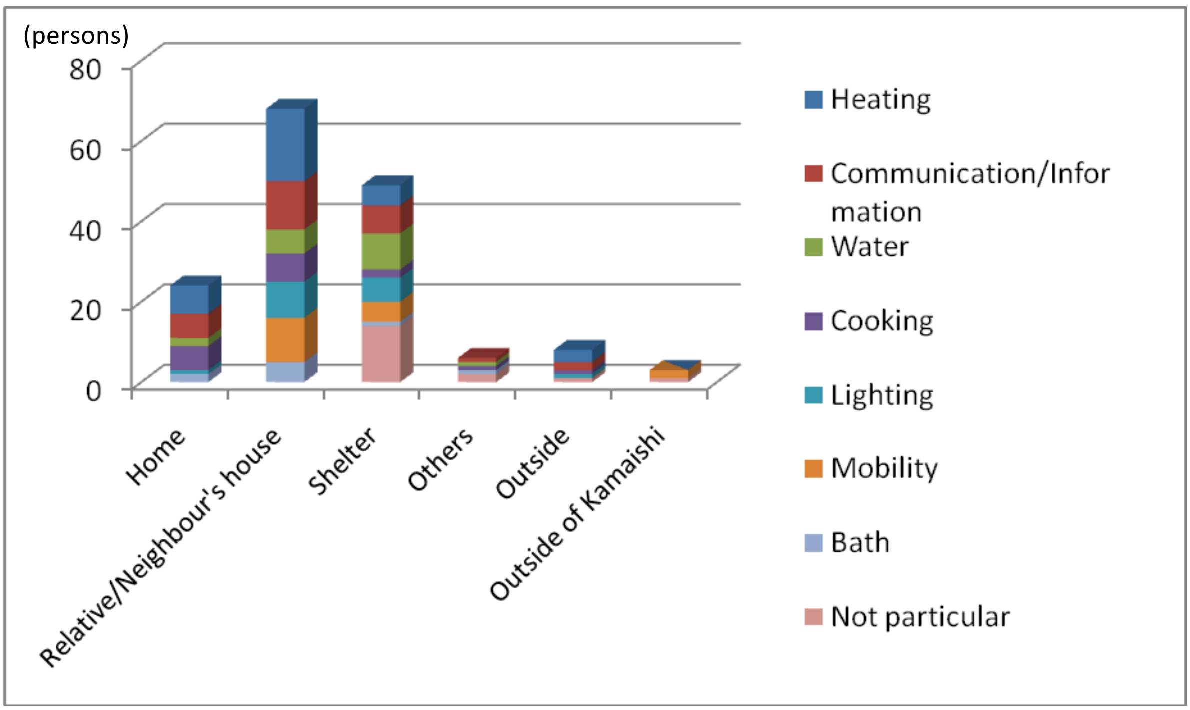


Figure 5: Place to evacuate and energy service needed

3.2.2 Steel Memorial Hospital's and Kamaishi Works of Nippon Steel Corporation's answers

There were not significant impacts on medical services and patients in Steel Memorial Hospital. Although electricity was not supplied from the regional grid system, the electricity generator for emergency worked and the enough light oil for electricity generation was remained. Some light oil was also supplied from Kamaishi Works of Nippon Steel Corporation as the hospital belongs to the group of the company. Heating also functioned although the fuel use was a little saved. According to the interview with the hospital, there were not significant impacts of energy supply shortage on medical services in other hospitals that were not directly affected by the tsunami in Kamaishi, either.

The crucial problem in Kamaishi Works of Nippon Steel Corporation was protecting their facilities in the situation of blackout. Kamaishi Works had the coal-thermal plant (MW) running as Independent Power Producer (IPP), which produced and sold electricity to Tohoku Electricity Corporation through the regional grid system. When the blackout occurred, the turbine of the plant needed to be kept rotating with alternative electricity supply since its temperature was high. Otherwise, damage for the turbine would be quite huge, which means the shape of the turbine would be changed because of its temperature. Thus, electricity was supplied to keep rotating the turbine by the electricity generator for 3 days, until the temperature decreases enough. Since the amount of light oil for the generator was for a half day in the fuel tank, which was in maximum, additional fuel was necessary to be supplied from the tanks of the tracks of Nippon Steel Logistics Corporation in the same area every half day.

3.3 Systems Analysis of the impacts of the earthquake and tsunami based on the information gathered from literature survey and the interviews

After gathering the necessary information from literature and the interviews, systems approach and causal loop diagramming methodology were applied to identify and analyze the causes and effects of the energy supply shortage in Kamaishi. Following that, alternative measures to respond, recover from and reduce the shortage in energy supply were identified.

3.3.1 Causes and Impacts of Energy Supply Shortage

Causal loop diagram given by Figure 5 shows the key elements of the total energy supply system in Kamishi. Causes for the energy supply shortage and the negative impacts of this shortage on the individuals' life are shown with this CLD.

Some of the interrelations between the components of the system are simplified for easy understanding. Words written in red are original causalities of energy supply shortage (i.e. magnitude of earthquake), those in blue with underline are energy services in need (i.e. heating, lighting), and those in a rectangular means 'stock' (i.e. heating oil available, water available).

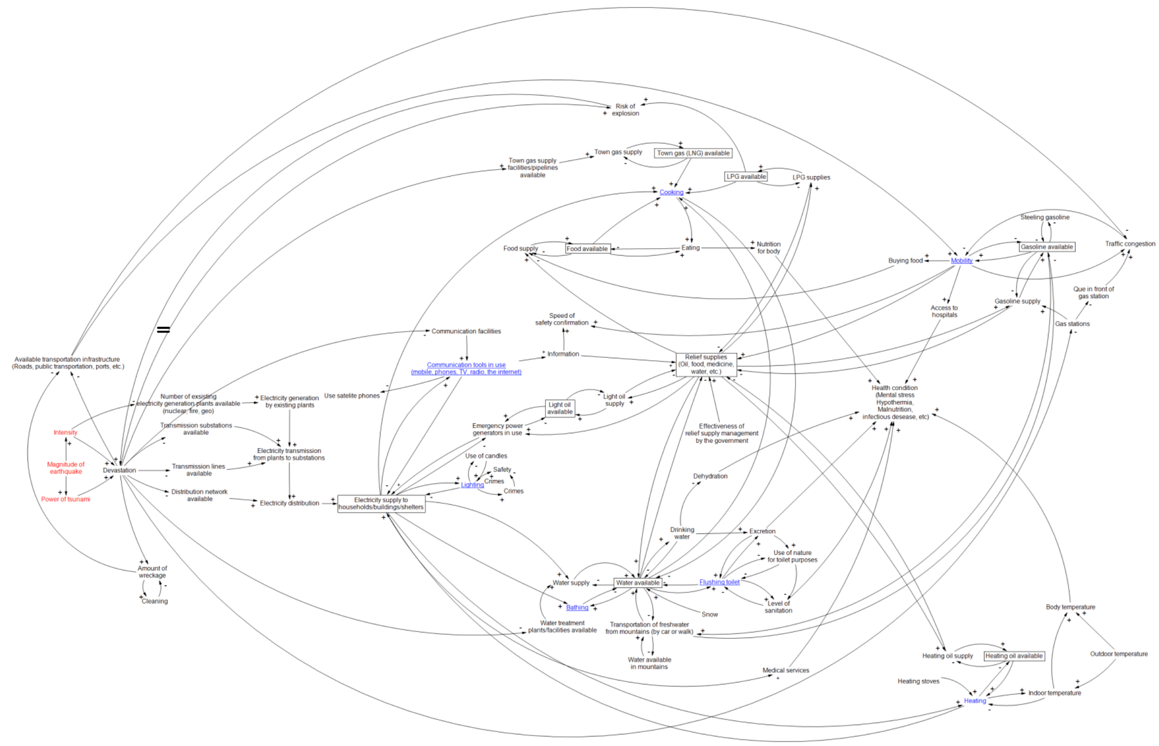


Figure 5: CLD of causalities, impacts and feedbacks of Energy Supply Shortage in Kamaishi

Generally, the higher the magnitude of the earthquake the higher becomes the intensity of the earthquake and the power of tsunami. Several other factors affecting the intensity of the earthquake and the power of tsunami (i.e. location of earthquake origin and topography of coastal areas etc.) are not shown in the CLD. Both the intensity of earthquake and the power of tsunami determine the level of devastation. The higher the devastation, the larger the amount of wreckage, together which destroy the transportation infrastructure (i.e. roads, rails, ports etc.)

Electricity supply – As the CLD shows, the number of electricity generation plants available reduces with the intensity of the earthquake. Once the intensity of earthquake exceeds a certain level, the electricity generation plants automatically shut off due to safety systems. This in fact what had happened in Tohoku region, where the electricity is produced and transmitted to Kamaishi. More devastation leads to less number of available transmission substations, transmission lines (including towers) and distribution networks. In the coastal areas in Kamaishi, tsunami or wreckage of buildings severely damaged distribution networks such as power lines and utility poles. Needless to say, with no electricity produced and distributed to these areas, the households suffered from electricity outage. Areas where distribution networks were not destroyed received their electricity once the transmission substations and lines were restored.

When electricity is not supplied through the regional distribution network, it can still be generated by emergency electricity generators mostly stationed in shelters and hospitals. Fuel needed to run these generators is light oil and once there is shortage of it, it comes from other locations as a relief supply (see below for further information about other relief supplies). Lack of electricity creates a range of impacts on society varying from communication to water availability, to heating etc.

Water availability- Electricity is necessary for water supply system including the water treatment plants, which were severely damaged by the devastation in Kamaishi. The main problem caused by the water supply shortage is the reduced health conditions due to decreased levels of sanitation and dehydration.

Interviewees highlighted four areas of water usage; drinking, cooking, bathing and flushing the toilets. Flushing water is one of vital problems here as relatively a large amount of water is required and lack of water generates sanitary and in turn health issues. Use of the nature as an alternative to toilets does not require water, where as it decreases the level of sanitation. People can also suffer from dehydration incase of not drinking enough water. Transportation of freshwater from neighboring mountains and melting of accessible snow were mentioned as two alternative ways of increasing the water available.

Lighting – Lack of lighting due to electricity outage generates some safety issues including increased level of crime. Use of candles as an alternative way of lighting was mentioned by the majority of the interviewees.

Communication – Because of communication facilities (e.g. electric wave towers) destroyed by the devastation and the lack of electricity, people cannot not use communication tools. This prevents them to access to vital information (i.e. situation, information of relief supplies) and to confirm the safety of family members and the relatives.

It is also difficult for them to inform outside of the city what types of assist is needed. Satellite phones are used in such a case, but number of satellite is quite limited in general. Use of satellite phones allows the user to have access to information.

Heating – Lack of proper heating is a vital problem especially when the outdoor temperature decreases to below 0 degrees. Houses with only electric heating facilities suffer dramatically when there is no electricity. Those who are forced to stay outside for a few days struggle with the coldness as well. Risk of hypothermia, especially for elderly people and young children, may increase if they stay in the cold environment for many hours. Oil heating stoves can be used as alternative as far as heating oil is remained. Additional heating oil together with other relief supplies come from other locations.

Cooking – Lack of cooking becomes a serious problem in households with only electric cooking systems. Even those houses using town gas (LNG) have the same problem, since the devastation affects the town gas supply facilities including the pipelines. But, those with

LPG (Liquefied Petroleum Gas) tanks do not have such problem. In addition to the means for cooking availability of water and food are the two other factors affecting cooking. Available food is limited in the beginning stage after disaster occurs. In such a situation, those who do not eat sufficiently may lack nutrition. It is also important to mention that LPG has risk of explosion when severe natural disaster hits, which can cause fire and further devastation.

Mobility – When gasoline is in shortage mainly because of the gas stations out of order due to the devastation, lack of mobility becomes a crucial problem. Since available transport infrastructure is damaged or blocked due to devastation by tsunami and wreckage of buildings, more traffic congestion is enhanced. Public transportation does not function, either. Long queues in front of the gas stations that are functioning created traffic congestion. Traffic congestion decreases mobility, and it eventually would affect delivering relief supplies. Cases of stealing gasoline increase when available gasoline is limited.
Three major negative impacts of the lack of mobility are defined as having problems with access to hospitals, to food and the speed of safety confirmation of the family members.

Relief supplies – Supplies needed to maintain the daily life such as food, drinking water, emergency electricity generators, batteries, light oil, heating oil and LPG constitute the relief supplies. They are mostly brought from outside of Kamaishi, all over Japan and there are several factors affecting the speed of the transportation and the amount of the relief supplies. Problems with the transportation infrastructure and lack of gasoline affect the level of mobility in a negative way. Communication plays a crucial role to pass the information concerning which and how much of relief supplies are needed. The effectiveness of governmental (national, prefectural and municipal) management of relief supplies affects the speed and accuracy of transporting. The complication in the national government might delay the decision of the transportation.

3.3.2 Potential Alternative Measures for respond, recover and Risk Reduction

Figure 6 is the CLD with some potential alternative measures for energy supply. Response stage is the most important here in terms of resilience enhancement because its aim is to increase ability of society - energy supply system to survive or persist against natural disasters so that human needs (energy services) are met. Response is defined as the period that immediately follows the occurrence of the disaster. This means that there are alternative energy supplies, which support individual’s life or other social functions (i.e. medical services) with self-reliance (until assists from outside of the city arrive, which takes a few days) although natural disasters stop or disturb existing energy supply system functioning.

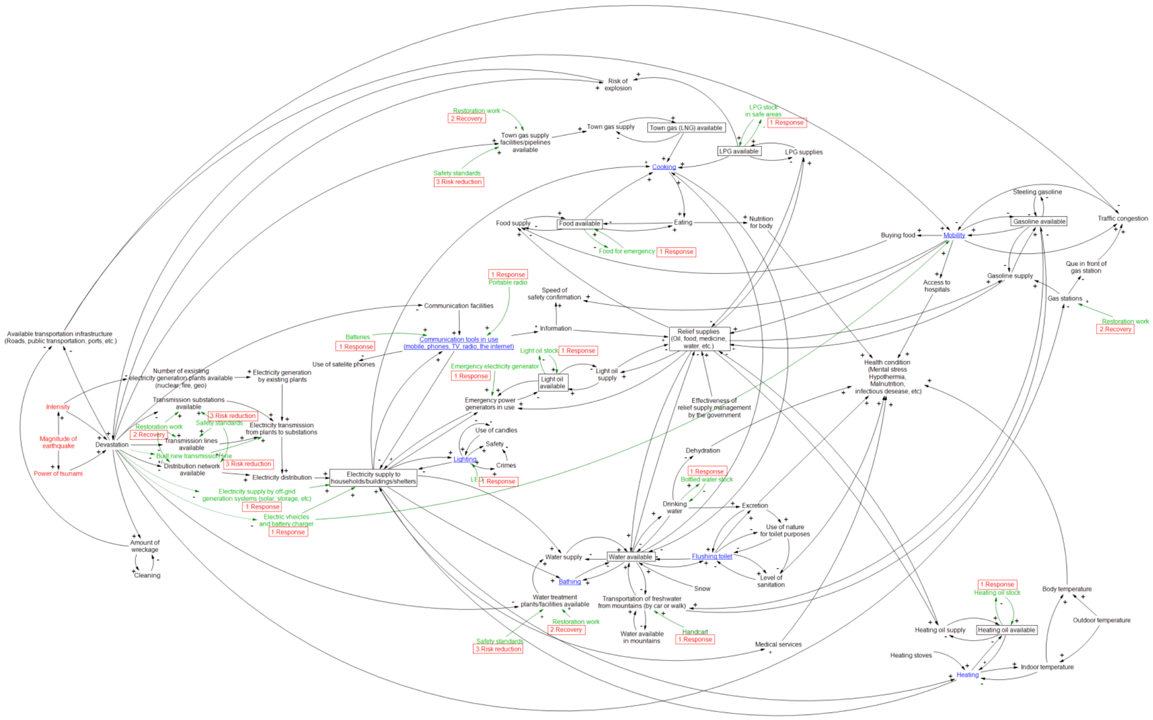


Figure 6 : CLD with potential alternative measures for risk reduction

Response – As the CLD shows, once power distribution lines are destroyed, there is no electricity supply until they are restored. Thus, it is important to increase off-grid electricity generation systems. The easiest measure is to prepare emergency electricity generators in shelters with certain amount of light oil that can last at least 3 - 4 days. In mid- to long-term, use of electric vehicles as electricity storage is a potential measure if electricity can be charged by off-grid power system in private residence or in a community. Electric vehicles also contribute to mobility when gasoline supply is limited. Use of LED lights instead of candles enables brighter and safer lighting with batteries. Portable radio with batteries is useful and affordable communication tool if electricity outage and troubles with communication facilities occur. It is also easy to have stock of emergency food and drinking water. Handcart is an affordable and convenient tool to transport large amounts of freshwater without driving a car. It is possible to have heating oil and LPG in stock, although it is important to note that LPG has relatively higher risk of explosion if severe devastation occurs.

Not only supply side measures mentioned above, but also demand side measures are important to note. Strong social networks within a community, for instance, are quite important in the sense that evacuees can help each other and have access to limited amount of resources or energy services (i.e heating and lighting) in a more effective way. It is practical to deliver relief supplies to shelters, where many evacuees stay together as compared to individual private residences. Therefore, it is quite important to inform the residents in advance about where relief supplies are delivered in case of disasters.

Recovery – Recovery is defined as phase when the immediate needs of the population are met, when all medical help has arrived and people have settled from the hustle. Restoration work for facilities (i.e. electricity transmission substations and line, distribution networks, water treatment plant, town gas pipelines/facilities and gas stations) needs to be conducted as quickly as possible to recover energy supply systems.

Risk reduction – This is the phase when the population has returned to predisaster standards of living. But, they recognize the need for certain measures, which may be needed to reduce the extent or impact of damage during the next similar disaster. Strengthening safety standards of facilities (i.e. transmission substations and lines, distribution networks, town gas facilities/plants and water treatment plants/facilities) is a potential measure to reduce risk of future disasters. Building new transmission lines also reduces risk of electricity outage.

4.Conclusions and Recommendations

This paper addresses the problem of vulnerable energy supply systems when severe natural disasters occur by studying the case in Kamaishi City.

Causal-loop diagramming methodology contributes to analyzing and visualizing causes, impacts and feedbacks of energy supply shortage due to earthquake and tsunami. The methodology also helps analyzing potential alternative measures to enhance resilience of society in terms of energy supply. Resilience is an important concept to consider and prepare measures to supply energy in response phase when the existing energy supply system does not function due to devastation. It is expected that CLD will serve as a decision support tool that can be used by both the residents of Kamaishi city and the policy makers in preparing future disaster risk reduction plans.

Social, economic and technological feasibility of the suggested potential alternative measures (i.e. off-grid energy generation systems, electric vehicles) requires further research ideally including a set of group modeling workshops with broad stakeholder participation and system dynamics modeling for decision support.

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