The Sendai Microgrid Operational Experience in the Aftermath of the Tohoku Earthquake: A Case Study

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1. Introduction

This case study describes the Sendai Microgrid, located on the campus of Tohoku Fukushi University in Sendai City in the Tohoku district in Japan, and focusses on its operation in the aftermath of the Tohoku Earthquake.

The Sendai Microgrid was initially designed in 2004 as a test bed for a demonstration project of the New Energy and Industrial Technology Development Organization (NEDO), entitled "Experimental Study of Multi Power Quality Supply System (MPQSS)." The demonstration project was conducted by NTT Facilities, Inc. (NTT-F). The microgrid supplied power to facilities at the Tohoku Fukushi University. After the study was completed in 2008, the microgrid system continued in operation under the management of NTT-F.

On March 11, 2011, the devastating Great East Japan Earthquake hit the Tohoku district, inflicting catastrophic damage on the district's energy supply system for a number of days. Despite the extreme devastation, the Sendai Microgrid continued supplying power and heat to customers, proving its effectiveness.

The primary focus of this case study is an analysis of the operations of the Sendai Microgrid in the aftermath of the earthquake.

2. Configuration of Sendai Microgrid

The Sendai Microgrid is the system constructed by NTT-F for the "Experimental Study of Multi Power Quality Supply System (MPQSS)", implemented by NEDO between 2004 and 2008. The configuration of the microgrid system has changed several times since the NEDO demonstration project. The configuration of the microgrid at the time of the earthquake is shown in Figure 1.

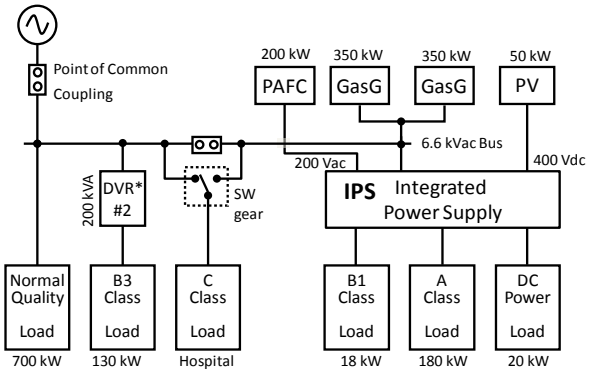


Figure 1 System Configuration of the Sendai Microgrid

The Sendai Microgrid has several generation sources: two gas engines, a phosphoric acid fuel cell (PAFC)[1] and a photovoltaic array. It was designed according to a concept of multi-power quality, to be capable of supplying various classes of power quality within a microgrid, as shown in Figure 1. An overview of the requirements for each class of power quality is shown in Table 1.

Table 1: Requirements for Power Quality Classes

Requirements	Power Quality Class Category				
	DC Power	AC Power			
		A-Class	B1-Class	B3-Class	C-Class
Interruption	NI	NI	< 15 ms	< 15 ms	< 15 ms
Voltage Dip	Y	Y	Y	Y	-
Outage	Y	Y	Y*	-	Y*
Voltage Fluctuations	Y	Y	-	-	-
Voltage Harmonics	Y	Y	-	-	-
Voltage Unbalance	N/A	Y	-	-	-
Frequency Variation	N/A	Y	-	-	-

Key: NI = No Interruption; Y = With compensation; - = Without compensation
** When Gas engine sets operate*
Power supply to B2-Class was suspended after completion of the demonstration project.

[1] The original configuration of the Sendai Microgrid included a molten carbonate fuel cell (MCFC); after the earthquake a phosphoric acid fuel cell (PAFC) was substituted.

DC power and the loads of A and B1 classes are supplied via an Integrated Power Supply (IPS). As shown in Figure 2, the IPS is configured with four types of two-way converters: high-quality inverter, DC-DC converter, PV connected converter, and a valve-regulated lead-acid battery as an emergency backup, enabling the supply of high quality power. The control center is DC powered.

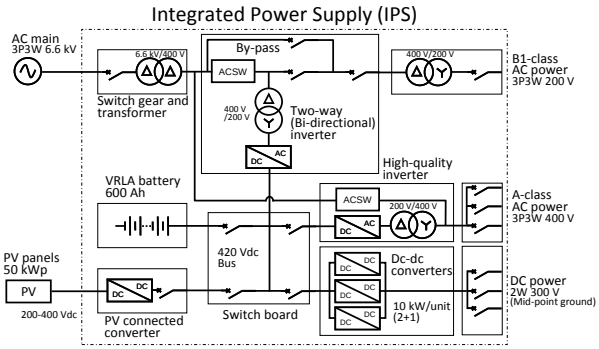
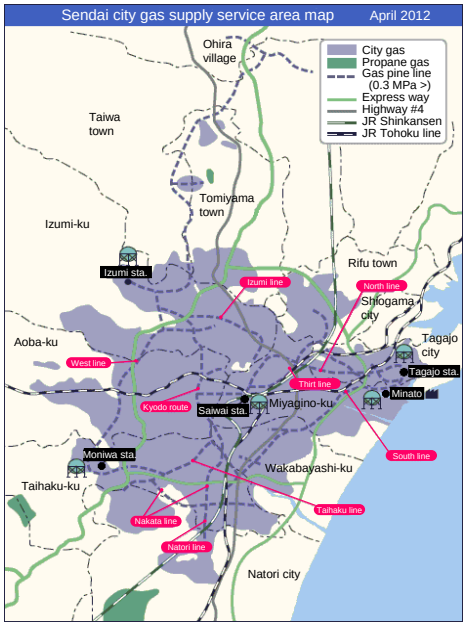


Figure 2 Integrated Power Supply (IPS)

The main energy source for the Sendai Microgrid is fuel for the gas engines, purchased from the gas utility of Sendai City. The Sendai City Gas Bureau procures LNG imported from overseas and natural gas brought from the Niigata prefecture via a wide-area pipeline. The fuel for the gas engines is supplied through a medium pressure pipeline. The coverage area of the Sendai City Gas Bureau is shown in Figure 3.



Source: Sendai City Gas website[2]

Figure 3 Supply Area of Sendai City Gas

The electric power company in the Sendai area is the Tohoku Electric Power Company (Tohoku EPC). An agreement with the Tohoku EPC permits the Sendai Microgrid to supply power to loads within the area shown in Figure 4 (including the hospital and nursing care facilities located on the campus of Tohoku Fukushi University).

As shown in Table 1, electricity supplied by the Sendai Microgrid is divided into five classes according to the level of power quality. The magnetic resonance imaging machine (MRI) and server installed in the clinic and laboratory are supplied with A-Class power. The nursing care facilities are supplied with B1 and B3 Classes to meet the critical needs of its elderly residents. Four elderly people, dependent on ventilators for life support, are residents in the nursing care facility, a B3-Class load. The hospital, which serves patients with psychiatric illnesses and internal diseases, receives C-Class power.

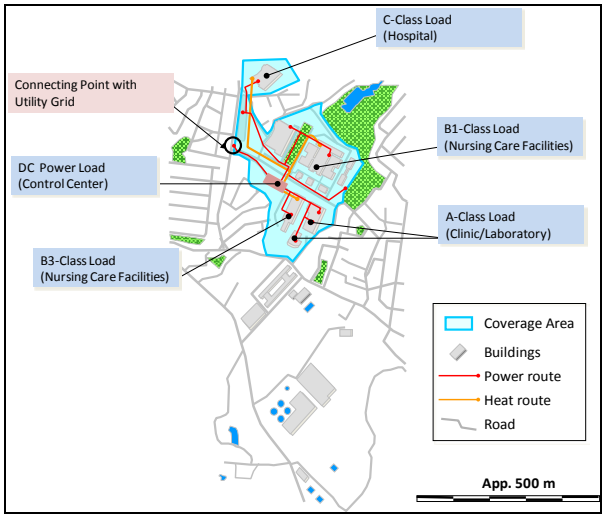


Figure 4 Supply Area of the Sendai Microgrid

After the NEDO demonstration project was completed, the system was modified to enable it to act as a "co-generation system" utilizing thermal energy from the waste heat produced by the gas engines used in the hospital and medical facilities to supply heat, hot water, and chilled water, cooled by absorption chillers. Thus, the Sendai Microgrid has evolved to become a comprehensive energy system producing and delivering not only electricity, but thermal energy as well.

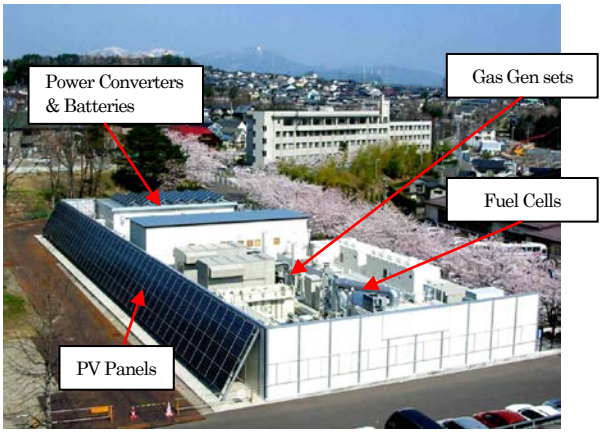


Figure 5 Sendai Microgrid

[2] http://www.gas.city.sendai.jp/top/about_us/area/index.php

3. Earthquake 3.11 in Tohoku Area and Energy System

The Tohoku Region Pacific Coast Earthquake occurred at sea bottom 130km off the east-southeast coast of the Oga Peninsula of Miyagi prefecture at 14:46:18 JST on March 11, 2011, with a magnitude of 9.0. It was the most powerful earthquake in the country's recorded history, resulting in devastating damage in northeastern Japan. The tsunami it produced caused tremendous loss of life and property. The inland areas of the Tohoku and Kanto regions suffered from damage to lifeline utilities due to the shutting down of power plants and collapse of infrastructure, forcing residents to endure significant hardship until the restoration.

Source: Central Disaster Management Council[3]

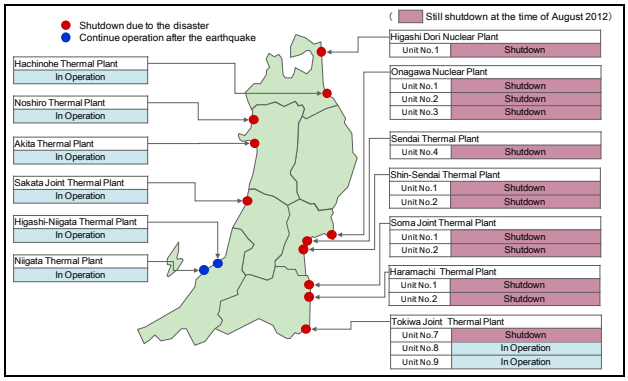
Figure 6 Devastation by the Great East Japan Earthquake (Kamaishi City, Iwate Prefecture)

A blackout occurred immediately after the earthquake in most areas served by Tohoku EPC, with many power plants shutting down completely, as shown in Fig 7. Power supply from the utility to the area surrounding the Sendai Microgrid was not restored for almost three days.

Table 2: Blackout in Tohoku Area after the earthquake

Volume of power supply interruption	Approx. 7,900,000kW (Approx. 60% of loads suffered from the power outage.)
Maximum number of households losing power	Approx. 4,660,000 households
Blackout area	All areas of Aomori, Iwate and Akita prefectures. Almost all areas of Miyagi and Yamagata prefectures. Parts of Fukushima prefecture.
Power restoration*	Approx. 80%* of the power restored within 3 days after the occurrence of the outage. Approx. 94%* of the power restored within 8 days after the occurrence of the outage. At 11:03 on June 18th, power was fully restored.

** In all areas where recovery work on physical infrastructure was possible.* Source: Central Disaster Management Council[4]



Source: Central Disaster Management Council[5]

Figure 7 Status of thermal and nuclear power plants of Tohoku EPC

The gas supply system suffered enormous damage as well. In eight prefectures in Tohoku district, sixteen gas utilities affected by the earthquake were forced to suspend gas supply.

Due to the earthquake, gas supply by the Sendai City Gas Bureau to three major blocks of the service area was suspended. The tsunami after the earthquake was absolutely "beyond assumption" for the Gas Bureau.

Then due to the tsunami, the Minato Gas Plant, the LNG terminal of Sendai City Gas Bureau, shut down. This was the first ever shutdown of a LNG terminal in Japan. Also, as shown in Figure 8, the Minato Gas Plant suffered severe damage, and the restoration work required for approximately 310,000 households made it extremely difficult to supply gas to residential customers.

Figure 8 Severe damage at Minato Gas Plant

As it was estimated that it would take nearly a year to restore the LNG terminal, a wide-area natural gas pipeline was used as an alternative to transmit gas from Niigata prefecture in west-north Japan, supplying mid/high-pressure gas to Sendai. This mid/high-pressure gas pipeline was constructed with high-strength steel pipes and welded joints that were highly quake-resistant and were not affected by the earthquake.

[3] http://www.bousai.go.jp/jishin/chubou/higashinihon/9/sub2.pdf
[4] Ibid
[5] Ibid.

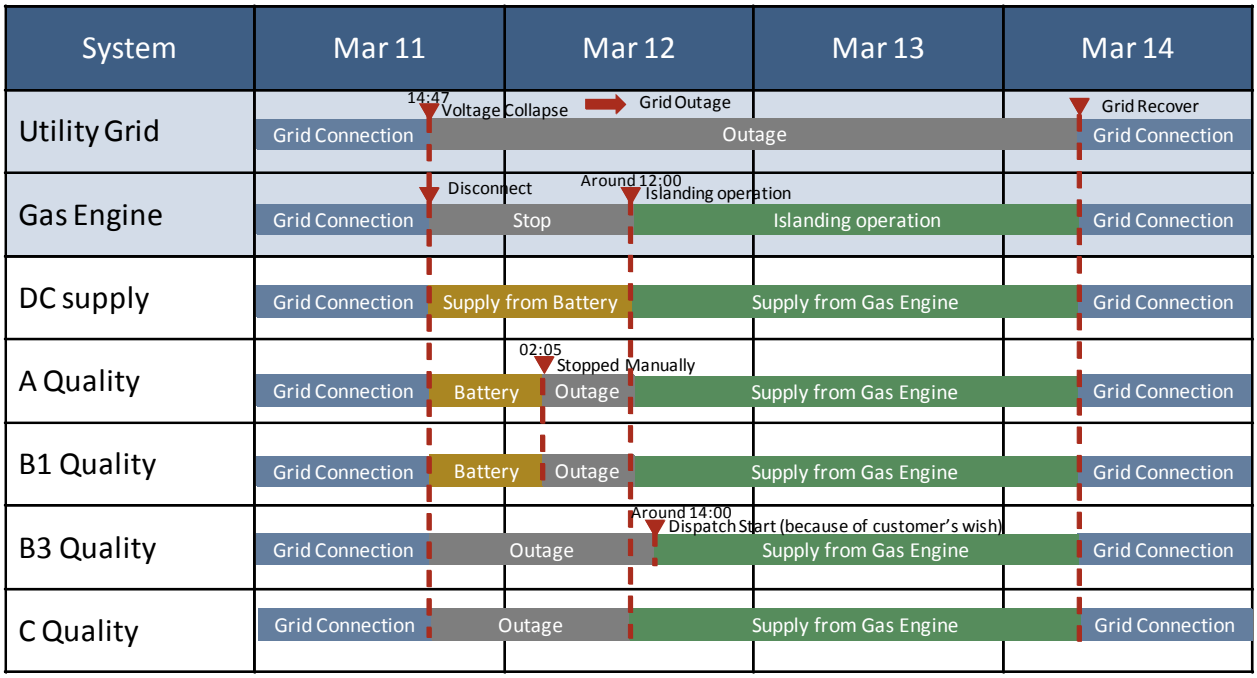


Figure 9 Operation of Sendai Microgrid during Grid Interruption

4. Sendai Microgrid Operation

As described above, the earthquake caused massive damage to the Tohoku district where the Sendai Microgrid is located. When the earthquake occurred, Tohoku EPC stopped supplying power to the area surrounding the Sendai Microgrid, resulting in a three-day outage.

Nevertheless, the Sendai Microgrid was able to supply power to loads within its service area continuously. The timeline for microgrid operations from the time it was disconnected from the distribution system until reconnection is presented in Figure 9.

●11th/Mar/2012 14:47

Beginning several tens of seconds after the occurrence of the earthquake at 14:46 on March 11, there were a series of major voltage fluctuations in Tohoku EPC's commercial grid, then a gradual drop in voltage, leading to the outage. Accordingly, the Sendai Microgrid switched over to island mode.

The gas engines were affected by the grid's abnormal voltage. They were forced to stop generating power due to their design for preventing abnormal operation, causing the system go into an outage on the 6.6kV bus. Thus, power supply to B3 and C classes was stopped.

Three hours later, the microgrid operator arrived at the site and attempted to restart the gas engines manually. However, the gas engines did not activate because the control system batteries were totally discharged, and did not recover until about noon on March 12th.

Even after the gas engines stopped, the microgrid continuously fed power to customers of DC Supply, A class and B1 class (which are connected to the IPS) by utilizing storage batteries in the IPS and PV as the power source.

●12th/Mar/2012 02:06

As the remaining level of battery storage in the IPS fell and the voltage extended beyond the operating range, the microgrid operator stopped operation of the battery for safety reasons, resulting in the outage of A-Class and B1-Class. On the other hand, DC Supply continued feeding power even after the power interruption of A and B1 classes, because the DC Supply's minimum operating voltage was slightly lower than that of the inverters and the load was not so great.

●12th/Mar/2012 approximately 12:00

The gas engines were restarted manually after the local operator implemented provisional cabling work that supplied power to the control source circuit from another power panel. The operator checked the power feeding the facility, including the gas engines, and confirmed their safe operation. The Sendai Microgrid resumed power supply to A, B1 and C classes with the gas engines operated in island mode.

●12th/Mar/2012 approximately 14:00

As shown in Figure 1, the Sendai Microgrid excludes B3-Class from its island system. However, at the time of the earthquake, there were four elderly people using ventilators in the nursing care facility. Considering that further interruption of the power supply would be fatal to those people (customers), Tohoku Fukushi University requested B3-Class power supply.

Responding to this request, the microgrid operator supplied B3-Class power by switching the feeding route to the bypass route.

●14th/Mar/2012 08:16

Tohoku EPC's commercial grid was restored. Once all microgrid equipment for two-way power flow with the grid was checked and readied for interconnection, the Sendai Microgrid was reconnected to the distribution grid and returned to its normal operating mode.

5. Lessons Learned

As described above, the Sendai Microgrid continued to supply power despite the devastating damage to the power delivery system in the Tohoku area due to the earthquake. The lessons learned from this experience have many implications for the future design, siting and construction of microgrids. These are examined in the four points below.

Point (1): Importance of microgrids in times of disaster

First of all, it was demonstrated that microgrids are a very effective power supply system in times of disaster.

The earthquake and tsunami together were an unprecedented disaster which was totally "SOUTEI-GAI" – "beyond assumption." In recent memory, the Japanese people have never experienced being without electricity for as long as three days. Therefore, remediation on this scale was neither anticipated nor planned for. It is noteworthy that the Sendai Microgrid was able to continue uninterrupted supply of electricity under such severe circumstances.

The temperature was approximately 5℃ when the earthquake occurred, and under 0℃ from midnight through early morning of the next day, making the provision of heat for survivors a critical issue. This was especially a challenge for Tohoku Fukushi University, with its extensive medical and health care facilities. There it was crucial to supply not only electricity, but also thermal energy to sustain hospital patients and elderly nursing home residents. The microgrid made this possible through its co-generation system supported by the gas engines.

The most striking point is that the microgrid saved lives. Fatal accidents did not occur in the hospital which specialized in internal diseases, the C-Class Load. The nursing care facility, categorized as a B3-Class Load, accommodated four elderly persons who relied on ventilators for life support. It would not be an exaggeration to say that the judgment and actions of the microgrid operators saved the lives of these people. Mr. Toshiharu Nakabayashi of Tohoku Fukushi University, representing consumers, remarked as follows:

Comment by Mr. Nakabayashi

I believe that the quick rerouting to form the additional bypass of power supply to B3-Class Load resulted in saving people's lives. I am really glad that we introduced the microgrid into our university because energy supply involving human lives is extremely important. I would like to improve the reliability of the energy supply system for the facilities with life-support systems.

This result can be attributed to the "immediate and flexible" response with uninterrupted power supply that is possible with microgrids, which by definition serve defined loads in a limited area. Mr. Kouichi Hoshi and Mr. Masayuki Suzuki from Sendai City Gas Bureau talked about the Sendai Microgrid as follows:

Comment by Mr. Hoshi and Mr. Suzuki

We are happy that, from our experience this time, we could realize the importance of microgrid in the time of disaster as well as the effectiveness of the microgrid based on gas supply.

Various purposes can be served by the establishment of microgrids, such as minimizing energy loss, maximizing the use of renewable energy, and creating new business models for electricity generation and distribution. However, this experience demonstrates that microgrids offer significant advantages and benefits in the areas of disaster survivability and resiliency. This should be kept in mind when microgrids are designed, sited and constructed.

The Sendai experience shows us that microgrids have an important role in providing back-up power for extended periods of time to critical facilities during disasters, especially when the care of hospital patients and nursing home residents must be sustained.

Point (2): Importance of a diversity of power sources

It is evident that the key to the Sendai Microgrid's continuous power supply during the disaster was a diversity of energy sources. Equipped with gas engines and photovoltaics, the microgrid was capable of operating in island mode following the outage.

The gas engines used natural gas supplied through medium pressure pipeline as fuel. In Japan medium/high gas pipelines are composed of high-strength steel pipes and welded joints which are highly disaster-resistant. These were used to deliver a stable energy supply to the gas engines in the Sendai Microgrid despite the disruption caused by the earthquake.

Gas engines with access to an energy supply were central to the Sendai Microgrid's capability to supply power over the extended period of the outage when islanded due to service interruption from the distribution company.

Fuel cells and PV arrays may not be sufficient sources of power during disasters; for example, solar panels can be broken during an earthquake and rendered useless during long periods of rain. The energy sources of microgrids are determined by various factors, including economic efficiency, environmental compatibility, and supply reliability. The Sendai Microgrid is designed to use multiple sources of energy, most importantly natural gas supplied via a disaster-resistant medium pressure pipeline. This provides a stable energy supply in times of disaster.

Point (3): Importance of backup equipment

Another factor that enabled a continuous power supply to the Sendai Microgrid was the lead battery in the IPS as a backup for power outages. The Sendai experience clearly demonstrated that an energy storage system, which is currently becoming increasingly important, was critical to maintaining a stable power supply during the disaster.

Storage batteries, however, are very expensive and cost considerations dictate that they should only be relied in situations of urgent necessity. It is therefore important to specify the loads which should be given the highest priority in the worst situation. "Load prioritization" is implicit within the concept of a multi-power quality microgrid, such as the Sendai Microgrid. The events of the earthquake/tsunami demonstrated the value of this concept which was validated by the successful operation of the Sendai Microgrid in its aftermath.

Point (4): Importance of comprehensive operations and training

Finally, a comprehensive plan involving the operators was shown to be indispensable for effective microgrid operations. Operations in times of disaster are different from normal operations. Also, there are many disasters that are "beyond assumption", such as the earthquake and tsunami.

Looking back on the disaster, the designer of the Sendai Microgrid, Mr. Kijirou Mineta, Hibiya Engineering (formerly NTT-F), said as follows:

Comment by Mr. Mineta

There were so many accidents that were beyond assumption in the earthquake disaster. There was a disaster manual in the Tohoku Fukushi University, but because the disaster was much more extensive than one could assume, no clear instructions on how to respond to such disaster were found in the manual.

Even for microgrid operators, things were all beyond assumptions. It was extremely difficult for them to rush to the scene because they could not find a way of communication and because of traffic paralysis. When they finally arrived at the scene and tried to activate the gas engine manually, the battery of control gas engine were totally discharged, which was beyond assumption.

It was due to the prompt and appropriate response of the operators that the Sendai Microgrid was able to supply power through this unprecedentedly challenging situation. The operators took appropriate actions in the face of events that were "beyond assumption." For example, they conducted provisional wiring work to restart the gas engines, and carried out operating procedures very differently from usual to supply B3-Class power to loads to meet the needs of elderly people dependent on ventilators for their lives.

As microgrid technology advances, attention is mostly paid to combinations of energy sources and storage, equipment configurations, computing hardware and software applications. At the same time, the importance of operators who have full knowledge and good command of the system must be part of the equation. Operating procedures and the training of operators are important elements in the implementation of microgrids and essential for their successful functioning, especially in times of disasters that are "beyond assumption."

In conclusion, we may observe that the foresight in the design of the multiple power quality microgrid – the Sendai Microgrid – by NEDO and its continued operation by NTT-F provided a critical resource of high value during a totally unforeseen event – an event "beyond assumption."

6. Acknowledgement

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7. References

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