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Learning from non-failure of Onagawa nuclear power station: an accident investigation over its life cycle

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ABSTRACT

This article investigates the successful survival of the Onagawa nuclear power station during and after the 2011 Tohoku earthquake and tsunami. As a research method, a system approach investigation and analysis— CAST (Causal Analysis based on Systems Theoretic Accident Model and Processes)—is applied over the life cycle of Onagawa. The main aim of this study is to identify how seismic and tsunami disaster risk reduction was implemented in different stages of the Onagawa nuclear power station's life cycle. It is found that three safety cultures were built and developed over its life cycle: a nuclear safety culture, an earthquake safety culture, and a tsunami safety culture. These three safety cultures played important roles in the non-failure and success of Onagawa in 2011. Furthermore, the operator of Onagawa, Tohoku EPCo has a dynamic approach and a strong leadership towards earthquake and tsunami risk mitigation in all life cycle stages; flexibility and voluntary safety actions have been in place at Tohoku EPCo and Onagawa . Nevertheless, the 2011 events strongly influenced the decision to decommission the Onagawa Unit 1 early, brought to attention the length of the decommissioning process (which will surpass the operation stage), the high costs involved, and tremendous challenges linked to the permanent storage of radioactive waste. The successful survival of the Onagawa emphasizes that in order to achieve energy security through the nuclear energy in Japan and elsewhere in the world, safety always needs to come first. Furthermore, it supports dynamic learning not only for the nuclear industry, but also for the oil and gas and maritime industries; particularly, those situated in earthquake and tsunami risk areas.

1. Introduction

Societies are continuously challenging the limits of safety engineering through the rapid development of technology, increased complexity and coupling, competing priorities in various industries and systems, the emergence of new types of hazards, and a reduced capacity to learn from previous events and experiences [1].

At present, there are 450 nuclear power reactors in operation and 55 reactors are under construction in many countries around the world, such as China, India, Pakistan, Turkey, the United Arab Emirates, and Belarus [2]. Nuclear energy has immense potential, but also may have catastrophic impacts when accidents or “low probability, high consequence” events occur [3–5].

A few years before the Chernobyl nuclear disaster in 1986, Perrow [6] warned that usage of nuclear power could have catastrophic potential in the very near future. Accidents such as nuclear meltdowns and the dispersion of nuclear radioactive material into the environment were seen by Perrow [6] as inevitable events or even normal accidents within the next few decades. Nuclear power has been seen as a high-risk system and a high-risk technology, and Perrow [6] highlighted that risk can never be eliminated from such systems, due to high interactive complexity and tight coupling.

Krausmann and Cruz [7] warned about an escalating probability of disasters concerning natural hazards and, particularly, Natech (natural hazards triggering technological disasters) events. The Natech events which occurred after the 2011 Tohoku earthquake and tsunami surprised the world, particularly because they occurred in Japan, which has generally been considered to be a country with high levels of earthquake and tsunami preparedness and with highly advanced emergency response capacities and an accountable governance system [7–9]. In reality, the preparedness of the Japanese nuclear industry to severe accidents, including natural hazards, and the regulatory regime in Japan sparked criticism from both national and international communities starting from late nineties, particularly, after the 1999 Tokay-mura

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nuclear accident. The investigation of Tokyo Electric Power Company (TEPCO) in 2000, after concealing 29 nuclear incidents and accidents and the impact of Niigataken Chuetsu-oki earthquake in 2007 on Kashiwazaki Kariwa nuclear plant revealed acute shortcomings in the nuclear industry in Japan [10,11].

Prior to Fukushima 2011, Japan had 54 operating nuclear power reactors at 17 plant sites all over the country. This included 24 Pressurized Water Reactors (PWRs), 30 Boiling Water Reactors (BWRs), and 2 reactors under construction. These nuclear reactors together provided about 30% of the Japans electricity supply [12].

The Tohoku earthquake and tsunami in 2011 directly affected five nuclear power plants located along the northeastern coast of Japan: Fukushima Daiichi, Fukushima Daini, Onagawa, Tokai Daini, and Higashidori; see Fig. 1. These five nuclear power plants had a total of 15 nuclear reactors between them; 11 reactors were in operation at the time of the earthquake and four reactors were out of operations for maintenance purposes [8,13].

Moreover, the 2011 Tohoku earthquake in March 2011 and its aftershock on the 7th of April 2011 affected the Rokkasho reprocessing plant and uranium enrichment facility, which lost off-site power after the earthquake; however, its emergency power supply was in operation [14].

The Fukushima Daiichi nuclear power plant confronted severe core damage in three of its nuclear reactors; reactors 1, 2, and 3 melted down and hydrogen explosions occurred [15]. As a result of this nuclear catastrophe, an enormous amount of radioactive substances were emitted into the environment [16]. An estimated number of 167 workers were exposed to more than 100 millisieverts of radiation during and after the accident. According to estimations, more than 1800 square kilometers of land in the Fukushima prefecture were contaminated by a cumulative radiation of 5 millisieverts or even higher per year [17]. The Fukushima Daiichi 2011 event was a large-scale and long-term nuclear contamination Natech event. The catastrophe was rated as Level 7 on the

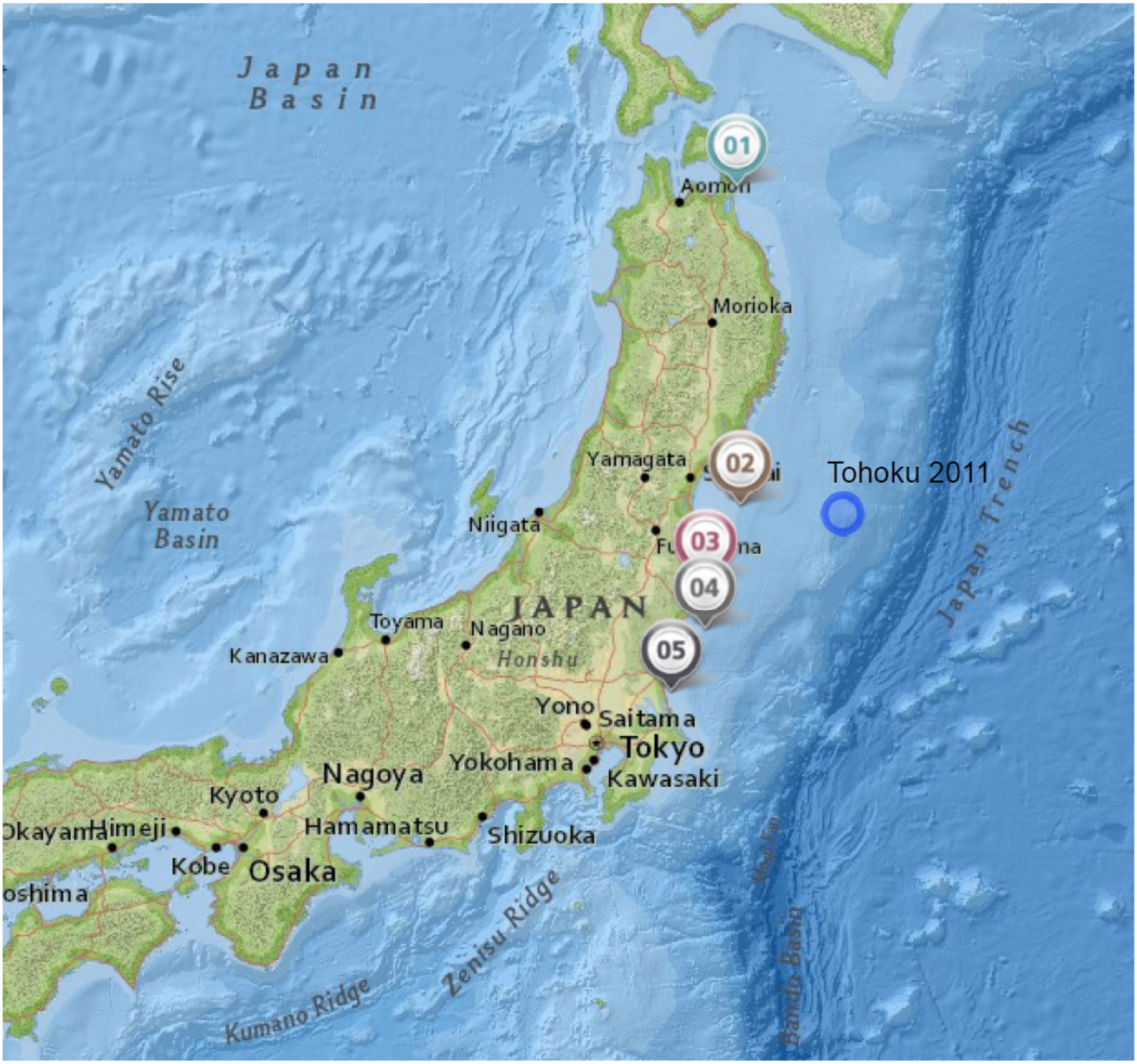

Fig. 1. Locations of the five nuclear power plants on northeastern coast of Japan affected by the 2011 Tohoku earthquake and tsunami; 01, Higashidori; 02, Onagawa; 03, Fukushima Daiichi; 04, Fukushima Daini; and 05, Tokai Daini.

International Nuclear and Radiological Event Scale (INES) of the International Atomic Energy Agency—the same rank as the Chernobyl nuclear disaster in 1986 [8].

Dr. Kiyoshi Kurokawa, the chairman of the Fukushima Nuclear Accident Independent Investigation Commission, which was delegated by the National Diet of Japan, officially declared that the Fukushima Daiichi nuclear power plant disaster in 2011, although triggered by the earthquake and tsunami, was a profoundly "man-made disaster". Despite Japan's global reputation for excellence in engineering and technology, the 2011 nuclear major accident was a disaster "Made in Japan" [17], where a cascade of industrial, regulatory, and engineering failures occurred [13].

Prior to the nuclear disaster of Fukushima Daiichi, the Japanese government and the Japanese nuclear power industry argued that nuclear power was completely safe in Japan. However, the Natech events after Fukushima 2011 strongly questioned the nuclear safety myth in Japan [17]. Nevertheless, alarming signs about the weaknesses of Japanese nuclear power stations were raised after the 2007 Niigataken Chuetsu-oki earthquake, which affected Kashiwazaki-Kariwa, the largest nuclear power plant in the world. At that time, the peak ground acceleration exceeded the design basis value for seven units of the nuclear plant and brought the seismic safety of nuclear power plants in Japan under scrutiny. In order to garner international support for easing the restart of a nuclear power plant after an earthquake, the Japanese Government asked the International Atomic Energy Agency (IAEA) to launch a program and to establish the International Seismic Safety Center as part of IAEA's Department of Nuclear Safety and Security with a main focus on the seismic safety of nuclear plants. The program was funded mainly by Japan and the United States, along with contributions from several member states operating nuclear power plants [11,18].

According to Juraku et al. [19], Fukushima Daiichi 2011 cannot be considered as an event in the past, but as an ongoing and developing story over the coming years, with a continuous need to remind the world about not only the achievements of science and technology, but also about complexities of nuclear technology, with high risk and high impacts on the environment, society, politics, and economies. In this view, since the 2011 Tohoku earthquake and tsunami, many studies have focused on Fukushima Daiichi and the analysis of nuclear disasters, nuclear regulatory failures, failure of nuclear power plant systems, and investigation of their utility [8,9,13,15–17,19,20].

The 2011 Tohoku earthquake and tsunami had different impacts on the four other nuclear power plants. The Fukushima Daini nuclear power station (NPS)—see Fig. 1—suffered damages from the earthquake and tsunami but, due to a dedicated team of 200 human operators, all four of its nuclear reactors were brought successfully to a cold shutdown and managed to avoid the occurrence of a nuclear disaster. Among the extraordinary efforts, dedication, and personal risk taken by the team of operators at Fukushima Daini, the most extraordinary was the laying—within one day—of a temporary cable with a length of 9 km, an action which, in normal conditions, would be accomplished within more than one month.

The Tokai Daini NPS (see Fig. 1) lost all off-site power after the earthquake but, luckily, the tsunami reached only to 5.4 m in height, which could not reach its critical facilities. Two emergency diesel generators (EDG) survived the tsunami, which were used to achieve cold shutdown of its reactors. A side wall of 6.1 m with the role of protecting sea water pumps was completed on March 9, 2011, only a few days before the occurrence of the Tohoku earthquake and tsunami.

The Higashidori NPS (see Fig. 1) was in maintenance at the time of the Tohoku earthquake. However, during the seismic aftershock on April 7, 2011, it lost off-site power; however, its emergency power supply operated well, ensuring cooling of the spent fuel pool.

While the Onagawa NPS (see Fig. 1) was the closest to the epicenter of the 2011 Tohoku earthquake and received the highest impact from both the earthquake and the tsunami, it kept its integrity and managed to successfully to bring its nuclear reactors to a cold shutdown [5,13].

Within the research arena, in comparison with the Fukushima Daiichi nuclear disaster, few studies have been dedicated to the Onagawa nuclear power station. Ryu and Meshkati [21] performed a root-cause analysis for the different courses of events faced by both Fukushima Daiichi and Onagawa after the 2011 Tohoku earthquake and tsunami. Onagawa was 60 km closer to the epicenter of earthquake, the difference in seismic intensity experienced by both nuclear power plants was negligible, and height of the tsunami at Onagawa was higher than that at Fukushima Daiichi. Ryu and Meshkati [21] identified, as a root-cause, the safety cultures of utilities prior to the 2011 Fukushima disaster. Obonai et al. [22,23] focused on the impact of 2011 Tohoku earthquake and tsunami on Onagawa's emergency response and successful cold shutdowns. Tojima [24] focused on the response of Onagawa to the 2011 Tohoku earthquake and tsunami. Sasagawa and Hirata [25] emphasized the process of tsunami evaluation and countermeasures at Onagawa. Sato [26] concentrated on the social responsibility of managers and engineers at the Tohoku company with regards to the Onagawa NPS.

There are many lessons to be learned, not only from the nuclear disaster at Fukushima Daiichi, but also from the other nuclear plants such as Onagawa NPS, which successfully maintained their integrity and reached a cold shutdown after the impact of the 2011 Tohoku earthquake and tsunami. Ibrion and Paltrinieri [27] brought to attention that disasters are built over time and the dramatic impact of a hazard such as earthquake or tsunami is just a context which brings massive destruction and huge human loss. A reactive approach of learning based on past disasters needs to be constantly supported by a proactive approach and dynamic learning, as future disaster risks may well exceed the proportions of disaster risk from the last and present century [27–29]. Moreover, risk is never static in safety-sensitive industries and the present digital era, with highly advanced and complicated technological systems, has been bringing up its own uncertainties and risks [3,30–33].

Complex technological systems and safety-sensitive industries (such as nuclear power generation) require the application of a systemic accident approach and an integrated system-oriented model [1,3,5,16,34]. As per Meshkati [34], modern engineering involves systems, micro-systems, and macro-systems. Moreover, engineering approaches can be characterized by two main features: system orientation and designs under constraints. A system perspective and system-based approaches are recommended to be employed for complex technological systems such as nuclear power stations. Failures of such dynamic systems can have terrible and long-lasting consequences for public health and the environment and, given their inter-connectivity and inter-dependency, they can threaten and affect the integrity of other systems operating in the same area or in neighboring regions [3].

Towards systematically learning from the success of the Onagawa nuclear power station after the impact of the 2011 Tohoku and tsunami and beyond, in this article, a system approach accident investigation and analysis—CAST was applied over the life cycle of Onagawa. The acronym CAST stands for Causal Analysis based on STAMP (Systems Theoretic Accident Model and Processes). A novel integration of the CAST accident analysis with the life cycle research approach allows a sharp understanding why a failure and a disaster did not occur at Onagawa. Moreover, it captures in a systematic way the approach of Onagawa about disaster risk reduction over time and encourages a dynamic learning from this case.

2. Research methodology

Within the following two subsections, the CAST accident analysis approach, its steps, the life cycle, and its stages are further explained.

2.1. CAST accident analysis method

As CAST is based on STAMP, a few insights about STAMP are presented within the followings paragraphs. STAMP is a comprehensive accident model based on systems theory, which views accidents as complex processes. STAMP consists of three principles: safety constraints, hierarchical safety control structures, and process models. As per STAMP, accidents are viewed as violations of system safety constraints and inadequate or ineffective control in enforcing safety constraints on the design, development, and operations of a system. Moreover, due to the safety control structure and the behavior of individuals with respect to it, accidents are also seen as dynamic processes. STAMP treats systems as dynamic processes which are continuously adapting and safety is considered as a dynamic control problem, where the goal of control is to enforce safety constraints. There is no single root cause for accidents, and safety becomes a control problem where the goal of control is to enforce safety constraints [1].

CAST requires an understanding of the dynamic processes that lead to loss and multiple views about an accident can be unveiled. Usage of CAST does not merely lead to the identification of causal factors or variables, but also provides insights about social-technical system design, examines safety control structures, and identifies weaknesses and possible required changes at each level of the control structure. CAST tries to shift away from assigning blame—usually placed on human operators or those which were very close to events operationally—and focuses on analyzing why an accident occurred and what can be done in future in order to prevent losses. CAST aims to determine how to change or to re-engineer safety control structures, in order to prevent accident processes from occurring again [1]. The CAST approach has been used by Uesako [16] for the analysis of the nuclear disaster at Fukushima Daiichi in 2011.

According to Leveson [1], the accident analysis approach of CAST is comprised of nine steps: 1- Identify the system(s) and hazard(s) involved. 2- Identify the system safety constraints to be enforced and system requirements associated with specific hazards. 3- Document the safety control structure in place, in order to control hazards and to enforce safety constraints. 4- Determine the proximate events which lead to loss. 5- Analyze the loss at the physical system level. 6- Analyze the higher levels of safety control structure, in order to understand how and why they allowed or contributed to inadequate control at the current levels. 7- Examine the overall co-ordination and communication of contributors to loss. 8- Determine the dynamics and changes in the system, in order to identify losses and weaknesses of the safety control structure over time. 9- Generate recommendations.

2.2. *Life cycle research approach*

The life cycle approach has been employed for other safety-sensitive industries; for instance, in the oil and gas industry by Faber [35], Moan [36,37], and Ibrion et al. [30,32], and in the offshore wind industry by Torsvik et al. [38].

According to Vattenfall [39], the life cycle assessment of electricity generation (including from nuclear) is based on the ISO 14040 and ISO 14044 standards. The life cycle covers all the processes, which starts with uranium mining and ends with the deposition of waste in an underground repository. The process includes construction of the nuclear power plant, operations, dismantling, handling of radioactive waste, re-investments, and transportation of fuel. These ISO standards draw attention to environmental impact of power generation over the life cycle. However, information about emissions is given for normal operations only, where breakdowns and accidents are not considered.

With regards to the life cycle of nuclear power systems, Koltun et al. [40] identified three parts: the nuclear power life cycle itself, as well as the primary and secondary nuclear fuel cycles. The nuclear power life cycle contains the following stages: plant design and construction, plant operations and maintenance of reactors, decommissioning, radioactive waste storage, and recovery of land. Furthermore, Koltun et al. [41] presented a life cycle assessment for fourth generation nuclear power plants, which comprises the following stages: design, construction, power plant operations, spent fuel storage, decommissioning, final storage of radioactive waste, disposal, and land reclamation.

The International Atomic Energy Agency (IAEA) offers comprehensive recommendations on the life cycle assessment of nuclear power plants [42–50].

In this study, the life cycle stages of a nuclear power plant are shown in Fig. 2, inspired by the life cycle stages recommended by IAEA and Koltun et al. [40,41].

In the following, the stages of a nuclear power plant's life cycle, as shown in Fig. 2, are explained.

According to the IAEA [44], the siting of a nuclear power plant is a process which comprises several phases such as site survey, site selection, site evaluation, site assessment, and derivation of site design base. The siting process is crucial for the following stages of the life cycle. The decisions for selection and assessment of a site are normally based on three types of criteria: exclusion, avoidance, and suitability. There are various parameters which need to be considered when siting a nuclear power plant: health, safety and security parameters, engineering and cost parameters, socio-economical parameters, and environmental considerations. The health, safety, and security parameters include (but are not limited to) the magnitude and frequency of natural hazards, characteristics related to radiological impact, essential supply (such as access to electricity grid), security and safeguard, and human-induced external events. Natural hazards refer to earthquakes, volcanoes, landslides, flooding, tsunamis and other coastal hazards, and extreme meteorological events, among many others [44].

With concern to the design stage, it is important to underline that it refers to the nuclear power plant design, and not to the reactor unit design. The reactor unit design is usually separated from the design of a nuclear power plant. As a note, in case of multi-units plant sites, each unit or set of units will encompass a separate site design, or at least an update to the overall site design in order to integrate the additional units.

The availability of cooling water needs to be also considered when siting a nuclear power plant (see Fig. 2), as nuclear facilities require water to absorb the heat generated during normal operations, to remove the decay heat which is produced by the reactor core in the case of an accident, and for the service water system of the plant, in order to cool down equipment, components, and buildings; even when the nuclear plant is shut down, water is required [51]. As an example, in 2011, after shutting down of reactors at the Fukushima Daiichi, the fuel rods within the reactors 1, 2, and 3 together required about 70 tons of water per hour for a period of 10 days in order to avoid a fuel core meltdown [10]. Nuclear power plants rely heavily on water sources even months after routine shut downs. The nuclear energy is using high amounts of water and seems to be the "thirstiest" power source, followed shortly by the coal industry [4].

Essentially, there are three ways of cooling down a nuclear reactor:

- Direct cooling (or “once-through”), when the plant is situated near a large water body, such as a river, sea, or ocean;
- Indirect cooling (or wet “re-circulation”), when a cooling tower and an on-site pond or canal are used for cooling water; or
- Dry cooling of the plant, which is done by air.

Direct cooling or “once-through” is more energy-efficient and less costly to build, compared with indirect cooling or wet “re-circulation”.

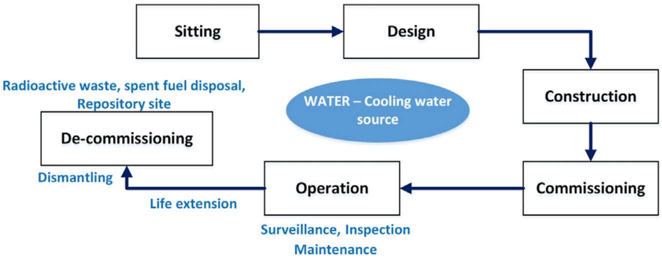

Fig. 2. Life cycle stages of a nuclear power plant.

Direct cooling or "once-through" are used in many countries for their nuclear power plants; among these countries are Japan, China, Korea, Finland, the United Kingdom, Sweden, and South Africa. While siting near coasts is common for many nuclear power stations, siting can be also near large lakes or rivers. For a nuclear plant using a seawater source, higher-grade materials must be used to prevent corrosion, but cooling is more efficient. In case a nuclear plant is cooled by water from a lake or river, there are limits imposed on the temperature of return water and on temperature differential among inlet and discharge [51]. The availability of low-temperature water is another important criterion when siting a nuclear power plant [4,51]. Among other factors which may affect the site location are proximity to electricity demand, transmission infrastructure, local populations.

The design stage of a nuclear power plant takes into account site characteristics, the complexity of operational aspects, comprehensive risk and safety assessments, and even future decommissioning plans. The states considered in the design of nuclear facilities are based on both the operational state—normal operations and anticipated operational occurrences—and accident conditions. Accident conditions refer to design basis accidents and design extension conditions, such as accidents without significant fuel degradation and with core melting in the case of severe accidents [46,52]. Nevertheless, attention needs to be paid to the terminology "beyond design basis accidents" which is used to indicate conditions outside the planned design basis. Severe accidents are covered under "beyond design basis accidents" and do not necessarily fall under design extension conditions which are regulator dependent.

After the Chernobyl nuclear disaster in 1986, the defense in depth concept was defined as a fundamental principle of nuclear safety, which concerns the design and operations of nuclear facilities. This concept refers to the implementation of multiple independent and redundant levels of defense (Levels 1, 2, 3, 4, and 5) and to their reliability and safety requirements [46].

With regards to construction of a nuclear power plant, the ultimate goal of construction is to correctly build the approved design of a new nuclear plant or to carry out major design modifications and refurbishments of existing nuclear installations. Such construction needs to be carefully planned and rigorous processes must be implemented in order to ensure the nuclear plant design, materials, and personnel are ready before construction starts. Construction requires co-ordination among all involved organizations and implementation of safety culture, standards, and procedures. Moreover, the construction is required to be carried out with high quality and with great concern for safety, as commissioning cannot test all aspects of the design [48].

The commissioning stage aims either to put into service an entire nuclear power plant or a new component, system, or structure within an existing nuclear facility. During this stage, components, systems, and structures are verified in order to comply with the design, are tested in order to confirm that they meet expected performance criteria, and are made operational. The acceptance criteria, test methods, and commissioning personnel play an important role during commissioning. The commissioning of a nuclear facility must include all necessary tests, which demonstrate that the facility as built and as installed safely operates, as per operational limits and conditions, and meets the requirements of safety. The future operating personnel of a nuclear facility should be directly involved in the commissioning process, in order to ensure their proper preparation for operations [47].

The operation stage of a nuclear power plant is generally the longest stage of its life cycle. Operational procedures are developed for normal operations, anticipated operational occurrences, and accident conditions. These are very rigorous requirements about the operation of control rooms, control equipment, core management, and fuel handling. Effective and rigorous programs for well-planned maintenance, testing, surveillance, and inspection activities need to be in place throughout the whole operation. Maintenance includes preventive and corrective measures, which ensure the capacity of structures, systems, and components to perform their intended design functions [42,47].

According to Vattenfall [39], the technical service life of a nuclear power plant is often set at 50 years. As per Koltun et al. [41], the life span of a power plant is, on average, about 60 years. IAEA [42] advised that operating license of a nuclear power plant can be re-validated or renewed for operations beyond the originally intended life of a nuclear facility; this phase is known as a long-term operation or the life extension phase.

IAEA has brought to attention that the decommissioning strategy of a nuclear power plant should be conducted in accordance with national policies and strategies for radioactive waste and as per regulatory requirements. IAEA [49,50] emphasized that, after the permanent shutdown of a nuclear facility, the recommended decommissioning strategy for a nuclear power plant is immediate dismantling. IAEA [49] advised that, before the initiation of decommissioning, as a good practice, all sources of radioactive waste and spent fuel must be removed from the facility. As a note, the full dismantling and deconstruction of a retired nuclear plant is a staged process. After removal of all spent fuel and nuclear waste, the facility may be left in a safe storage configuration before dismantling and return to brown or green field steps of the decommissioning process. An in situ decommissioning may be also chosen for the site.

With regards to the repository sites for radioactive waste generated through the operation of a nuclear facility, some countries may decide to store the nuclear waste on the site of the nuclear facility until the time of permanent shutdown and decommissioning. Special considerations have been given to the management of nuclear waste and geological aspects of repository sites [44]. According to IAEA [45], there are different types of disposal facilities for radioactive waste:

- Specific landfill disposal, for very low-level radioactive waste;
- Near-surface disposal, for low-level radioactive waste;
- Disposal of intermediate-level waste;
- Geological disposal for high-level radioactive waste and spent fuel; and
- Borehole disposal.

Fig. 3 illustrates the research approach employed in this study, where the nine steps of CAST accident investigation method are applied to the life cycle stages of the Onagawa NPS.

The application of these 9 CAST steps is discussed as follows:

Step 1 represents identification of the system and the hazards involved; this step is applied to the Onagawa NPS, to earthquake and tsunami hazard/risk, and to the 2011 Tohoku earthquake and tsunami.

Step 2 is to identify the system safety constraints to be enforced and system requirements associated with specific hazards. Step 2 CAST is

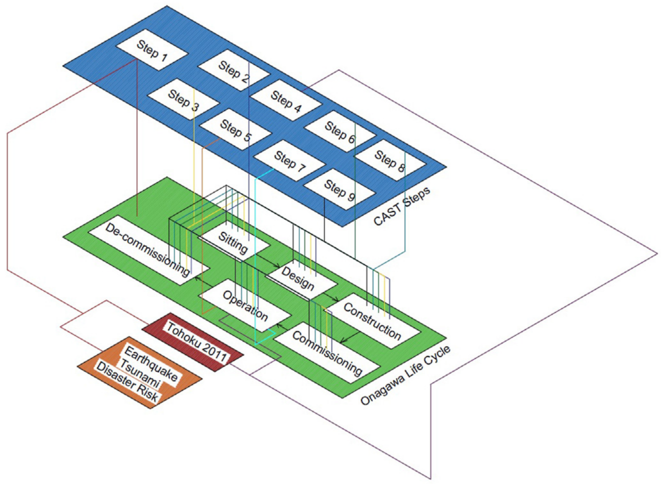

Fig. 3. CAST accident investigation and analysis approach applied to the Life cycle stages of the Onagawa.

linked to all life cycle stages of the Onagawa NPS, as safety constraints and system requirements with regards to specific hazards are present over the entire life cycle of Onagawa NPS.

Step 3 targets to document the safety control structure in place in order to control hazards and to enforce safety constraints. Step 3 CAST is linked to all life cycle stages of the Onagawa NPS, as the safety control structure in place in order to control hazards and to enforce safety constraints is present over the entire life cycle of Onagawa NPS.

Step 4 is to determine the proximate events which lead to loss; this fourth step of CAST is particularly linked to the operation stage within Onagawa's life cycle and the impact from 2011 Tohoku earthquake and tsunami, see Fig. 3).

Step 5 refers to analysis of loss at the physical system level; this fifth step of CAST is linked to the impact of 2011 Tohoku earthquake and tsunami and the operation stage of Onagawa's life cycle.

Step 6 is to analyze the higher levels of safety control structure, in order to understand how and why they allowed or contributed to an adequate control at the current levels. As a remark, for the sixth step of CAST, an adaptation was implemented for the investigation of the Onagawa NPS case study, and an inadequate control term as presented in the step 6 of Leveson [1], was replaced by adequate control. Step 6 CAST is linked to all life cycle stages of the Onagawa NPS, as the higher levels of safety control structure are present all over the entire life cycle of Onagawa NPS.

Step 7 targets to examine an overall co-ordination and communication of contributors to success. Regarding the seventh step of CAST, an adaptation was implemented for the investigation of the Onagawa NPS case study and term "loss" as presented in the step 7 of Leveson [1] was replaced by "success". Step 7 CAST is linked to the operation stage of Onagawa's life cycle.

Step 8 refers to determine the dynamics and changes in the system and to identify the enhancement of the safety control structure over time—Onagawa NPS before the impact of the 2011 Tohoku events and Onagawa NPS after the impact of the 2011 Tohoku, planning for restart and decommissioning. Regarding the eighth step of CAST, an adaptation was implemented for investigation of the Onagawa NPS case study; more precisely, the losses and weaknesses of the safety control structure as presented in the step 8 of Leveson [1] was replaced by the enhancement of the safety control structure. Step 8 CAST is linked to the all stages of Onagawa's life cycle.

Step 9 is to generate recommendations and this ninth CAST step is linked to the all stages of Onagawa's life cycle.

As a remark, the adaptations to the steps 6, 7, and 8 of CAST are possible to be done for the specific case study of Onagawa. The non-failure/success of Onagawa nuclear power station after the impact of the 2011 Tohoku and tsunami is a known fact, and by making these adaptations, we would like to further emphasize the potential of learning from the success of Onagawa. Moreover, the CAST accident analysis approach is a systematic approach, but not a rigid or inflexible approach, and encourages adaptations and facilitates learning from case studies.

With the following section, the structure of the analysis follows the above explained 9 steps of CAST integrated with the stages of Onagawa's life cycle. The eighth step of CAST comprises two parts - Onagawa before and after the impact of the Tohoku 2011.

3. CAST accident investigation over stages of onagawa NPSs life cycle—Analysis and recommendations

3.1. Step 1 CAST - identification of systems and hazards involved

The system is represented by Onagawa NPS which is located on the coast of the Pacific Ocean, at the southern part of the Sanriku Coast on the Oshika Peninsula near Matsushima, which is considered to be one of the three best scenic places in Japan. It is in an area containing both Onagawa-cho town and Ishinomaki city, located in the Miyagi Prefecture at a distance almost 70 km north of Sendai city (see Fig. 1). This area is surrounded by mountains on three sides and consists of a mountainous district and a narrow flatland. The site has an almost semi-circular shape and comprises about 1,730,000 square meters [53].

The owner and operator of Onagawa NPS is the utility provider Tohoku Electric Power Co. Inc. (Tohoku EPCo). Tohoku EPCo is the fourth-largest electric utility provider in Japan, in terms of revenue, after the Tokyo Electric Power Company Holdings (TEPCO), the Kansai Electric Power Co (KEPCO), and Chubu Electric Power [54].

Onagawa NPS includes three units with three nuclear reactors having a combined electric generation capacity of 2174 Megawatts. Technical specifications of each unit are provided in Table 1 [53,55].

The construction and commissioning of all three units of Onagawa NPS—particularly the Nuclear Steam Supply System (NSSS) and the Balance of Plant (BOP) engineering—were carried out by the Toshiba company and, for Unit 3, by Toshiba and Hitachi [12].

Regarding the hazards of the Onagawa NPS, earthquakes and tsunamis are to be highlighted. Large earthquakes and tsunamis are well-known in the area and have been documented for a long time for the Northeastern area of Japan; see Table 2 [13].

In 2011, the Onagawa NPS was hit by the Tohoku earthquake and tsunami during its operation stage. The Tohoku earthquake, known also as the Great East Japan earthquake, occurred on March 11, 2011 at 14:46, off Japans Pacific Ocean coast. The Tohoku earthquake was the largest instrumentally recorded earthquake to ever strike Japan and was the fourth largest earthquake in the world record. The magnitude of earthquake reached 9.0 Mw (moment magnitude) and produced very strong ground shaking, which exceeded 1 g (ground acceleration); values as large as 3 g were recorded. A huge tsunami with a tsunami magnitude (Mt) of 9.1 was generated, following the Tohoku earthquake. This tsunami was the fourth largest tsunami in the world record and the largest in Japan, affecting almost 2000 km and inundating an area of over 400 square kilometers [8,9,55].

3.2. Step 2 CAST - identify the system safety constraints to be enforced and system requirements associated with specific hazards

Among Onagawaâ€™s most important safety constraints the following were highly considered, starting from the siting and design stages of its LC:

- Safety constraints with reference to earthquake disasters;
- Safety constraints with reference to tsunami disasters; and
- Onagawa NPS shall safely achieve a cold shutdown in the case of scram.

Scram represents the emergency shut down of a nuclear reactor through a prompt insertion of control rods within a few seconds. In order to remove the decay heat and to prevent a reactor core damage and a nuclear accident, the availability of a reactor coolant - water - must be assured. The core cooling system shall properly remove decay heat; cooling water is injected through different types of pumps. The principles of nuclear safety assurance requires nuclear plants to be operated according to the principle of defense in depth and the safety related

Table 1
Onagawa NPS: Technical details for its units, adapted from Tohoku EPCo [53] and Japan Nuclear Safety Institute (JNSI). [55]; MW - Megawatts, BWR - Boiling Water Reactor.

Unit No.	Capacity (MW)	Reactor Type & Containment	Start date	Main contractor
1	524	BWR4 - Mark 1	Jun. 1984	Toshiba
2	825	BWR5 Improved Mark 1	Jul. 1995	Toshiba
3	825	BWR5 Improved Mark 1	Jan. 2002	Toshiba/ Hitachi

Table 2
Earthquakes and Tsunamis in Northeastern Japan over the centuries, adapted from Synolakis and Kanoglu [13]. M, Magnitude of earthquakes; I, Intensity scale for tsunamis.

Name	Date	Magnitude	Intensity
Jogan	13 July 869	8.6	4
Keicho Nankaido	January 31, 1605	7.9	4
Keicho Sanriku	December 2, 1611	8.1	4
Empo Sanriku	April 13, 1677	8.1	2
Empo Boso-oki	November 4, 1677	8.4	2.5
Kansei Sanriku	February 17, 1793	7.1	2
Meiji Sanriku	June 15, 1896	7.6	3.75
Showa Sanriku	March 3, 1933	8.5	3.5
Tokachi-oki	May 16, 1968	8.0	2

functions - shut down, cool down and confine [56]. These principles of safety assurance were highly and carefully implemented at Onagawa NPS and a nuclear accident was successfully managed not to occur in 2011 [12,24].

A continuous earthquake and tsunami awareness and implementation of measures for increasing the seismic and tsunami resistance of Onagawa NPS were seen as important matters, from the early planning stages of Onagawa NPS unit 1 onwards.

The site of Onagawa NPS was excavated to place the buildings of the nuclear power station on deep, rigid bedrock and artificial rocks [57]. In the design stage of the Onagawa NPS, the Tohoku EPCo conducted many in-depth sediment-related surveys, archaeological investigations, historical tsunami research, numerical calculations, and simulations and models for earthquakes and tsunamis [55].

The Onagawa NPS site elevation was considered to be an important measure against the tsunami; the design margins for the Onagawa NPS were decided to be O.P. + 14.8 m (where O.P. represents the Onahama Peil or Onahama Port Construction Standard Surface, referring to the tidal level measured from the Onahama Port Construction Standard Surface [58,59]). With regards to tsunami disaster mitigation, a tide gauge was installed for daily usage during the construction of Unit 1 [25].

The seismic design of all three units of Onagawa NPS was based on a regulatory guide from 1978 and in-house regulations. According to these regulations, the Design Basis Earthquake Ground Motion (DBEGM) S1 was 250 Gal and DBEGM S2 was 375 Gal; an evaluation of earthquake ground motion with response spectra was performed [12].

In Japan, prior to 2011, there were two type of criteria for generation of the DBEGM: Before 2006, basic criteria were utilized in the design of existing nuclear power plants; and, after 2006, the previous criteria were updated based on the revised Nuclear Safety Commission Regulatory Guide. The post-2006 criteria recognize the possibility of an earthquake which can produce ground motion at the site of nuclear power plant exceeding the DBEGM; this possibility was termed, at that time, as a residual risk which was required to be minimized as practically possible [12].

3.3. Step 3 CAST - document the safety control structure in place in order to control hazards and to enforce safety constraints

The safety control structure in place in order to control hazards and to enforce safety constraints at the Onagawa NPS is illustrated in Fig. 4.

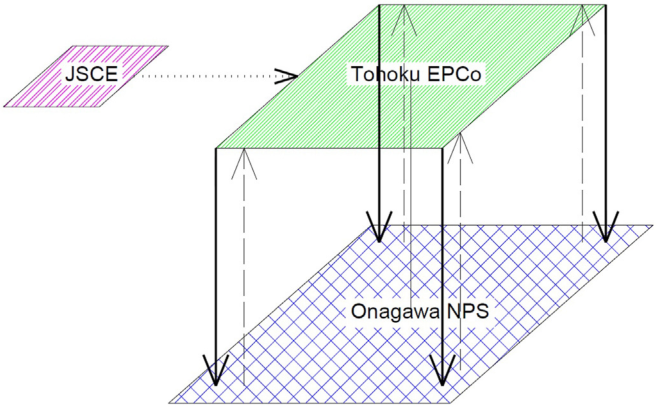

Fig. 4. Safety control structure for Onagawa NPS. JSCE, Japan Society of Civil Engineers.

It can be observed, from Fig. 4, that the main controller within the safety control structure at Onagawa NPS is its owner and operator, Tohoku EPCo. Over all LC stages of Onagawa NPS, Tohoku EPCo has provided control in order for the safety responsibilities to be executed adequately (control is represented by continuous arrows in the Figure) and has received continuously relevant feedback from Onagawa NPS (feedback is represented by dashed arrows in the Figure). A close collaboration and communication with the Japan Society of Civil Engineers (JSCE) has also been developed over time (collaboration and communication are represented by dotted arrows in the Figure). As a remark, the JSCE has emerged as an important player just after 2002, and the Onagawa NPS tsunami protection scheme was designed well before 2002.

Tohoku EPCos high awareness, in terms of earthquake and tsunami risk, has been supported by the constant implementation of measures and actions for reduction of earthquake and tsunami disaster risks at the Onagawa NPS. This awareness and actions started from the time of Yanosuke Hirai, the vice president of the Tohoku EPCo between 1960–1975. He played an important role in founding a strong safety culture for the company. According to certain narratives, as a child, he visited an ancient Shinto shrine that kept alive the legend of a destructive earthquake and tsunami in 869 CE. This visit impacted him for life and determined his actions taken later on, particularly towards Onagawa NPS. In 1963, he became a member of the Coastal Institution Research Association and continuously emphasized tsunami risk and the actions required to mitigate it. He took into account and examined folk tales, old records, books, and results of surveys on past tsunamis in the Onagawa area and Sanriku coast. Yanosuke Hirai was very firm and persistent in making no compromises regarding nuclear safety; particularly the nuclear safety which could be put at risk from natural hazards such as earthquakes and tsunami. At the time of the Onagawa NPS design, Yanosuke Hirai strongly influenced the tsunami resistance design and, despite oppositions from his colleagues, convinced the company president for approval. Initially, for the unit 1 of Onagawa NPS, the estimated tsunami height was designed as O.P. (Onahama Peil) + 3 m but, at the insistence of Yanosuke Hirai, referring to occurrence of old tsunamis like the Jogan tsunami in 869 or Keicho tsunami in 1611, the design margins were determined to be O.P. + 14.8 m; significantly larger than what was initially decided [12,25]. Furthermore, Yanosuke Hirai had fundamental contributions in promoting an internal committee of experts at the Tohoku EPCo, in order to study past tsunamis. Based on their findings—rich historical evidence of large tsunamis in the past; for example, the Jogan Tsunami of 869, the Keicho Sanriku Tsunami of 1611, the Sanriku tsunamis of 1896 (Great Meiji Tsunami), and the 1933 Showa Sanriku Tsunami—the company decided to locate the Onagawa NPS at a height of 14.8 m [24].

The siting of the Onagawa NPS at OP + 14.8 m was able to provide sufficient elevation to avoid the worst of the 2011 tsunami. The operator of Fukushima Daiichi was not as rigorous as Tohoku EPCo in adherence to an in-depth review of past historical data on tsunami in his area and decided on a lower site elevation which left the nuclear power plant subject to a high risk. It can be pointed out that in contrast to Onagawa NPS, the initial siting and design decisions for Fukushima Daiichi were not focus on earthquake and tsunami concerns, available historical records and further investigations and studies. In fact, at the Fukushima Daiichi, the original ground level was lowered in order to facilitate the site construction and delivery of equipment by seagoing barges. These two different approaches of Tohoku EPCo and TEPCO to siting of nuclear power stations brought from the initial stage of life cycle significant differences among Onagawa and Fukushima Daiichi, including the initial land elevation and the height of sea wall. Later on, over the operation phase, the awareness and concerns about earthquake and tsunami risk were also not in place at Fukushima Daiichi [13,21].

The mentality and safety culture of Tohoku EPCo was highly inspired by Yanosuke Hirai and that his legacy was emphasizing "If you do not think about tsunamis in Tohoku, what are you thinking then?". Tohoku EPCo was continuously involved in conducting surveys, studies, and simulations for estimating tsunami levels and ensuring preparedness at Onagawa NPS [21]. Moreover, external experts were permanently consulted and their reports were used in making strategic decisions with regard to risks from earthquakes and tsunamis. For instance, the JSCE published a quantitative assessment methodology for the estimation of maximum tsunami wave height at nuclear plants in Japan in 2002. The JSCE used historical earthquake and tsunami records to develop standard fault models for generating tsunamis. These models were simulated numerically by varying key fault model parameters, in order to identify "design tsunamis" which exceeded all recorded and calculated historical tsunami heights [8]. Tohoku EPCo, based on the methodology of JSCE, conducted an in-depth study of possible earthquakes and tsunamis in the area, and estimated the possibility of a tsunami with 13.6 m height, based on earthquakes with estimated magnitudes between 8.3 and 8.6 [13]. Tohoku EPCo implemented voluntary safety actions, but was also strongly motivated by the experiences from the Miyagi-oki earthquake in 2005 and lessons from Niigataken Chuetsu-oki in 2007, as well as Kashiwazaki-Kariwa.

From the upper management of the Tohoku EPCo to the level of normal workers at the Onagawa NPS, "A general prioritisation for nuclear reactor safety formed within the company" and a strong safety culture was established [21]. During the normal operation phase at Onagawa NPS, periodic training sessions, earthquake drills, and extensive simulation training with regards to a safe shutdown in the case of natural hazards and other technical malfunctions were conducted, and strict protocols were implemented with regards to nuclear safety and the risks posed by natural hazards. The staff at Onagawa NPS were unanimous in their statement that, for disaster preparedness, "It was the regular training that really mattered" [24].

In contrast to the Onagawa's earthquake and tsunami preparedness, major draw backs occurred from the early life cycle stages of the Fukushima Daiichi. The natural site of 30 m O.P. was significantly reduced without taking in consideration the tsunami risk. Studies about the risk of high magnitude and intensity earthquakes and tsunami were repeatedly ignored and not taken in consideration by TEPCO. Tsunami deposits were identified north to Fukushima Daiichi, but were dismissed by TEPCO. Moreover, the lessons about the 2010 Chile earthquake and tsunami, and the 2007 Niigata Chuetsu earthquake were also ignored at TEPCO and Fukushima Daiichi [13].

3.4. *Step 4 CAST - determine the proximate events which lead to loss*

The fourth step of CAST is linked to the 2011 Tohoku earthquake and tsunami and to the operation stage within Onagawa's LC (see Fig. 3).

The distance between Onagawa NPS and the source of the Tohoku earthquake was about 125 km, which was much closer compared to Fukushima Daiichi and the other affected nuclear power plants [13].

The statuses of the nuclear reactors at Onagawa NPS at the time of the 2011 Tohoku earthquake are presented in Table 3 [24,55].

Table 3
Statuses of the nuclear reactors of Onagawa NPS at the time of the Tohoku earthquake.

Unit No.	Status
1	Constant-rated thermal power output operation
2	Undergoing reactor startup, initiated from 14:00 (periodic inspection)
3	Constant-rated thermal power output operation

Onagawa NPS experienced the strongest shaking which a nuclear plant had ever experienced (until 2011) from an earthquake [21]. The Tohoku earthquakes maximum acceleration recorded for each floor of all three reactor buildings of the Onagawa NPS was almost equivalent to the basic design for an earthquake, but some records exceeded the maximum response acceleration value considered for basic design earthquake ground motion. At the site of the Onagawa NPS, the recorded intensity of shaking, in the Japanese scale, was Shindo 6. The peak ground acceleration of 567.5 Gal—an unprecedented level for a nuclear power plant—was measured in the second basement floor of the Onagawa unit 1 reactor building. For comparison, at unit 2 of Fukushima Daiichi, the peak ground acceleration was 550 Gal [8,12,21,24,55].

As a reminder, Onagawa NPS was designed to cope with a tsunami height of OP + 14.8 m. A comparison between the tsunami wave heights caused by Tohoku earthquake at the Onagawa NPS site and Onagawa NPS elevations is offered in Table 4 [8].

The maximum tsunami height at the Onagawa NPS was 13 m, the same tsunami height which was registered for Fukushima Daiichi. After the Tohoku earthquake, the Japan Geographical Survey Institute observed a subsidence of 1 m for the whole Oshika Peninsula, the place where Onagawa NPS is situated; thus, Onagawa NPS co-seismically subsided by 1 m [8,12,13,24,55].

The first tsunami wave arrived at Onagawa NPS site at 15:21 (35 min after the earthquake) and the time of arrival of the highest tsunami wave was at 15:29 (43 min after the Tohoku earthquake occurred) [24,55].

It can be emphasized that a main factor in survival of Onagawa NPS was the fact that its elevation and seawall protection exceeded the height of tsunami. However, after the Onagawa's subsidence by 1 m, it can be observed in Table 4 that Onagawa surpassed the height of tsunami with less than 1 m and was very near the border of high risk from flooding.

3.5. *Step 5 CAST - analyze the loss at the physical system level*

The fifth step of CAST is linked to the 2011 Tohoku earthquake and tsunami and the operation stage of Onagawa's LC (see Fig. 3).

Details about the three units of Onagawa NPS, its reactors, timing, status of operation at the time of Tohoku earthquake, automatic shutdown, sub-criticality, and cold shutdown conditions are shown in Table 5 [12,24,55].

After the Tohoku earthquake and tsunami, the operations of scram, cold shutdown, and nuclear radioactivity containment had been safely completed at Onagawa NPS. The Tohoku earthquake activated Onagawas reactor scram system and an emergency shutdown occurred. After the scram operation, all three units of Onagawa NPS reached a safe and successful cold shutdown. Unit 2 of Onagawa NPS reached a cold shutdown 3 min after occurrence of tsunami and Units 1 and 3 reached a cold shutdown in the early morning of 12 March [8,24]; see Table 5.

Before the earthquake, five power lines—Oshika main lines 1 and 2 (275 kV), Matsushima main lines 1 and 2 (275 kV), and Tsukahama branch line (66 kV)—were connected to Onagawa NPS as off-site power sources. Shortly after the Tohoku earthquake, only Matsushima main line 2 (with one circuit) was available, due to operation of the system protection circuits in association with the transmission line accidents that

Table 4
Tohoku's tsunami wave height versus Onagawa NPS site's characteristic elevations.

Item	Elevation (m)
Tsunami wave height	13
Main elevation	13
Seawall elevation	14.8
Emergency diesel generator level	14
Seawater pump elevation	14.8

Table 5
Status of Onagawa's nuclear reactor at the time of Tohoku earthquake until 12 h after earthquake.

Time	Unit 1	Unit 2	Unit 3
Earthquake at 14:46 on 11 March	In operation at rated output; reactor automatically shut down by seismic automatic trip system (SATS)	Just started operation at 14.00, after the 11th regular inspection; reactor automatically shut down by SATS	In operation at rated output; reactor automatically shut down by SATS
20 min after earthquake	At 15:05, Confirmation of reactor sub-criticality condition	Confirmation of reactor sub-criticality condition (the startup operation was initiated at 14.00; thus, the reactor was in sub-critical condition already)	At 14:57, Confirmation of reactor sub-criticality condition
12 h after earthquake	At 00:58 (12 March), reactor cold shutdown condition confirmed	At 14:49, reactor cold shutdown condition confirmed	At 01:17 (12 March), reactor cold shutdown condition confirmed

occurred in the area managed by Tohoku EPCo. Other lines were recovered on 12, 17, and 26 March [55]. As one off-site power line was available for units 2 and 3 at Onagawa NPS, only Unit 1 needed emergency diesel generators in order to maintain core cooling and achieve cold shutdown [12]. It can be remarked that availability of grid power for units 2 and 3 reduced the potential burden on emergency response crew.

The 2011 Tohoku earthquake and tsunami damaged some equipment and structures at Onagawa NPS, but none of these damages affected its structural integrity [8]. The IAEA report [12] indicated that Onagawa NPS experienced very significant shaking energy and prolonged ground shaking of its structures, systems, and components, but that "it remained remarkably undamaged given the magnitude, distance, and duration of ground shaking". Based on recorded data for all reactors of Onagawa NPS, a small-to-moderate exceedance of the seismic design basis occurred; however, Onagawa NPS performed all its intended functions [12,55].

The IAEA [12] report highlighted that "Remarkably, only six equipment items appear to have been damaged to the point of rendering their system inoperable" at Onagawa NPS. These six items were as follows:

- Two steam turbines;
- One 6.9 kV switchgear assembly;
- One fuse in the Boron tank level monitoring system;
- One strip chart record in a radiation monitoring system; and
- One overhead bridge crane was disabled, due to wheel bearing damage.

This very low rate of damage, considering the exposure of thousands of items, was appreciated to be "a remarkable rate of survival" of all equipment at Onagawa NPS [12]. The equipment was generally at standard industrial levels, but the seismic resistance was further enhanced at Onagawa NPS through anti-seismic bracing and anchorage. The operating personnel of Onagawa NPS identified 61 components which were damaged or which had compromised functions. Among them, the most significant was the breaker fire at unit 1, which was caused by the earthquake and one of the two trains at the Reactor Closed Cooling Water System (RCW) of unit 2, which was caused by the tsunami. The IAEA [12] report examined all of these 61 damaged/functionally compromised components. Furthermore, the IAEA report [12] analyzed the safety system of the Onagawa NPS, as classified by the critical safety functions of critical control, core heat removal, secondary heat removal, and containment integrity. All safety systems were satisfied and the containment integrity was not challenged. No emergency core cooling system was necessary, as there was no loss of coolant accidents in any of the three units in Onagawa NPS. Regarding the seismic performance of the control rooms for all three units, no safety-related instrumentation or controls were lost. After the earthquake, a short-circuit occurred in a 6.9 kV switch-gear breaker in unit 1. Failure of the high voltage breaker and start-up transformer tripped off-site power supply to unit 1 of Onagawa NPS. However, two emergency diesel generators allocated to unit 1 started automatically and supplied emergency power [12].

It can be highlighted that lack of seismic damages at Onagawa NPS can be attributed to continuous seismic improvements throughout the life cycle stages of design, construction and operation. The safety culture during operation can be credited to both a continuous upkeep and upgrade of systems.

Regarding the impact of the tsunami on Onagawa NPS, there was no direct damage by the tsunami, but flooding was reported through the seawater pit of Unit 2 into the reactor cooling water system room and through the seawater pit of Unit 3 into the Turbine Service Water (TSW) system. The loss of train B of the residual heat removal system for Unit 2 impacted the function of two out of the three diesel generators operating on standby. However, loss of two diesel generators did not affect the cold shutdown of Unit 2, as this unit was supplied by the off-site grid through the power plant cross-connected electrical system. Unit 3 was able to maintain off-site power until the tsunami but, afterwards, the TSW system and Circulation Water (CW) system were disabled and the operators manually used the Reactor Core Isolation Cooling (RCIC) and the Residual Heat Removal (RHR) systems to cool the reactor. Moreover, a non-safety related oil storage tank, the sea-level docks, and shore facilities were also damaged by tsunami [12]. The damages produced by the tsunami at the Onagawa were minor compared to those which occurred at the Fukushima Daiichi.

After the Tohoku earthquake, Tohoku EPCo reported the occurrence of leakage of water from spent fuel pools and at other facilities of the Onagawa plant. However, by 31 March, the contaminated water was removed and the area was totally cleaned. There was a limited loss of water (on the order of several liters) due to sloshing in the spent fuel pools; however, the spent fuel pool integrity was maintained [12,60].

3.6. Step 6 CAST - analyze the higher levels of safety control structure, in order to understand how and why they allowed or contributed to an adequate control at the current levels

Within Fig. 5, different higher levels of safety control structures can be observed with reference to the Onagawa NPS (control relations are represented by continuous arrows and feedback is represented by dashed arrows). Close collaboration and communication was observed among the Nuclear and Industrial Safety Agency (NISA), JNES, Tohoku EPCo, and the Japan Society of Civil Engineers (JSCE).

An organization with an important role was the Nuclear and Industrial Safety Agency (NISA), which was part of the Ministry of Economy, Trade, and Industry (METI) and had the responsibility of establishing standards and a regulatory framework for the nuclear industry in Japan. NISA was also responsible for the nuclear emergency response and represented the secretariat of the Nuclear Emergency Response Headquarters (NERHQ). Nevertheless, METI, while housing NISA, has been very active in promoting the nuclear power industry. Within the highest levels of the safety control structure was the Nuclear Safety Commission (NSC), with its commissioners appointed by the Prime Minister based on the approval of the National Diet. The NSC had the right to issue recommendations through the Prime Minister to regulatory bodies such as NISA. NSC had the responsibility to double-check nuclear safety regulations and to decide upon nuclear regulation policies. In case of a nuclear emergency, the NSC provided technical advice based on requests made by the Prime Minister. A very high level of hierarchy is represented by the Prime Minister's Office. In case of a nuclear emergency, the Prime Minister should issue a Nuclear Emergency Declaration and should establish the NERHQ, which is under his command. The Ministry of

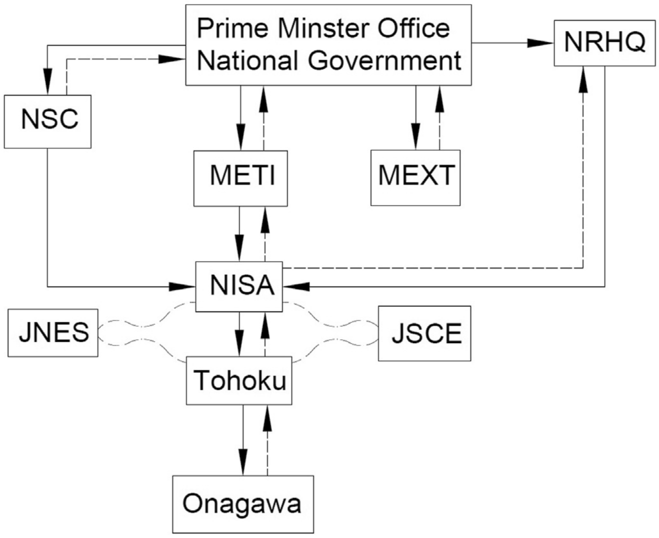

Fig. 5. Higher safety control structure with reference to Onagawa NPS. NSC, Nuclear Safety Commission; NERHQ, Nuclear Emergency Response Headquarters; METI, Ministry of Economy, Trade, and Industry; MEXT, Ministry of Education, Culture, Sports, Science, and Technology; JNES, Japan Nuclear Energy Safety Organization; JSCE, Japan Society of Civil Engineers.

Education, Culture, Sports, Science, and Technology (MEXT) served as an authority for radiation protection, including monitoring and radiation surveys. The NERHQ was established within the ministry, in the case of a nuclear emergency [16].

Shiroyama [20] offered an overview of the nuclear safety regulatory system in Japan and three major periods were identified over time: a first period from 1957 to 1978, a second period from 1978 to 1999, and a third period after 1999. The higher safety control structure, illustrated in Fig. 5, with reference to Onagawa NPS belongs to the third period (1999–2011); for example, the NSC was established during the second period, and NISA during the third period (in 2001). After the 2011 Fukushima Daiichi, the nuclear regulatory system in Japan entered into a fourth major period, characterized by the necessity of reformation concerning strengthening of independence and ensuring integrative capabilities for the nuclear regulatory authority body. Establishment of the Nuclear Regulatory Authority (NRA) in 2012, as an independent commission with decision-making power and absorption of JNES by NRA, has tried to cover the requirements for an institutional reform within the nuclear regulatory system. However, as per Shiroyama [20], doubts still exist whether the new regulatory system after 2012 can provide perfect solutions for the two major regulatory failures of nuclear safety regulations in Japan: failure of interdisciplinary communication and failure of voluntary safety efforts.

Until 2011, the higher safety control structure had been valid for all nuclear operators/utilities in Japan. However, it has been remarked that the differences in efficiency of regulatory systems depended on the actions of operators/utilities. Shiroyama [20] also emphasized that, until 2011, the nuclear safety regulations in Japan relied heavily on the voluntary safety efforts of operators. The high levels of organization which can be observed in Fig. 5 negatively contributed to a weak safety culture at the Fukushima nuclear power plant. The Japanese regulator NISA displayed a strange sort of tolerance and insufficient regulatory oversight towards the implementation of particular nuclear safety regulations with regards to earthquakes and tsunamis by the nuclear operators of commercial nuclear power plants in Japan. NISA did not exercise adequate control at the lower hierarchical levels of nuclear operators and, in the case of Fukushima, this had a highly negative impact. Higher hierarchical levels and existence of a complex administrative structure for promotion and regulation of the nuclear industry in Japan negatively impacted TEPCO's actions, as underlined by Uesako [16].

However, the impact of higher levels of safety control structure and their influence on the nuclear safety culture for Tohoku EPCo and Onagawa NPS was not a negative one. Paradoxically, for Onagawa NPS, the NISA position contributed, in some manner, to a diminution of pressure from the power of bureaucracy in Japan and encouraged a sort of flexibility. The dramatic events of 2011 showed that some nuclear operators in Japan (e.g., Tohoku EPCo) were prepared and committed to responsible and accountable actions and others (e.g., TEPCO) were trapped in financial and economical–political gains. Tohoku EPCo managed to implement safety constraints with regards to earthquake and tsunami disaster risks and to develop a strong nuclear safety culture with regards to the Onagawa NPS. Compared with TEPCO, Tohoku EPCo implemented nuclear safety regulations on a voluntary basis with reference to the risks posed by earthquakes and tsunamis, which were announced by the NISA to all nuclear operators in Japan not as legal requirements, but as voluntary measures. Tohoku EPCo initiated, conducted, and implemented adequate safety actions and adequate control in all LC stages of Onagawa NPS, both under normal operations and emergency conditions operations. Tohoku EPCo implemented, over time, safe control actions and made use of feedback in order to control (or, more precisely, to reduce) the risk posed to Onagawa NPS by natural hazards; particularly earthquakes and tsunamis. The utility provider Tohoku EPCo strongly acted as the primary/main controller for Onagawa NPS and constantly enforced safety constraints over its LC stages.

3.7. *Step 7 CAST - examine an overall co-ordination and communication of contributors to success*

During the impact of the 2011 earthquake and tsunami—the emergency phase— in order to achieve a safe cold shutdown of Onagawa NPS, safety control actions were conducted by Tohoku EPCo Headquarters and the senior operating and technical staff at Onagawa NPS. The emergency response at Onagawa NPS and Tohoku EPCo Headquarters was organized, collaborative, and controlled [21].

Immediately after the Tohoku earthquake, an Emergency Disaster Response Center was established, both at Onagawa NPS and at the Headquarters of Tohoku EPCo. The Emergency Disaster Response Center at the Tohoku EPCos Headquarters was company-wide, which attempted to obtain an immediate understanding of the damages from the earthquake and tsunami in the Tohoku district. It looked after enquiries from customers and the recovery at Onagawa NPS. Tohoku EPCos Headquarters immediately sent emergency materials, equipment, food, and water via helicopter which was led solely by Tohoku EPCos vice president. A heliport at Onagawa NPS, which was earlier built for emergencies in case Onagawa NPS was not accessible by land, was used for the first time [24].

Communication with Onagawa NPS was carried out through the Nuclear Power Division of Tohoku EPCo, which focused mainly on nuclear power-related matters. The general manager of this division was a former superintendent of Onagawa NPS, with a very good understanding of the nuclear power plant and handling of information. However, the command and decision-making were left to the Onagawa NPSâ€™s Emergency Disaster Response Center, which was under the leadership of the superintendent Watanabe. This response center was well-supported by teams at the headquarters which were familiar with Onagawa NPS. The headquarters had a high trust in the people on the ground of Onagawa NPS, who were very well-supported in order to make wise decisions and to act on them immediately. The communication channels and coordination of emergency response between Tohoku EPCo and Onagawa NPS were efficient and worked well in a timely and accurately manner, and the reports were kept to a necessary minimum [21,24,55].

The safety culture and training regimen at Tohoku EPCo and Onagawa NPS can also be credited for the rapid and professional emergency response and management of the accident.

3.8. Step 8 CAST - determine the dynamics and changes in the system; to identify the enhancement of the safety control structure over time—Onagawa NPS before the impact of the 2011 tohoku

In terms of dynamics over time, the owner and operator of Onagawa NPS (the utility provider Tohoku EPCo) had implemented important measures for earthquake and tsunami disaster reduction. Continuous seismic evaluations, regular seismic re-evaluations, and seismic improvement works significantly increased the seismic margins at Onagawa NPS. This supported and enhanced Onagawa NPS's safety control structure. For instance, with reference to the Design Basis Earthquake (DBE) for Onagawa NPS, seismic re-evaluations and seismic improvements were carried out by Tohoku EPCo starting from 1978 until the 2011 Tohoku earthquake and tsunami; starting from 2012, it has continued further on this, to present day. The regulatory seismic requirements prior to 2006 and new regulations after 2006 have all been implemented, together with extra seismic improvements based on the voluntary decisions of Tohoku EPCo [12].

During the operational phase, many investigations about fault activities around Onagawa NPS were carried out. Active faults on the land were not detected, but several submarine active faults were detected and evaluations were carried out with regard to the seismic design of Onagawa NPS. It was concluded that the estimated ground motions from these potential earthquakes were lower than the DBE for Onagawa NPS [61].

Lessons and learning from earthquake disasters were also implemented by Tohoku EPCo. In 2005, after the Miyagi offshore earthquake, a seismic integrity evaluation was performed by Tohoku EPCos for Onagawa NPS. An evaluation of earthquake ground motions by the method with fault models and an evaluation of earthquake ground motions with response spectra were performed. Afterwards, the earthquake ground motion for safety check was raised to 580 Gal for Onagawa NPS [12].

In 2006, after new regulatory guidelines were introduced, Tohoku EPCo performed an evaluation of all existing facilities at Onagawa NPS. The lessons from the 2007 Niigataken Chuetsu-Oki were also taken in account. In addition to previous evaluations, evaluations for earthquake ground motion, both with site-specific epicenters and with no specific epicenter, were performed. In addition to voluntary improvement of seismic safety, a strong economical motivation was also present. Onagawa NPS was shut down after the Miyagi-oki earthquake in 2005 and, in order to return to operations, its seismic safety was required to be upgraded.

A major seismic improvement to Onagawa NPS was conducted, by Tohoku EPCos voluntary decision, between 2008 and 2009. As a result, a total of 6600 points at Onagawa NPS were seismically improved [12].

Learning from tsunamis also occurred. For instance, Tohoku EPCo considered lessons from the Indian Ocean (or Boxing Day) tsunami in 2004 and from the tsunami which occurred in Chile on February 28, 2010. For implementation of tsunami resistance measures, Tohoku EPCo started at the planning, site selection, and design stages of Onagawa NPS. Initially, for Unit 1, the estimated tsunami height was only 3 m but, at insistence of Yanosuke Hirai, the site ground level was planned and designed as 14.8 m. For Unit 2 of Onagawa NPS, Tohoku EPCo conducted, for the first time in Japan, a geological (paleoseismological) survey of the 869 Jogan tsunami. After numerical simulations which estimated the tsunami height at 9.1 m, the site ground for Units 2 and 3 was decided to be at the same level as Unit 1 (i.e., 14.8 m). Moreover, in 1987, with reference to tsunami countermeasures, it was decided to perform additional reinforcements on the flood wall; more exactly, to protect it with concrete blocks up to a height of O.P. + 9.7 m from the base.

Another important measure taken at Onagawa NPS concerned the seawater pumps, which were installed in seawater pump wells (for units 1 and 2) and a seawater heat exchange building (for unit 3); all were built with a ground level of 14.8 m. Moreover, seawater was secured in water intake facilities for Units 1 and 2 for a period of 40 min and, for Unit 3, for 38 min [25]. In 2002, based on tsunami evaluation techniques proposed by the Japan Society of Civil Engineers (JSCE), the experts of Tohoku EPCo conducted further numerical simulations and estimated the tsunami level to reach to 13.6 m. In 2011, the height of the tsunami at Onagawa NPS reached to 13 m. During the 2011 Tohoku earthquake, the east coast of Japan subsided almost 1 m with regards to sea level. Consequently, at the time of tsunami, the height of ground level at the Onagawa NPS site was 13.8 m above sea level [12,24]. It is prudent to mention that the safety culture while preparing and benefiting Onagwa NPS would have been challenged if a flooding was to occur.

3.9. Step 8 CAST - determine dynamics and changes in the system to identify the enhancement of safety control structure over time—Onagawa NPS after the impact of the 2011 tohoku

After the impact of the 2011 Tohoku earthquake, Onagawa NPS had started to implement further tsunami and earthquake disaster risk reduction measures; which are expected to be finalized in 2021 and are estimated to reach a value of 340 billion yen (approximately 3.1 billion dollars). As an important measure, the estimated maximum seismic ground acceleration was revised from 580 Gal to 1000 Gal and appropriate actions have started to be implemented at Onagawa. An important anti-tsunami measure was the construction of a seawall with a length of 800 m and height of 29 m above sea level. Unit 2 of the Onagawa NPS applied for a safety screening in December 2013 and managed to clear the last year's new safety regulations imposed by the Nuclear Regulation Authority. Up to November 2019, nine pressurized water reactors (PWR) in Japan had been restarted and the only BWR which had gained approval from the NRA to restart—subject to consent from local authorities—was Unit 2 of Onagawa NPS. However, Tohoku EPCo and Onagawa NPS are still waiting to obtain consent from local governmental authorities. At present, Tohoku EPCo is still considering about whether to seek approval to restart Unit 3 of Onagawa NPS [62].

In October 2018, Tohoku EPCo announced its decision to decommission Unit 1 of Onagawa, as the required safety upgrades would be too expensive and time-consuming. Tohoku EPCo also took in account the generating capacity of Unit 1—a maximum output of 524,000 kW—and the number of years of remaining operational life. According to the stricter post-Fukushima safety standards, nuclear power plants are not allowed to operate for more than 40 years. Moreover, Onagawa Unit 1, which is the oldest among the three units, has a restricted space within its containment vessel, which makes it difficult to install additional safety equipment such as alternative water injection pumps, power supplies, and fire extinguishing equipment. Since the Fukushima disaster in 2011, Unit 1 at Onagawa NPS is the tenth operable reactor in Japan to be declared for decommissioning. In 2019, Tohoku EPCo filed an application to the NRA for approval of its decommissioning plan. The decommissioning plan outlines the facilities and equipment to be dismantled, as well as a timetable and required cost for completion of decommissioning [54,63–65]. The decommissioning process will take around 34 years and comprises four stages. Details about the total radioactive wastage and cost of decommissioning are provided in Table 6 [63–65].

Table 6
Decommissioning process for Onagawa Unit 1.

Stages	Time	Actions
1	8 years	Preparation of reactor for dismantling, removal of all fuel rods—unused fuel assemblies (41) and used fuel assemblies (821)—and their transfer to Units 2 and 3, and survey for radioactive contamination.
2	7 years	Dismantling of peripheral equipment of reactor and other major equipment.
3	9 years	Demolition of the reactor itself.
4	10 years	Demolition of the remaining building and release of land for other usage.

Types of radioactive waste and their quantities after the decommissioning process of Unit 1 at Onagawa NPS are shown in Table 7. The total cost of decommissioning Unit 1 at Onagawa NPS has been estimated to reach to an amount of 41.9 billion JPY (almost 392 million USD); the cost for dismantling activities has been estimated to be 30.0 billion JPY and waste disposal will claim around 11.9 billion JPY [54,63–65].

As a remark, in Japan, the term high-level radioactive waste refers to solidified glass matrix of highly radioactive liquid waste arising from the reprocessing of spent fuel. The term of relatively higher radioactive low-level waste refers to waste which contains for example, highly activated control rods, channel box, and others, by neutron irradiation in the reactor [66,67].

3.10. Step 9 CAST - generate recommendations

In terms of recommendations—the last step of CAST—the following four main aspects should be brought to attention:

- Development of safety cultures at operator level and over the life cycle of nuclear power stations;
- Preparedness and readiness of operator and nuclear power stations for an emergency response;
- Nuclear regulator and operator's compliance with regulations; the way forward after 2011;
- Challenges faced by the nuclear energy in Japan after 2011 and the way forward.

These four recommendations are further discussed in the following section.

4. Discussions

After application of the CAST steps to the life-cycle of Onagawa NPS, it was observed that three main recommendations emerged: development of safety culture at Tohoku and over the life cycle of Onagawa NPS, preparedness and readiness of Tohoku and Onagawa NPS for an emergency response, and Tohoku's compliance with regulations despite challenging matters related to nuclear regulator/regulatory system in Japan. All of these three recommendations can be considered as important factors which allowed Tohoku and Onagawa NPS to prevent occurrence of a nuclear disaster in 2011. Moreover, these recommendations can be part of lessons which have been recommended to be incorporated after 2011 into Japanese and international regulations, guidelines and policies and have been targeted to be implemented in industrial practice. Nevertheless, over time, the lessons from the Onagawa might become forgotten, then, it is advisable, on regular intervals of time, to bring back to focus the lessons from non-failures and successful prevention of a nuclear disaster.

Strengthening independence and ensuring integrative capabilities/expertise have been important measures in order to reform the nuclear safety regulations in Japan. However, the institutional reform in Japan, after 2012, still confronts further challenges such as interdisciplinary sensitivity and interdisciplinary communication, the matters related to seismic and tsunami risk are beyond the jurisdiction of the regulatory authority, and continuous availability of experts in nuclear safety regulations and Independence from nuclear operators [20].

Dealing with an increased complexity of safety-critical technologies is striking in industries such as nuclear and aviation industry. The regulatory oversight can occur, but providing adequate independence, competence and resources to regulators is also critical in order to avoid accidents [68]. The nuclear safety goes beyond the national borders and needs to be considered as a matter of regional and international concerns as nuclear radiation does not discriminate among places or stop at national borders. Nuclear nationalism, isolation and strong political considerations are required to be decoupled from nuclear safety [2,69].

Table 7
Radioactive waste after decommissioning process of Onagawa Unit 1.

Type of radioactive waste	Quantity (tons)
Relatively higher radioactive Low-level waste	60
Relatively lower radioactive Low-level waste	740
Very low-level radioactive waste	5340
Non-radioactive waste	12,400

Kushida [10] warned that unfortunately, the Fukushima nuclear disaster might not be the last one in Japan or in other countries which are making use of nuclear power. Consequently, both lessons from the Fukushima disaster and the successful survival of Onagawa should not be wasted or remained forgotten or ignored.

The eight step of CAST brought forward the fourth recommendation which refers to the challenges faced by the nuclear energy in Japan after 2011 and the way forward: the challenges of decommissioning, nuclear contamination, decontamination, permanent storage of high radioactive wastage, the market for nuclear fuel and the way forward for nuclear energy in Japan. These aspects represent lessons still pending to be learned/implemented in practice, not only by the Tohoku and Onagawa NPS, but also by other nuclear operators in Japan and worldwide.

Application of CAST to the life cycle of Onagawa NPS can be employed to support decision making process and contribute to the framework for the nuclear power plants' Integrated Risk Informed Decision Making Process (IRIDM). An overview about IRIDM has been provided by INSAG-25, issued by the International Nuclear Safety Group [70]. The CAST approach applied to the life cycle of a nuclear power station in this study can contribute to establish a systematic process for capturing operation experiences and good practices from successful nuclear power plants such as Onagawa NPS. The INSAG-25 brought to attention that a major factor in improving the design and operation of a nuclear power plant is through learning from experiences from the nuclear power plant itself, from other nuclear power plants or other safety critical systems. Furthermore, this can support the learning process for regulatory bodies and their operating experiences mentioned by IAEA's Safety Standards, for example the IAEA-TECDOC-1899 [71].

Within the following sub-sections the four main recommendations which emerged after application of CAST to the life cycle of Onagawa are discussed.

4.1. Development of safety cultures at nuclear operator level and over the life cycle of a nuclear power station

The constraints behind the existence and development of the nuclear power industry in Japan are linked to the development of nuclear safety [8]. Tohoku EPCo has constantly supported risk mitigation with regards to earthquakes and tsunamis, together with the development of a nuclear safety culture over the entire life cycle of Onagawa NPS. Furthermore, three safety cultures have co-existed and intersected within the safety culture triangle, before and after the 2011 Tohoku tsunami and earthquake at both Tohoku EPCo and Onagawa levels: a nuclear safety culture, an earthquake safety culture, and a tsunami safety culture, as illustrated in Fig. 6.

A non-exhaustive overview of the parameters or factors which have fostered the earthquake culture, the tsunami culture and the nuclear safety culture at both Tohoku EPCo and Onagawa NPS levels is offered by Table 8.

Fundamentally, the three safety cultures which can be observed in Fig. 6 have originated from the utility/operator level—the Tohoku EPCo level—and have been further transferred and supported at the Onagawa NPS level.

An important contribution in building and development of these three safety cultures is represented by the capacity of Tohoku EPCo to learn from the impact of past earthquake and tsunami events and to implement lessons from experienced earthquakes. Ibrion and Paltrinieri [27] emphasized that dynamic learning from earthquake disasters and a

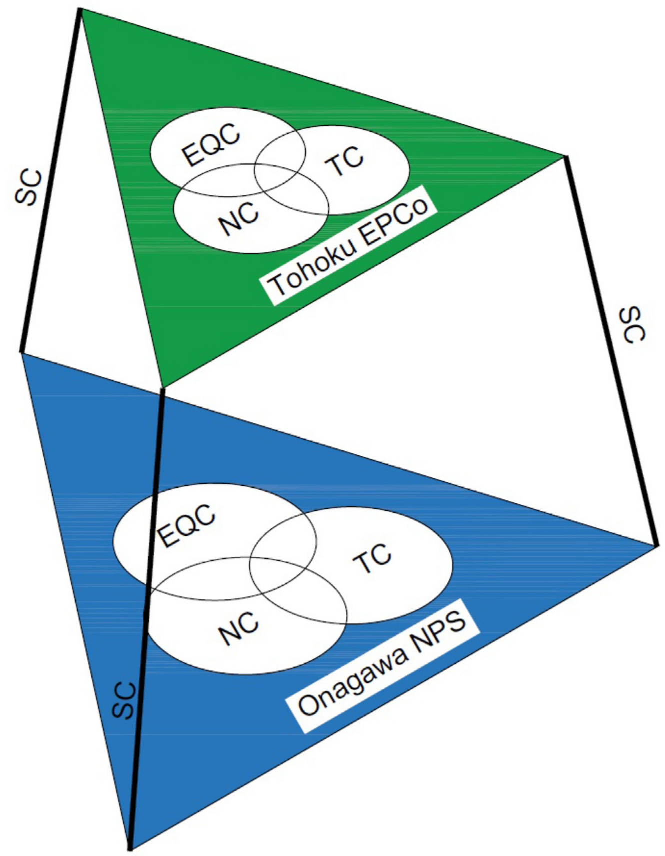

Fig. 6. Safety triangles at Tohoku EPCo and Onagawa NPS levels. EQC, Earthquake culture; TC, Tsunami culture; NC, Nuclear culture; SC, Safety culture.

Table 8
Parameters which fostered the earthquake culture, tsunami culture and nuclear safety culture at the Tohoku EPco and Onagawa NPS - a non-exhaustive overview.

Earthquake culture	Tsunami culture	Nuclear culture
learning from past earthquakes, 2007 Niigata	learning from 2010 Chile tsunami	learning from nuclear disasters (Chernobyl 1986)
lessons learned from experienced earthquakes - Miyagi 2005 (major seismic upgrade and improvement of 6600 points	lessons from 2004 Indian Ocean tsunami	nuclear safety culture as high priority
Yanosuke Hirai and his legacy	Yanosuke Hirai and his legacy	Yanosuke Hirai and his legacy
voluntary safety actions	voluntary safety actions	voluntary safety actions
continuous consultation with experts on earthquakes	continuous consultation with experts on tsunami	leadership responsibility
regular training and earthquake drills	training about tsunami	management commitment to safety (accountability, decision making, work environment)
involvement in surveys, studies, simulations and reports about high probability of occurrence of earthquakes	involvement in surveys, studies, simulations and reports about high probability of occurrence of tsunami	individual commitment to safety (accountability, safety communication)
legends, stories, folklore, old records, beliefs about earthquakes	legends, stories, folklore, old records, beliefs about tsunami	management system (continuous learning, problem identification and resolution, work process)
seismic resistance-anchorage, anti-seismic bracing	high elevation for seawater pumps and a seawater heat exchange building	continuous improvements to hardware and software
adequate/required resources	adequate/required resources	adequate/required resources
earthquake resistance design	tsunami resistance design	earthquake and tsunami resistance design
internal committee at Tohoku EPCo on earthquake risk	internal committee at Tohoku EPCo on tsunami risk	continuous improvements to safety monitoring and control system
siting of Onagawa NPS	siting of Onagawa NPS	siting of Onagawa NPS
in-depth review of past historical data on earthquake	in-depth review of past historical data on tsunami	adequate emergency control and command
conducted studies about earthquakes in area	conducted geological (paleoseismilogical) survey of 869 Jogan tsunami	learning from Kashiwazaki-Kariwa nuclear plant
seismic integrity evaluations	sea wall height and reinforcements, emergency diesel generator level	training and preparedness about an emergency safe shutdown, preparedness and readiness about an emergency response

sustainable earthquake culture can positively contribute to earthquake and tsunami disaster risk reduction and to enhance nuclear safety in Japan.

The roots of the three safety cultures at the Onagawa NPS level can be traced to the early stages of Onagawa NPSs life cycle. Tohoku EPCo strongly acted as the primary controller of disaster risk and has maintained a fundamental role in building strong safety cultures at Onagawa NPS. Onagawa NPS was impacted by the 2011 Tohoku earthquake and tsunami but, unlike Fukushima Daiichi, it was not confronted with a nuclear disaster and successfully managed to achieve a cold shutdown after activation of scram. After the 2011 Tohoku earthquake and tsunami, Toshiaki Yashima, the emeritus chairman of Tohoku EPCo and who was involved in the design of Onagawa NPS, repeatedly expressed a deep appreciation for his predecessors, particularly for the legacy of Yanosuke Hirai with regards to the earthquake and tsunami disaster mitigation at Onagawa NPS [24]. High levels of safety control structures, such as NISA, negatively contributed to a weak safety culture at TEPCO and Fukushima NPS [16]. However, the impact and influence of NISA on safety cultures at the Tohoku EPCo and Onagawa NPS levels was not a negative one but, to the contrary, encouraged flexibility, dynamism, and voluntary safety actions.

Existence of a strong earthquake and tsunami culture at Tokohu EPCo and Onagawa NPS impacted the development of a strong nuclear safety culture. According to the World Association of Nuclear Operators (WANO) [72], a nuclear safety culture is defined as the core values and behaviors which result from continuous and dedicated commitments and accountability of leaders and individuals towards nuclear safety culture, in order to ensure the protection of people and the environment. Moreover, WANO [72] emphasized the principles and traits of a healthy nuclear safety culture, such as individual commitment to safety, management commitment to safety, and particular traits of management systems in terms of continuous learning, problem identification, and resolution, and an environment for raising concerns and work processes. Nuclear safety refers to both industry and regulators, and improvements need to be made continuously to standards, hardware, design and configuration control, testing, extensive training, usage of simulators, emergency procedures and extensive preparedness, and human performance and attitudes towards safety. Furthermore, after the 2011 disaster, extreme events such as earthquakes and tsunami need to be taken in account, together with adequate emergency control and command and the required resources [72].

Comparative with the reactive/passive safety culture of TEPCO with respect to the Fukushima Daiichi NPS, Tohoku EPCo managed to build and to continuously support a proactive safety culture at the Onagawa

NPS [21]. The evidence that Tohoku EPCo exceeded under the loose control of NISA, and TEPCO faltered can be a strong indication that the safety cultures were the reason behind the overall safer posture of Onagawa NPS and continuous striving for improvements. This was mainly due to the TEPCO's near monopoly within the electric power industry in Japan. The difference between the TEPCO and Tohoku EPCo in terms of their position in the market likely played a factor for the TEPCO's complacency to the nuclear safety. Before the 2011 events, TEPCO provided electricity to the Greater Tokyo area and was one of the world's largest electric utility companies, with more than 190 power plants. In March 2010, TEPCO owned 17 nuclear reactors: 6 in Fukushima Daiichi, 4 in Fukushima Daini, and 7 in Niigata Kashiwazaki-Kariwa, the nuclear power from which accounted for almost 40% of the electrical output of TEPCO [16]. After the 2011 nuclear disaster, Hasuike Tooru, a former employee of TEPCO from 1977 until 2009 and former general safety manager at Fukushima Daiichi NPS, expressed his regret about how the management of TEPCO was focused only on financial profits and economical gains. TEPCO decided to lengthen the expected lifetimes of its nuclear power plants, such as Fukushima Daiichi, even when they were highly aware of the potential severe safety consequences [73].

Table 9 offers a succinct overview of the successful measures applied by the Onagawa NPS in comparison with the Fukushima Daiichi.

With regards to the parameters which contributed to the development of the three safety cultures at Onagawa NPS, Table 8 offers details about it.

According to the National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission (NAIIC) [17], over many years, TEPCO "resorted to delaying tactics, such as presenting alternative scientific studies and lobbying". Moreover, NAIIC [17] emphasized that ignorance and arrogance are unforgivable for any organization which deals with nuclear power. With regards to TEPCO and the Fukushima earthquake and tsunami disaster risk, Synolakis and Kanoglu [13] highlighted that a cascade of regulatory, industrial, and engineering failures occurred. There were gross mistakes in interpretation of geological and hydrodynamic findings, and no attention was paid to the evidence of large earthquakes and tsunamis which earlier occurred in the region, as well as to new research after the 2004 Indian Ocean earthquake and tsunami. Japan has been seen as "the least likely place anyone would have ever expected to have underestimated tsunami threats" and assertions such as the Japanese tsunami risk assessments are to be among the most advanced in the world were well-known. However, studies and reports about high probability of occurrence of earthquakes and tsunami events close to area where the 2011 earthquake occurred were repeatedly ignored by TEPCO. As a perplexing situation, the Nuclear Safety Commission in Japan included tsunami risk in the guidelines for nuclear power stations only in 2006 [13]. The operators of nuclear power plants were not urged to take actions, but urged to think about tsunamis as accompanying phenomena of earthquakes. Statements such as those belonging to Tsuneo Futami, a former TEPCO nuclear engineer, were perplexing not only in Japan, but also worldwide: "We can only work on precedent, and there was no precedent", and "When I headed the plant, the thought of a tsunami never crossed my mind". As a sad reality, the earthquake and tsunami preparedness for the NPSs was not a priority for nuclear regulators and many operators. In 2002, the Japan Society of Civil Engineers, a governmental advisory organization, published recommended tsunami guidelines for nuclear operators around Japan [74]. In the years prior to the 2011 Tohoku earthquake and tsunami, regulations with regards to tsunamis were announced by NISA to all nuclear operators in Japan not as legal requirements, but as voluntary measures [16].

Table 9

Successful measures applied by Onagawa NPS versus Fukushima Daiichi - a succinct overview.

Onagawa NPS	Fukushima Daiichi
Development of three safety cultures: earthquake, tsunami and nuclear	The earthquake, tsunami and nuclear safety culture: weak and undeveloped
Achieved a cold shutdown after activation of scram	Did not achieve a cold shutdown after activation of scram
Compliance with regulations	Non compliance with regulations
Voluntary safety actions	No voluntary safety actions
An efficient and good coordination and communication during the emergency phase	A deficient coordination and communication during the emergency phase
Immediately after 2011 Tohoku earthquake and tsunami served as a safe shelter for hundreds of evacuees for a three months period.	Nuclear disaster level 7 on INES scale; radioactive contamination, radiation, massive evacuation.

After the 2011 nuclear disaster, one of the biggest differences which emerged between the Onagawa NPS and the Fukushima Daiichi nuclear power plant was represented by their safety margins for earthquakes and tsunami disaster risk [24]. Tojima [24] underlined that the success of Onagawa NPS was not a "miracle", but was the result of earthquake and tsunami disaster preparedness and "readiness in place at the time that the reactors were shut down safely". Tohoku EPCo initiated, conducted, and implemented adequate safety actions and control with regards to earthquake and tsunami risk over all life cycle stages of Onagawa NPS. Towards development of the three safety cultures at Onagawa NPS, the conduction of regular training and drills had an important contribution. Ryu and Meshkati [21] emphasized also the existence of a strong safety culture at Tohoku EPCo. This safety culture was so ingrained that representatives of Tohoku EPCo, on a voluntary basis and out of working hours, attended many seminars and panel discussions held by the Japan Nuclear Energy Safety Organization (JNES) [21].

The three safety cultures at Onagawa NPS led to a positive outcome in 2011; however, further improvements and continuous learning are still required. The response to the Tohoku earthquake and tsunami in 2011 cannot be seen as a guarantee for future events. Continuous actions and efforts are required in order to keep the nuclear safety culture at high levels. There are always challenging matters in the nuclear industry, and a careful preparedness is required together with adequate safety countermeasures which require continuous implementation [22]. Moreover, as an awareness note, safety should be seen as a dynamic control problem [1] which requires continuous strategic actions. Furthermore, Omoto [15], with regards to safety culture, highlighted that "cultures are not good or bad by themselves but are good or bad in achieving certain outcomes".

Meshkati and Tabibzadeh [3] brought to attention that the Fukushima 2011 nuclear accident was a preventable major accident and disaster. This applied also to the 1986 Chernobyl nuclear disaster in Ukraine and the 1979 Three Mile Island nuclear accident in the USA. Furthermore, it has been emphasized that the safe and efficient operations of a NPS is a function of interactions among human, organizational, and technological or engineered subsystems. Metaphorically, a safety culture can be seen as analogous to the immune system, which protects a body from various pathogens and diseases. A healthy safety culture should be based on accountability, trust, and transparency and to govern all the relationships and activities of all organizations involved in nuclear energy [2]. Bernard [75] brought to attention a safety culture maturity model which can be adapted to nuclear regulatory bodies in order to offer them guidance for understanding their own safety culture; the holistic maturity level was identified as the highest level of a safety culture. Furthermore, safety culture needs to be addressed through three approaches: integration, differentiation and fragmentation [76].

Another aspect which emerged after the 2011 disasters is related to the important matter that nuclear safety should be decoupled from political feuds and considerations, as "nuclear safety is much too serious matter to entrust to politicians". Furthermore, nuclear safety is passing national borders and has become of continental and worldwide concern, as nuclear radiation does not know any border. According to the nuclear physicist Alvin Weinberg, "a nuclear accident anywhere [in the world] is a nuclear accident everywhere [in the world]" [2,69].

The nuclear safety culture requires continuous improvements, actions, and learning, from both disaster cases such as Fukushima and success cases like Onagawa NPS. There are many lessons to be learned, which are not limited to technical, organizational, and human aspects. Natural hazards, such as earthquakes and tsunamis, are dynamic phenomena and the uncertainty associated with them needs to be incorporated into the risk assessments and applied in order to enhance the safety of NPSs [13,27,34,69,77].

4.2. Preparedness and readiness of operator and nuclear power station for an emergency response

Kushida [10] highlighted when nuclear operators are considered "too big to fail", nuclear safety problems will become worse over time. The problems linked with governance system, strong political interests and weak regulatory bodies will bring also their negative impact. This was the case of TEPCO and the nuclear disaster in 2011.

After the 2011 events, WANO presented a Nuclear Excellence Award to Tohoku EPCo's Senior Executive Officer, Takao Watanabe, who was superintendent of the Onagawa NPS at the time of impact of the 2011 Tohoku earthquake and tsunami. The award was for promotion of excellence in safe operations at Onagawa NPS during the emergency and critical phase in 2011. After 2011, Tohoku EPCo promoted Takao Watanabe as the Managing Director and General Manager of the nuclear power department. Takao Watanabe declared that, prior to and after the 2011 earthquake and tsunami, the mindset of Onagawa NPS was to "Handle normal times with emergencies in mind so that you are able to handle emergencies like normal times". Moreover, in response to the question "What was the key to success?" of Onagawa NPS, the first thing Watanabe answered was "Because we were ready [for a disaster emergency situation]" [24]. Dedication, control, organization, leadership, taking advance actions, and tight collaboration among the team on the ground and headquarters during the emergency phase positively impacted the cold shutdown of all units at Onagawa NPS in 2011 [24].

Within complex technological systems like the nuclear industry, human operators can be seen as important layers of defence and the last barriers of society for preventing the occurrence of disasters. A human being with a full understanding of major safety critical systems and operational controls can contribute significantly to reducing disaster risk. Positive support of the operational personnel, dedication, improvisation when required, flexibility and boldness can further help during emergency response. As the systems cannot incorporate all possible failures, events, and contingencies, human operators need to remain in full control of complex technological systems, despite increasing levels of automation and computerization. In this regard, the cases of Onagawa NPS and Fukushima Daini NPS serve as illustrative examples [5,68]. The study of Meshkati and Tabibzadeh [3] recommends a system-oriented emergency response in the case of accidents and failures in complex technological systems such as nuclear and oil and gas industries. The need for effective interoperation and integration among all stakeholders has also been brought to attention.

At the time of the 2011 earthquake and tsunami, the number of staff at Onagawa NPS was 500, with an available stock of food for three days and 1500 L of drinking water. However, due to affiliated companies, subcontractors, visitors, and evacuees, the number of people reached to 1800 on 12 March. Until recovery of the road on 16 March, provisions were supplied from Tohoku EPCo 's headquarters with the help from a helicopter over the Sea of Japan [21,24,55]. The 2011 tsunami heavily affected the town of Onagawa-cho, as 900 people of a total of 10,000 residents died and around 4411 homes were totally or partially destroyed. After the tsunami, hundreds of residents from nearby areas came to the Onagawa NPS, as the nuclear power station was perceived as a safe place to retreat to. Onagawa NPS served as a shelter for evacuees and people were housed in the gymnasium and provided, for a period of three months, with electricity, water, food, and blankets [26].

Taking into account the findings of Meshkati and Khashe [5], Meshkati and Philippe [68], and Ibrion et al. [31], present study also highlights, despite increased automation and tendency towards autonomous highly complex systems, humans operators are vital in fulfilling the fundamental role in operational control and in understanding of major safety critical system and prevention of disasters.

4.3. Nuclear regulators and operator's compliance with regulations; the way forward after 2011

Among the important matters which emerged in Japan after the dramatic events of 2011 were the failure of nuclear regulators and the power of bureaucracy in Japan. Previous to the Fukushima nuclear disaster, the nuclear safety regulations in Japan suffered major reforms after two accidents: In 1974, after the Mutsu nuclear ship accident, and in 1999, after the Tokai-mura accident at a fuel preparation plant operated by the Japan Nuclear Fuel Conversion (JCO), a subsidiary of Sumitomo Metal Mining Co [20]. The Government of Japan has acknowledged that, prior to 2011, regulators together with TEPCO were deficient in establishing, implementing, and maintaining a strong nuclear safety culture [8].

Increased complexity of technology can challenge the capacity of regulatory organizations, which very often have limited resources and staff shortages. In this regard, the 2011 Fukushima disaster and the certification of Boeing 737 Max in 2019 by the US Federal Aviation Authority (FAA) are both examples of bad regulatory oversight. In order to avoid disasters, it is critical to provide adequate authority and resources to regulatory organizations. Moreover, accountability, transparency, competence, independence, and trust need to become an ingrained part of the regulatory paradigm for all safety-critical industries [68].

After 2011, a reform of nuclear organizations occurred in Japan and, from September 2012, NISA was replaced by the Nuclear Regulation Authority (NRA) which is affiliated with the Ministry of Environment. All nuclear regulatory functions were integrated into this new organization and various organizations like the Japan Nuclear Energy Safety (JNES) and all technical support organizations were merged into the NRA. Other organizations, such as the NSC, were abolished.

Based on lessons from Fukushima, IAEA [46] emphasized the requirements related to robustness of design against natural hazards exceeding those which are derived from site evaluations, independent of different levels of defense in depth, emergency power supplies, and the use of non-permanent sources of electric power and coolants. Nevertheless, Sato [26] drew attention to the fact that many companies have a tendency to think and act that everything is just fine if they comply with codes and standards. Based on economical reasons, bureaucracy, and high inertia, they often do not take into account something unexpected which is not cited in standards and codes.

NRC [8] highlighted that an important lesson which emerged after 2011 brought to attention that nuclear regulators and nuclear power plant operators should continuously seek out and act on information about seismic and tsunami risks. The risk profiles of nuclear power stations/nuclear power plants with regards to natural hazards (particularly earthquakes and tsunamis) require continuous updates.

The concept of defense in depth has remained valid for nuclear safety after the 2011 Fukushima disaster. However, it recommends the enhancement of earthquake and tsunami safety in order to cope with events that go beyond the design basis. With regards to seismic safety, NRA requires the seismic design to take into account faults which were active more than 126,000 years ago and even older; if necessary, fault activity needs to be examined up to 400,000 years ago. With reference to tsunami standards, the NRA has defined the design basis tsunami as a design exceeding the largest ever recorded tsunami [78].

The findings and lessons gained after the Fukushima Daiichi accident justify the actions of the European Nuclear Safety Regulators Group (ENSREG) concerning European nuclear power plants. Comprehensive risk and safety assessments (known as stress tests) have been carried out for the European nuclear plants; the three main areas targeted were natural hazards, loss of safety systems, and severe accident management [79].

4.4. On the challenges faced by the nuclear energy in Japan after 2011 and the way forward

Before Fukushima 2011, Japan was the third largest producer of electricity by nuclear power in the world (after the United States and France). After the nuclear disaster in 2011, all nuclear reactors in Japan were shut down by April 2012, and Japan experienced the worst energy crisis since the second world war. Afterwards, in Japan, it has been a step-by-step restart of only some of the nuclear power plants. In December 2019, only nine out of 38 commercial reactors were in operation [8,80,81].

In July 2013, the NRA promulgated new technical standards, stating that a nuclear power plant re-startup would be possible only after confirming whether important safety measures have been appropriately taken. The operators in Japan need to implement one of the world's toughest safety standards and to obtain the approval from local authorities or what is called the Safety Agreement. However, the Japanese public distrust in nuclear safety grew high and majority of the Japanese population is opposed to usage of nuclear power. As an example, in Onagawa town, a place where more than 800 people died and 80% of buildings were destroyed, people were divided whether or not to give their acceptance to restart the Onagawa NPS Unit 2. Among the Onagawa town population, narratives such as "It is OK to restart if it's safe", "The town has reaped benefits from the nuclear plant. I cannot say I'm opposed" have been counter-balanced by other narratives, such as "I think there's sufficient electricity without nuclear power" and "Taking into account our children and grandchildren, no nuclear power is better" [55,62,80,82].

In Japan, after the Fukushima 2011, there is an on-going debate and polarity about usage of nuclear energy. Suzuki [82] argued that it is required to establish an independent oversight organization in order to solve the policy issues linked with the nuclear energy and to gain the public trust in Japan.

An important challenge faced by the nuclear energy is the decommissioning process of a nuclear power plant which is a very lengthy and costly process; see, for instance, the decommissioning process of the Onagawa NPS Unit 1 in Table 6. It can be observed that the decommissioning process of the Unit 1 at Onagawa NPS will take around 34 years, while the operation stage within the life cycle of the Unit 1 covered merely 27 years, from the start day in 1984 until the 2011 Tohoku earthquake and tsunami.

In 2019, nuclear operators submitted plans in order to decommission nearly half of the Japan's pre-Fukushima fleet of nuclear reactors. For instance, TEPCO submitted a plan for decommissioning five reactors at the Kashiwazaki-Kariwa NPS, the biggest nuclear power plant in the world; three of its reactors were shut down after the Niigata earthquake in 2007, and the rest of units after 2011 disaster. Just two of its units won approval from regulators to restart, but they are yet pending approval from local authorities. TEPCO is left with only two units of Kashiwazaki-Kariwa NPS of a total of 17 units which functioned before the Fukushima catastrophe [83].

With regards to the Fukushima Daiichi NPS, according to the governmental estimates, the total cost for dismantling, radioactive decontamination, and compensation will reach a value of 21.5 trillion JPY (or about 199 billion USD), representing around a fifth of the annual budget of Japan. However, as per an estimation done by the Japan Center for Economic Research (JCER), the total cost would be between 50 and 70 trillion yen. The removal of melted fuel and radioactive materials from damaged reactors at Fukushima is expected to be a very lengthy process, which may take more than four decades [82,84].

The decontamination operation after the 2011 Fukushima represents the biggest nuclear clean-up in the world, involving about 70,000 workers and reaching a cost of 2.9 trillion JPY. Nevertheless, in many contaminated areas, the radiation levels are still too high for the safe return of residents. The radioactive soil is estimated to reach, by 2021, an amount of 14 million cubic metres, which will be kept temporary in the Fukushima prefecture until 2045. After this, the government needs to identify a permanent storage location, as no prefecture in Japan, including Fukushima prefecture, has agreed to permanently accommodate this radioactive soil [85].

During the nuclear disaster at Fukushima, the seawater which was pumped into reactors and used fuel storage pools contaminated more than 100,000 tons water, and about a tenth of this water was released into ocean by middle of 2011 [10]. In the following years, TEPCO has struggled with problems linked with contaminated groundwater, which amounts for more than 100 tonnes per day—groundwater continues to enter the site of the Fukushima NPS and become contaminated. The Japanese government has allocated 34.5 billion JPY to build a frozen underground wall in order to prevent groundwater from reaching the Fukushima Daiichi reactor buildings. This frozen soil wall or land-side impermeable wall has been in operation from 2016. However, many experts in the field have raised their doubts about effectiveness of such expensive solution. This wall was useful in only reducing the flow of groundwater from 500 tonnes to almost 100 tonnes per day [82,86,87].

Currently, more than 1 million tonnes of contaminated water are held at Fukushima Daiichi and TEPCO has warned that they will run out of space in 2022 [88]. The contaminated water from the Fukushima NPS is treated through a process - Advanced Liquid Processing System (ALPS) - with capacity to remove 62 radionuclides, with exception of tritium, below the requirements from the regulatory standards for discharge into the environment. The tritium separation technologies which are deployed worldwide - CANDU NPPs, for example - are not applicable for the ALPS treated water due to a large volume of water and a relative low concentration of tritium [89].

IAEA has considered the water management at Fukushima and the disposal of treated water as critical steps towards decommissioning of Fukushima Daiichi. IAEA assessed two options for discharging the treated water - control discharges into sea (the Pacific Ocean) and controlled vapour release - as technically feasible. Both these options were assessed as mature technically, particularly, the discharge into the sea as it has been used routinely by operating nuclear power plants in Japan and worldwide. Other three options - geosphere injection, hydrogen release and underground burial-have no precedent for their implementation and are linked with technical and regulatory uncertainties. According to the IAEA, the ALPS treated water from Fukushima will be further purified in order to meet the regulatory standards for discharge before dilution into the Pacific Ocean. Furthermore, the discharge into the Pacific Ocean of the treated water will be accompanied by comprehensive environmental monitoring programs and timely dissemination of information to stakeholders and general public [89].

Other challenges faced by the nuclear energy in Japan relate to nuclear spent fuel and the high stock of plutonium. Over the years, Japan has heavily relied on imports of uranium and is the only non-weapon state part of the Nuclear Non-Proliferation Treaty which has major nuclear fuel cycle facilities. The reprocessing plant Rokkasho is the first such plant which is under full IAEA safeguards. Japan has the biggest inventory of plutonium held by a state without nuclear weapons in the world. At the end of 2017, Japan possessed more than 47 tons of separated plutonium; almost 11 tons in Japan and more than 36 tons in the United Kingdom and France with whom Japan has commercial reprocessing contracts. In Japan, the spent fuel is not considered in the category of waste, but as an asset - resource, as the basic policy is to reprocess all spent fuel and to recover plutonium and uranium and recycle them for energy usage. Nevertheless, the prices in the uranium market are different to those before the 2011 and, according to experts, the uranium market will further depress. The nuclear fuel is booked on the balance sheets of Japanese operators as fixed assets, but some experts have argued that this represents more of a liability than an asset if the utilities are not going to use the fuel [82,90,91].

Another challenge which is faced also by many other countries around the world is that Japan did not find yet a final repository site for the high-level radioactive wastage [82].

Prior to the 2011 nuclear disaster, nuclear energy was seen to bring many advantages in terms of energy security and supply stability in Japan. However, the 2011 disaster has overshadowed the benefits of nuclear energy in Japan. The NRA has imposed tough safety standards and critical safety upgrades which require high investments. Many of these safety upgrades have almost equal cost to building new reactors. Utilities, in order to get a return on their huge investments, look forward for long-term operations of nuclear power plants and high utilization rates. The length of operation stage for a NPS, including life-extension, can be a maximum of 60 years [90].

According to the governmental strategy and energy policy, there will be no construction of nuclear power plants in Japan. Nevertheless, the nuclear energy is considered in Japan as an important energy source or what is called “a base-load energy power”, an essential power source which should be operated 24 h per day, and without suffering changes in its output [82]. The nuclear power is confronting an uncertain environment in Japan and is very much surrounded by three major uncertainties: political uncertainty, policy uncertainty, and regulatory uncertainty [90].

The nuclear energy landscape has encountered various changes, both in Japan and worldwide. Worldwide, after 2011, countries such as Germany and Switzerland decided to end dependence on nuclear power and shift to renewable, while many other countries, and among them, the United States and France, have continued to rely on nuclear energy. Towards boosting the energy security, countries such as Turkey, Argentina, Poland, Bangladesh, Pakistan have shown interest in building new nuclear power plants. As per The World Nuclear Industry Status Report in 2019 [80], the worldwide demand for building nuclear reactors have stirred interest from the Japanese public-private partnership. The export of the nuclear-related technology has been part of the Japan’s economic strategies for growing of infrastructure export, particularly, after 2011. China and Russia have shown also their big interest for foreign markets through their state-owned companies and organizations [80]. In terms of the nuclear power generation, the leading countries in the world are the United States, France, China, Russia and South Korea. With reference to the nuclear power plants under construction or planned to be built, China is constructing a very large number of nuclear power plants [92].

Before the Fukushima disaster, nuclear energy covered nearly 30% of Japanese energy needs [64]. In 2017, the energy self-efficiency ratio in Japan was 9.6% which is quite low in comparison with the ratio of 20.2% in 2010. This has hinted to heavy dependence on other countries for resources and has raised serious concerns about the energy security in Japan [92].

According to the Agency for Natural Resources and Energy, the Ministry of Economy, Trade and Industry (METI), the fundamental principle of the Japanese energy policy for future is known as the 3 E + S concept where the safety needs always to come first in order to achieve energy security in Japan, economic efficiency and environmental protection. The strategy for 2030 is to create a multi layer energy supply called “energy mix” which combines various energies and power resources including nuclear and renewable energy. Within this energy structure, each type of energy will deliver maximum strength and compliment weaknesses of others [92].

The nuclear industry of Japan has been very much linked to the energy security and is still well embedded within the economic and political environment. Over the years, the nuclear industry in Japan has been a major provider for jobs and has sustained important manufacturing and service industry. Moreover, the nuclear industry and technology has represented a source of technological prestige and export revenues for Japan [93].

5. Conclusions

In this study, the successful survival of the Onagawa NPS during and after the 2011 Tohoku earthquake and tsunami was investigated through a system approach investigation and analysis method—CAST which was applied throughout the life cycle of the nuclear plant. A novel integration of the CAST with life cycle approach constitutes a system investigation research approach which is genuinely dynamic and enriches the application of CAST. Moreover, it has allowed to capture in a systematic way why a failure and disaster did not occur to Onagawa and to encourage a dynamic learning from this case.

Learning from the non-failure and success of Onagawa in 2011 and beyond brings forward following lessons:

- Development of three safety cultures at the Tohoku EPCo level and over the life cycle of Onagawa NPS: an earthquake culture, a tsunami culture and a nuclear safety culture; these three safety cultures supported the success of Onagawa NPS in 2011;
- Tohoku EPCo and Onagawa NPS exceeded under loose control of the regulator; voluntary safety measures were implemented over the life cycle of Onagawa;
- An efficient and good communication and coordination among Tohoku EPCo and Onagawa NPS during the emergency response time contributed to the non-failure and success;
- Length of decommissioning process for the Onagawa NPS Unit 1 surpassed the length of its operational stage; high costs and challenges with permanent storage of radioactive waste emerged;
- After 2011, reservation and polarity in debate about restart of the Onagawa NPS Unit 2, despite its strong safety cultures;
- The non-failure and success of Onagawa in 2011 shall not be seen as certain guarantee for future; the safety cultures shall be continuously monitored and enhanced.

It was identified that strong earthquake and tsunami cultures, built over the entire life cycle of Onagawa and continuously supported by Tohoku EPCo positively impacted the development of a nuclear safety culture at Onagawa NPS. The co-existence of these safety cultures successfully mitigated the impact of the 2011 Tohoku earthquake and tsunami on the Onagawa NPS, and did not allow sliding of the nuclear system and subsystems towards a state of high risk and occurrence of a nuclear disaster. Nevertheless, it was noticed that Onagawa surpassed the height of the 2011 tsunami with less than 1 m and was very near the border of risk of flooding. Consequently, a continuous enhancement of its earthquake and tsunami cultures is recommended.

The utility/operator of Onagawa NPS, Tohoku EPCo, played an important and decisive role over all life cycle stages of Onagawa. The flexibility in learning from past earthquakes and tsunami events and the dynamic approach to earthquake and tsunami disaster risks and nuclear safety conducted to development of a proactive approach and supported a very good emergency preparedness and response at Onagawa.

Tohoku EPCo did not only comply with regulations as legal requirements, but also with regulations as voluntary measures and voluntary safety actions were implemented continuously over the life cycle of Onagawa NPS. The codes and standards are the best available practices that set, not necessarily, the maximum limitations, especially when a high risk is posed by systems such as nuclear power plants.

The nuclear energy landscape in Japan suffered changes after 2011, but the nuclear industry in Japan is still very much linked to energy security and continues to be considered as an important energy source.

Learning from the non-failure of Onagawa NPS has brought to attention that in order to achieve and boost the energy security in Japan and elsewhere around the world, safety always needs to come first within the nuclear energy. Moreover, learning from success of Onagawa, has the potential to contribute the nuclear safety in Japan and worldwide. A close collaboration among Japan and other countries with mature nuclear power industries and developing nuclear projects is recommended.

This study, in line with the findings of Ryu and Meshkati [21], also emphasizes that the 2011 Onagawa NPS non-failure can be categorized as a "made in Japan" success, which can be used as a proactive means for learning in order to prevent major accidents, such as Natech events and the nuclear disaster at Fukushima Daiichi.

With regards to recommendations for improvement of decision making for nuclear power management, the CAST accident analysis approach applied in this study to life cycle can be employed to support the integrated risk decision making process for nuclear power plants. It can contribute to establish a systematic process for capturing operation experiences and good practices from successful nuclear power plants such as Onagawa NPS. This can further support the learning process for regulatory bodies and their operating experience.

Furthermore, learning from the Onagawa NPs can support the dynamic learning and transfer of knowledge to other industries such as oil and gas, offshore wind, maritime, and autonomous shipping.

In terms of suggested directions for future work and potential research studies to provide value, it would be interesting to apply the CAST approach to another nuclear power plant - Fukushima Daini - which survived the 2011 Tohoku earthquake and tsunami without a disaster. Furthermore, it would be also an interesting study to compare the cases of Fukushima Daiichi and Fukushima Daini as both are owned by TEPCO and presumably, they were subjected to similar safety cultures. These research directions together with the present study about non-failure of the Onagawa and the study of Uesako [16] about disaster of the Fukushima Daiichi can contribute to application of the CAST approach in the nuclear industry.

Credit author statement

Michaela Ibrion, Conceptualization, Methodology, Data curation; Formal analysis; Investigation; Writing - original draft; Writing - review & editing. Nicola Paltrinieri, Methodology, Supervision; Amir R. Nejad, Methodology, Visualization. Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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