December 1, 2013

Environmental risk assessment of CdTe PV systems to be considered under catastrophic events in Japan

Dr. Yasunari Matsuno, Associate Prof., The University of Tokyo, Japan

1. The Goal and Scope

The purpose of this report is to summarize the environmental risk assessment of CdTe PV systems to be considered under potential catastrophic events in Japan. Earthquakes, tsunami and big fires caused by tsunami are some of the catastrophic events which are of most concern in Japan. So, the potential environmental risks caused by these disasters should be considered for CdTe PV systems, and the mitigation method to minimize the risks should be clarified. This review is undertaken at the request of First Solar.

2. Huge disasters to be considered for CdTe PV systems in Japan:

An earthquake is a potential catastrophic event of particular concern in Japan. It is still fresh in our minds that a massive earthquake hit the north-east of Japan and triggered a tsunami that had caused extensive damage on March 11th, 2011. In addition, the tsunami caused big fires at 177 places in Japan. These big fires also had occurred in the big earthquakes and subsequent tsunami in the past[1]. The main sources of the big fires were the reservoirs of fuel and liquefied petroleum gas (LPG) located along the coast that had been damaged by the tsunami[2].

Since many cities are located along the coast, earthquakes, subsequent tsunami and fires are catastrophic events of particular concern in Japan, which should be considered for CdTe PV systems.

Fig. 1 Large fire caused by tsunami in Kesenuma City on March 11, 2011[2]

3. Hazard map data for earthquakes and tsunami

Ministry of Land, Infrastructure and Transport and Tourism, Japan releases “Hazard Maps” for earthquakes, and tsunami, etc. which cover many regions in Japan. They are available on Web site[3, 4] (in Japanese):

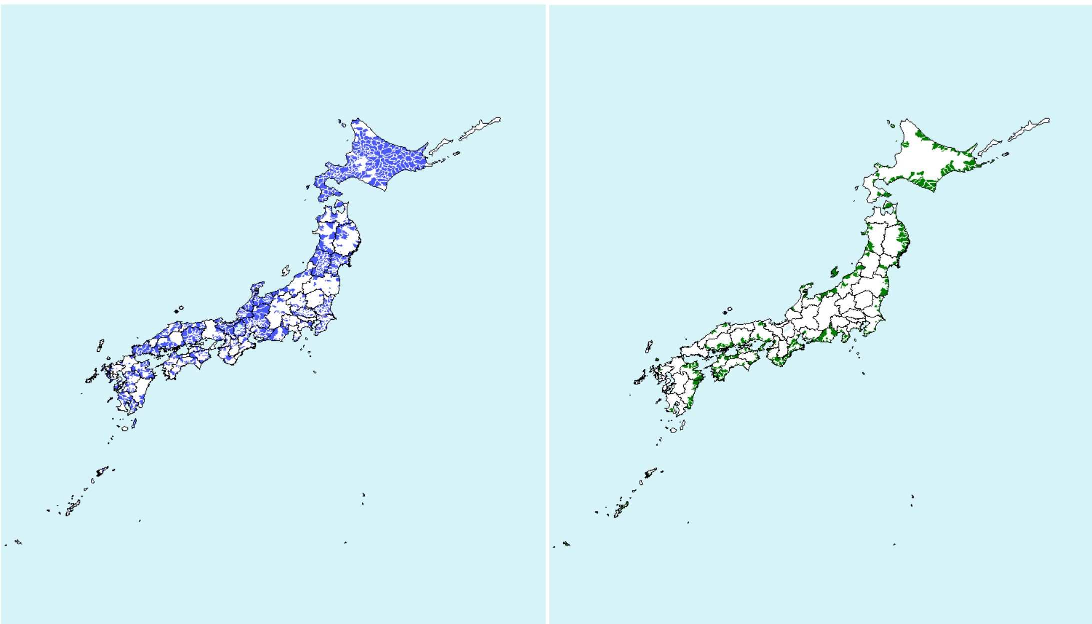

Fig. 2 Hazard map availability for earthquake (left) and Tsunami (right)

The details and data availability for these hazard maps vary in regions (cities and towns). Some examples of hazard maps for earthquake and tsunami of Cities in Tohoku area are shown in Figs. 3(a)-(b).

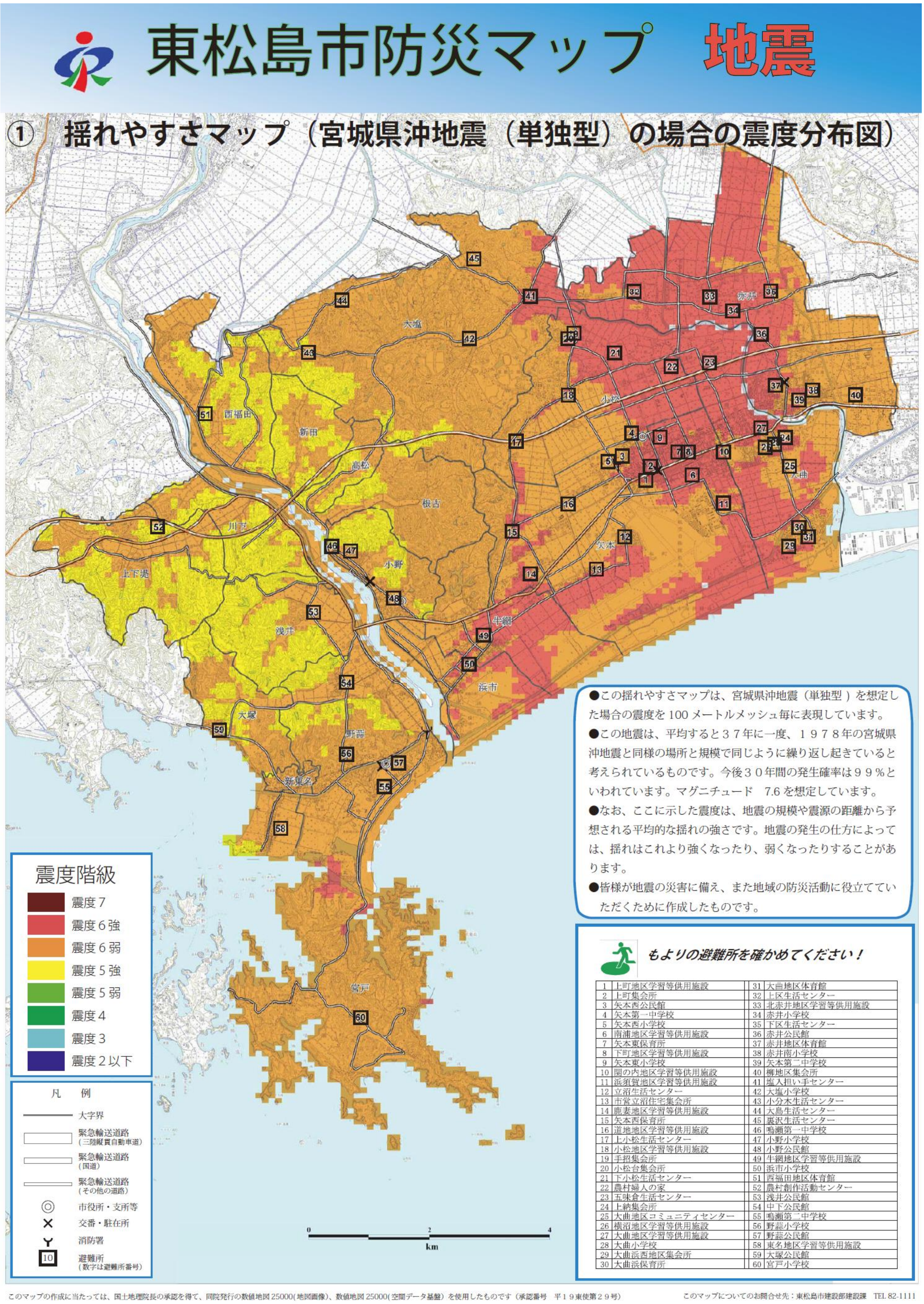

Fig. 3(a) Earthquake Hazard Map for Higashi-Matsuyama City – Seismic Intensity Map for the case of Reoccurrence of the 1978-type Miyagiken-Oki Earthquake

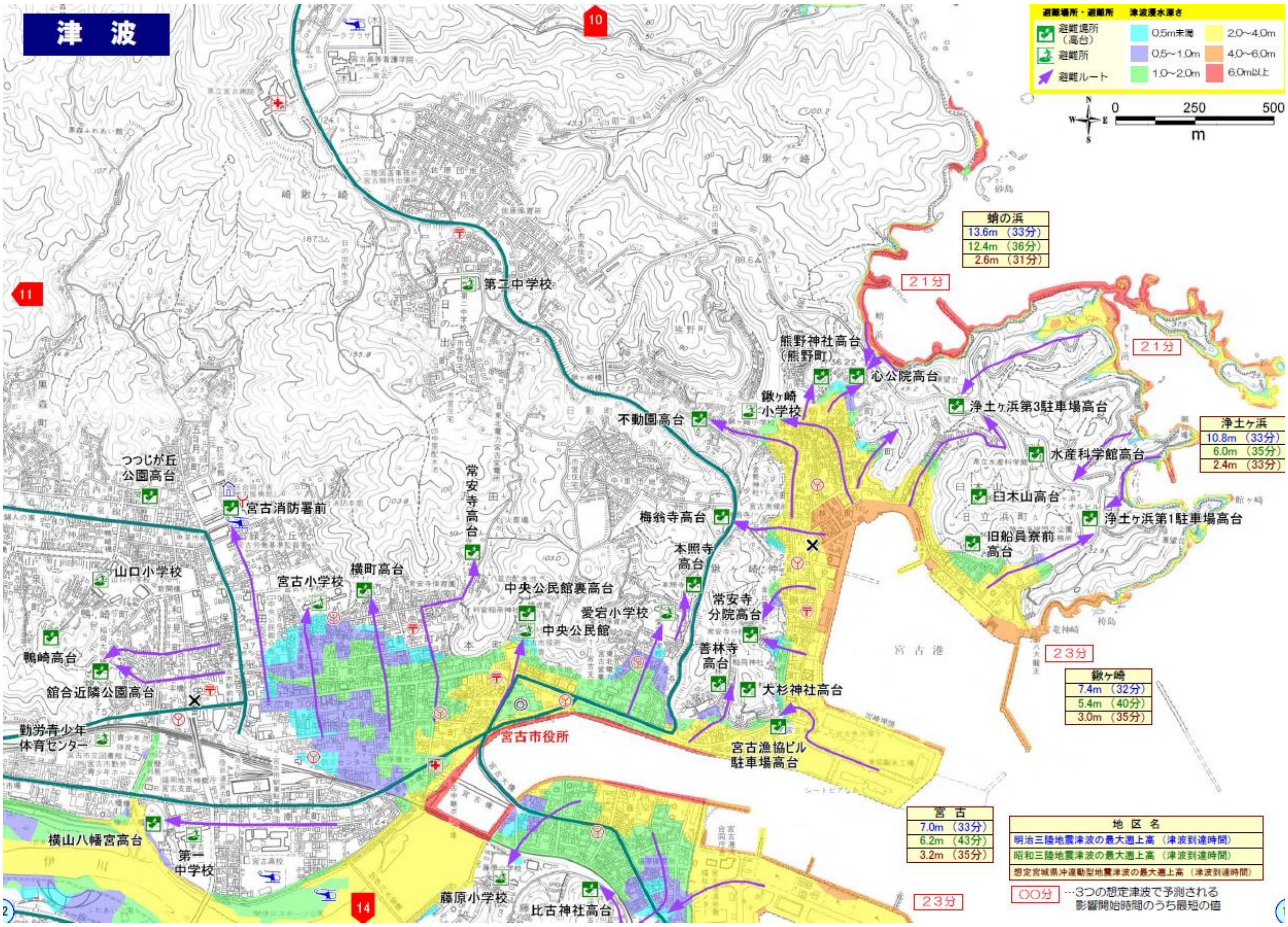

Fig. 3(b) Hazard Map for Tsunami of Miyako city

4. Evaluation of environmental risks of potential catastrophic events and the mitigation methods to minimize the risks

Environmental risk assessment is the standard scientific method for evaluating potential health and environmental impacts from exposure to chemicals in the environment (Fig. 4).

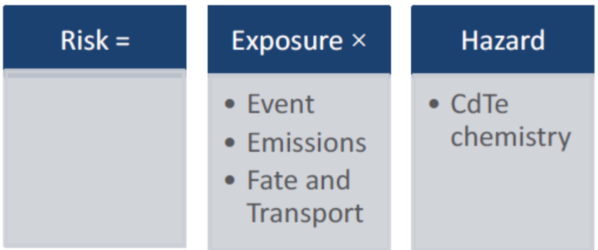

Fig. 4 Environmental risk assessment framework

Use of heavy metals (e.g., Pb, Cr, Cd compounds) is commonplace in the PV industry. The environmental risk related to each catastrophic event involving CdTe PV systems is discussed below.

4.1 Earthquake

Environmental risks for PV modules impacted by an earthquake would be related to the breakage of the modules in the impacted geographic area.

CdTe is classified as insoluble in water due to an extremely low solubility product (9.5×10^{-35}). Even if modules become broken or damaged, CdTe would not mobilize from the glass and into the environment except under very specific conditions. One condition would be if glass modules are crushed to fine pieces (< 1 cm) and then subjected to agitation in an acidic environment. These conditions would not occur in the field during any project operations[5)].

Experimental evaluation of CdTe mobility in pure compound form has been conducted with transformation and dissolution testing. The testing is designed to determine the rate and extent to which sparingly soluble metal compounds can produce soluble available ionic species in aqueous media under a set of standard laboratory conditions representative of those generally occurring in the environment. Specifically, the testing measured the concentration of Cd resulting from a 1 mg/L loading of CdTe after 28 days in a standard aqueous medium at pH 6. 15 µg/L Cd resulted from 1 mg/L CdTe loading, corresponding to approximately 1.5% solubility[6].

Note that the transformation and dissolution test results are for the pure CdTe compound, whereas in CdTe PV, CdTe is bound under high temperature to a sheet of glass by vapor transport deposition, coated with an industrial laminate material, and covered with a second sheet of glass. The module design results in the encapsulation of the semiconductor material between two sheets of glass thereby preventing the exposure of CdTe to the environment under normal conditions, and greatly reducing potential exposure under broken-module conditions.

In addition, First Solar's PV Module Performance Detection and Handling Plan that have been used in the large-scale CdTe PV projects in the western U.S[7] may be able to identify, handle, and remove broken PV modules after the earthquake. Specifically, routine inspections and power output monitoring can diagnose broken modules for prompt removal. These measures will further mitigate the environmental risks of CdTe PV systems.

4.2 Tsunami

Potential risks for PV modules impacted by a tsunami would be related to the scattering of the modules over the impacted geographic area. For metals in general, environmental mobility is a function of pH, with decreased mobility at higher pH. Because sea water is alkaline (Fig. 5) with pH in the global ocean surface waters ranging from 7.9 to 8.2[8], metal solubility would be expected to be limited for modules dispersed in sea water. In addition, even when fully dissolved (at aquatic saturation), aquatic toxicity testing of CdTe showed no ecological health effects on the standard zebrafish test species[6]. To further quantify the potential impacts of tsunami on CdTe PV modules, First Solar conducted leaching tests with seawater as a solvent[9].

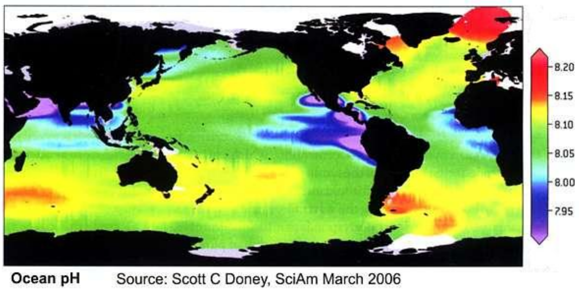

Fig. 5 Variations in pH in sea water

4.2.1 Seawater Leaching Test[9]

The experimental method for the seawater leaching test made use of the DIN standard batch leaching test modified with synthetic seawater as a solvent. The potential impacts are considered for module fragments in still sea water conditions, such as a flooded inland area of low elevation. In such condition, there is no current so module fragments would settle and not undergo continuous tumbling. To reflect this scenario, the seawater leaching test was conducted without tumbling. (Table 1)

In accordance with a 10:1 liquid/solid ratio, 90 grams of 9 mm by 9 mm PV module samples were subjected to 900 mL of seawater solution for 24 hours. After this period, the sample solution was filtered (45 µm filter) and acidified using HNO_3 to bring the solution below 2 pH, followed by analysis of Cd with ICP-MS. Five samples were tested with results ranging from 17-37 µg Cd/L per 24 hr. (Table 1)

Table 1 Analytical results of seawater leaching test for CdTe PV modules with DIN batch leaching test modified with synthetic seawater as a solvent and with no tumbling for closed sea water scenario

LAB #	Sub ID	Cd (ppb)	Pb (ppb)	specific gravity	Temp before (deg C)	pH before	conductivity before (uS)	Post Temp	post pH	post conductivity (uS)
AA63862	130925261888	17	<5	1.0225	20.7	8.17	46400	21	8	42900
AA63863	130925261885	37	<5	1.0225	20.7	8.18		20.4	8.22	43600
AA63864	130925261886	19	<5	1.0215	20.3	8.17		20.5	8.22	42800
Acid Blank		<10	<5	1.0215	20.3	8.17		20.5	8.18	43600

With the measured Cd concentration in seawater leachate ranging from 17-37 µg Cd/L, the percentage of dissolved Cd to the total CdTe was estimated as approximately 0.03%/day.

4.2.2 Interpretation of potential environmental risks caused by tsunami

In the case of tsunami, broken module pieces may be dispersed in seawater. To evaluate the potential environmental risks caused by tsunami from the results of the leaching tests, a scenario of 1 MW of PV module fragments in closed sea water was considered.

The potential impacts were estimated based on the following equation.

$$C = (T \times E) / V$$

C: Incremental Cd concentration (µg/L/day)
T: Total CdTe content (µg)
E: Cd emissions fraction (%/day)
V: Volume of seawater (L)

For parameter "T" based on 13% efficient PV modules, there is approximately 0.127 g CdTe per W (1.27×10^{11} µg CdTe per MW). For parameter "E", the measured Cd concentration in seawater leachate in Table 1 corresponds to a percentage of dissolved Cd to the total CdTe of approximately 0.03%/day. For parameter "V", a 1 MW installation requires approximately 2 hectares (20,000 m^2). If this area is flooded with 2 m of seawater, the total volume of seawater is 40,000 m^3 (40,000,000 L). Based on these parameters and the equation, the average incremental concentration of dissolved Cd in the total volume of closed seawater is approximately 0.95 µg/L/day. However, it should be noted that these results can be considered to reflect the worst case scenario in which all of the PV modules would be broken into small pieces, i.e. 9 mm by 9 mm pieces, by tsunami and submerged in a closed seawater. Therefore, it is likely that the average incremental concentration of dissolved Cd in the closed seawater is significantly lower than 0.95 µg/L/day.

In Japan, environmental quality standards for water pollutants - environmental quality standards for the human health has been set as 3.0 µg/L for Cd. This standard is based on the annual mean and can be considered for chronic (long-term) exposure. The environmental quality standard for Cd to conserve aquatic life has been discussed, but not established in Japan[10). In addition, there is no distinction in the standards for acute (short-term) exposure and chronic (long-term) exposure. In contrast, US EPA has established national recommended water quality criteria for the protection of aquatic life and human health in surface water for approximately 150 pollutants including Cd, in which criteria have been distinguished for acute and chronic as well as freshwater and saltwater[11). Since leaching of Cd from broken PV modules by tsunami is an accidental release, it can be considered as an acute (short-term) exposure. Therefore, if we compare with U.S. EPA's acute limit of 40µg/L, Cd concentration in sea water which contain submerged PV module after tsunami will not exceed the aquatic screening criteria for a certain (long) period.

Nonetheless, it should be recommended that the prompt recovery of submerged PV modules should be conducted to minimize the leaching of Cd.

4.3 Big fires caused by tsunami

Beckmann and Mennenga investigated[12) the effects of CdTe modules on the neighborhood and the general public in the case of fire. They estimated Cd concentrations in air on the surface around the burning CdTe PV modules. In the worst case, the Cd concentration in air from a fire with the largest area (1,000 m^2) with the maximum Cd contents (66.4 g/m^2) and at the shortest calculable distance (100 m) from the emission site was calculated. However, the result (0.66 mg/m^3) was still substantially below the acute exposure guideline level, AEGL-2 (10 min.) of cadmium, 1.4 mg/m^3, which is the peak concentration value for the threshold to irreversible effects or other severe, long-lasting health effects[13).

It should also be noted that they assumed in their calculations that all Cd contained in the module was released completely from the CdTe compound as Cd fumes. Reaction with CdO or a possible diffusion of cadmium in the molten glass was not considered in determining the Cd emission concentrations. Fthenakis et al. investigated CdTe modules, which were heated to temperatures ranging from 760° C to 1,100° C, typical for fires in residences and service buildings, and showed that more than 99% of the Cd remained within the molten glass matrix[14). In addition, as mentioned in 4.2.2, First Solar's 13% efficient PV modules contain significantly small Cd content, approximately 7.7 g/m^2. Therefore, it is quite likely that Cd concentration in air on the surface around the burning CdTe PV modules will be quite small compared with the acute exposure guideline level.

There are uncertainties whether and where big fires will occur after tsunami, how long they last, and whether CdTe PV modules will be subject to the big fires or submerge in sea water. So, PV modules may not necessarily be subject to the big fires. Therefore, the environmental risks of CdTe PV systems by big fires caused by tsunami can be considered very small.

4.4 Other previous works related to the environmental risks of CdTe PV systems

Central Research Institute of Electric Power Industry, Japan investigated the environmental risks of CdTe PV systems in the fiscal year of 1998 with the financial support by NEDO, in which Cd emissions in cases of fire and leaching of Cd from broken modules were investigated[15).

The combustion tests were conducted to measure the volatilization rate of Cd from various CdTe thin-film PV modules at 750-1000 centigrade. The volatilization rates of Cd from the modules were measured as <0.25% at 800-1000 centigrade. These results were used to estimate the Cd concentration in a plume generated in a wooden house on fire as well as those on surfaces around the house. It was concluded that the estimated concentration was lower than the legally regulated value in either case.

The batch leaching tests were conducted with broken CdTe PV modules in the acid rain atmosphere (pH = 4.8, 40 centigrade) with continuous tumbling for 10 minutes to 72 hours. It was found that the Cd concentrations were below the minimum detectable quantity in all leaching tests. So, it was concluded that Cd leaching from broken CdTe PV modules in an ordinary atmosphere would be negligible.

From the all results mentioned above, it was concluded that there would be no problem to use CdTe PV systems from the view point of the environmental risks.

5. Conclusion

In this report, environmental risks of CdTe PV systems under catastrophic events in Japan were considered with a focus on earthquakes, tsunami and big fires caused by tsunami. There is a big uncertainty on how many CdTe PV modules will be broken in earthquakes, and in a subsequent tsunami, how many will be subject to big fires or be submerged in sea water. However, even in the worst case scenarios, it is unlikely that the Cd concentrations in air and sea water will exceed the environmental regulation values. So, the environmental risks of CdTe PV systems under catastrophic events can be considered small.

For commercial reasons, power systems are not likely to be constructed in tsunami hazard areas; nevertheless, the prompt recovery of broken and submerged PV modules should be conducted to minimize the leaching of Cd after earthquakes and tsunami.

Reference

1) http://www.shimz.co.jp/theme/earthquake/fire.html
2) Kitamura, Y. Consideration to the tsunami fire in Kesennuma city 2012
3) http://disapotal.gsi.go.jp/bousaimap/index.html?code=1
4) http://disapotal.gsi.go.jp/viewer/index.html?code=1
5) First Solar. 2013a. Memo from P. Sinha to K. Brutsaert. Environmental Risk Assessment of Potential Catastrophic Events. July 2.
6) Kaczmar, S., Evaluating the Read-Across Approach on CdTe Toxicity for CdTe Photovoltaics, SETAC North America 32nd Annual Meeting, Boston, MA, November 2011
7) First Solar. 2012. Appendix 10: PV module detection and handling plan", Topaz solar farm project.
8) Takahashi, T., and S.C. Sutherland. 2013. Climatological Mean Distribution of pH and Carbonate Ion Concentration in Global Ocean Surface Waters in the Unified pH Scale and Mean Rate of their Changes in Selected Areas. OCE 10- 38891. Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY
9) First Solar. 2013b. Memo from P. Sinha to K. Brutsaert. Environmental Risk Assessment of Potential Tsunami Impacts. Nov. 1
10) http://www.env.go.jp/council/toshin/t094-h1504/houkoku_2.pdf
11) http://water.epa.gov/scitech/swguidance/standards/criteria/current/index.cfm
12) Beckmann, J., and Mennenga A., 2011. Calculation of emissions when there is a fire in a photovoltaic system made of cadmium telluride modules. Bavarian Environmental Agency, Augsberg, Germany.
13) http://www.epa.gov/oppt/aegl/index.htm
14) Fthenakis, V. et al (2005): Emissions and Encapsulation of Cadmium in CdTe- PV Modules During Fires. Progress in Photovoltaics: Research and Applications
15) Central Research Institute for the Electric Power Industry (CRIEPI). 1999. Fiscal 1998 Report on the Results of Work Entrusted to the Renewable Energy and Industrial Technology Development Organization.