17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

Development of Earthquake Vulnerability Functions for Renewable Energy Facilities

J. Sakai(1), M. Masuda(2), C. Williams(3)

(1) Principal Modeler, Model Development, RMS Japan Corporation, Tokyo, Japan, Junichi.sakai@rms.com
(2) Senior Director, Model Development, Risk Management Solutions, Inc., Newark, CA, USA, Manabu.masuda@rms.com
(3) Senior Director, Product Management, Risk Management Solutions, Inc., Portland, OR, USA, Chesley.williams@rms.com

Abstract

Exposure value in the industrial sector has increased rapidly over the past few decades, specifically in developing countries. This creates a strong incentive for the global insurance market to better understand this sector's unique risk profile. Industrial risks consist of a variety of specialized facilities, with a wide range of damage susceptibility. Both the vulnerability and the replacement cost of the on-site machinery, equipment, production lines, raw materials, intermediate-final products and stocks vary significantly across the range of industrial facility types or occupancies. To incorporate the unique nature of industrial facilities, an advanced component-level performance-based approach was used to derive vulnerability functions for the Industrial Facilities Model (IFM).

The IFM has a suite of customized vulnerability functions designed to represent the risk of relatively large, well-engineered/maintained industrial facilities. The IFM covers a wide range of facility types that cannot be modeled using a more generic model. It provides a comprehensive set of unique combinations of building, machinery/equipment and business interruption functions for specific types of industrial facilities. Although the generic industrial line occupancy class in risk assessment models can represent the entire industrial lines risk on average, using the generic model is not adequate for modeling specific types of facilities, such as energy, pharmaceutical, electronics, petrochemical, pipeline, etc. The damageability of such facilities can be significantly higher or lower than the general industrial average. The differentiation of risk between specific facility types reduces the uncertainty in industrial facility loss results and permits better decisions in insurance underwriting for industrial risks on both individual accounts and entire portfolio exposure management basis.

In recent years, demand for renewal energy driven by global warming, by energy security concerns, and by rising fuel costs have resulted in increased wind and solar power capacity. These alternative energy sources have expanded rapidly over the past few years and are projected to increase even further. To meet strong insurance market demand, new vulnerability models for wind and solar farms have been developed.

The component-based approach requires understanding the structural behavior under strong ground shaking and the replacement cost breakdown of each structural component. Wind farms primarily consist of a number of wind turbines, together with sub-components such as transmission and distribution lines, transformers, and substations. In general, a supporting tower of a wind turbine is made from steel and has a thin walled circular hollow section. To develop the vulnerability functions for wind farms, the inelastic behavior of wind turbines, which results from local buckling of the steel towers, was distinguished by size category (Large/Mid/Small) based on the statistical study of structural properties of 510 wind turbines. Structural periods of wind turbines were estimated by size using similar approach. The vulnerability functions of solar farms have been developed using a similar component-based approach.

Modeled losses at locations with high seismic hazard in California using the newly developed wind and solar farm functions are significantly lower than those computed for generic industrial buildings or generic electric power stations, which is consistent with observed damage/losses from the recent damaging earthquake events.

Keywords: Probabilistic Model; Loss Estimation; Industrial Facilities; Wind Farms; Solar Farms

1. Introduction

Exposure value in the industrial sector has increased rapidly over the past few decades, specifically in developing countries. This creates a strong incentive for the global insurance and re-insurance market to understand this sector's unique risk profile. Industrial risks consist of a variety of specialized facilities, with a wide range of damage susceptibility. Both the vulnerability and the replacement cost of the on-site machinery, equipment, production lines, raw materials, intermediate-final products and stocks vary significantly across the range of industrial occupancy types. To incorporate the unique nature of industrial facilities, an advanced component-level performance-based approach was used to derive vulnerability functions for an Industrial Facilities Model (IFM).

The IFM has a suite of customized vulnerability functions designed to represent the risk of relatively large, well-engineered/maintained industrial facilities. The IFM covers a wide range of facility types that cannot be modeled by a more generic model. It provides a comprehensive set of unique combinations of building, machinery/equipment and business interruption functions. Although the generic industrial line occupancy class in risk assessment models can represent the entire industrial lines risk on average, using the generic model is not necessarily adequate for modeling specific types of facilities, such as energy, pharmaceutical, electronics, petrochemical, pipeline, etc. The damageability of such facilities can be significantly higher or lower than the general industrial average. The differentiation of risk between specific facility types reduces the uncertainty in industrial facility loss/damage results and permits better decisions in insurance underwriting for industrial risks for on both individual accounts and entire portfolio exposure/risk management.

In recent years, demand for renewal energy sector driven by global warming, by energy security concerns, and by rising fuel costs have resulted in increased wind and solar power capacity. These alternative energy sources have expanded rapidly over the past few years and are projected to increase further as shown in Fig. 1 [1]. To meet strong market demand, new seismic vulnerability models for wind and solar farms have been developed.

This paper introduces the component-based approach that was employed to develop the vulnerability models for both wind and solar farms. The paper also discusses modeled losses from the newly developed vulnerability functions.

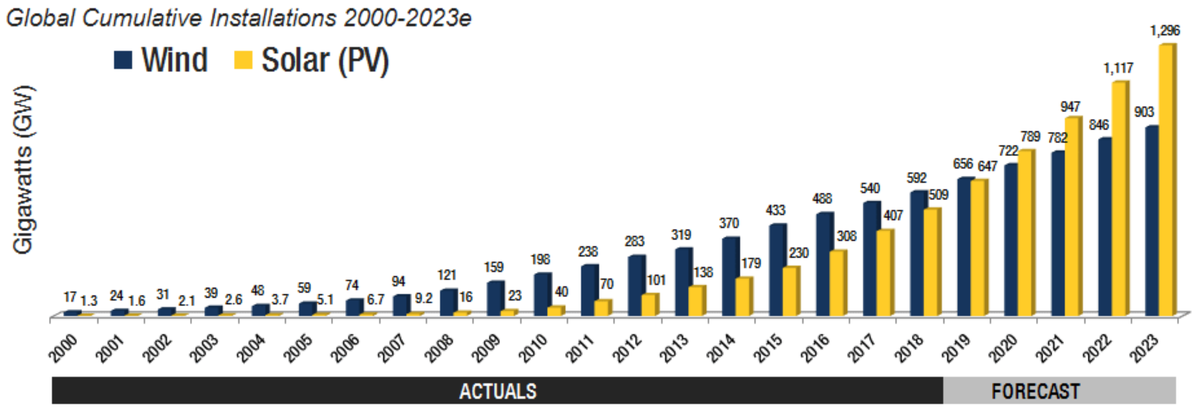


Fig. 1 – Global installed wind and solar power capacity [1]

2. Industrial Facility Modeling Approach

To develop the Industrial Facilities Model, the catastrophe modeling company, Risk Management Solutions (RMS) established a vulnerability modeling approach that describes the performance of each component of an industrial facility under various catastrophe loss scenarios. To build the component-based vulnerability model, we divided each industrial facility class into components broadly having three key insured coverage categories: (1) structures, which correspond to building envelope, (2) machinery and equipment (M&E) including production lines and (3) stock, which corresponds to content coverage.

We combined these curves using a weighting scheme to obtain individual facility curves by facility occupancy type and coverage. The relative structure and content values for each component, determined through input from experts, and analysis of proprietary claims data, and benchmark valuation research, are the basis for the weighting scheme.

RMS developed the component mean conditional damage functions in several ways depending on the coverage type. For the structure coverage, all components across the 40 different occupancy classes can be reduced to seven different broad categories of structure types: control room, warehouse, laboratory, office, storage, workshop, and the building shell. We then developed mean conditional damage functions for each of the seven types and assigned these to the respective component in each occupancy class. We used a similar approach for machinery and equipment, and stock.

To develop these composite mean conditional damage functions, engineering specs/requirements, site visits, and reconnaissance are used as references.. Then, we validate these component functions to "General Industrial" insurance losses.

In summary, the IFM methodology follows four key steps:

- Step 1: Identify IFM classes (Heavy industrial, chemical processing, light industrial, petrochemical, electric power, electric power generation and other/miscellaneous)
- Step 2: Split facilities into components and associated replacement costs
- Step 3: Conditional damage functions for each component
- Step 4: Facility vulnerability functions (Fig. 2) based on Eq. (1)

$$MDR = \Sigma(DR_i \times CR_i) \qquad (1)$$

where MDR: Mean damage ratio of overall facility
DR_i: Damage ratio of each component
CR_i: Component ratio of each component, which is obtained from replacement cost contribution

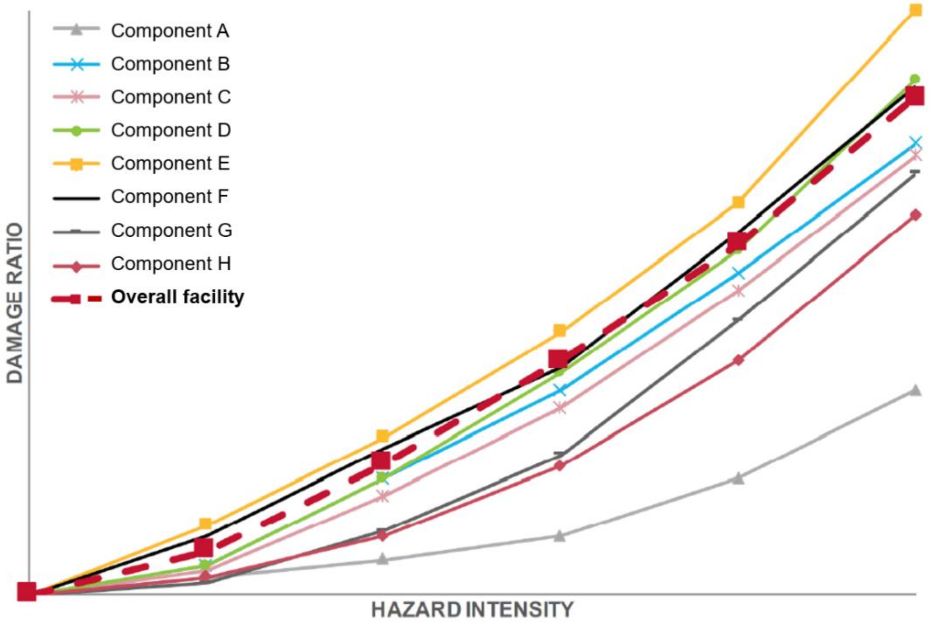


Fig. 2 – Vulnerability function of overall facility and each component

3. Development of Earthquake Vulnerability Model for Wind Farms

Fig. 3 shows the growth in size of wind turbines since 1980 [2]. As the installed capacity has increased, so has the capacity of individual wind turbines. The typical capacity of wind turbines that were installed in the US in 2015 was 2.0MW [3].

Fig. 4 shows an example of a wind farm in the U.S. Wind farms primarily consist of number of wind turbines, together with sub-components such as transmission and distribution lines, transformers and substations. A wind turbine itself has 4 primary components:

- Foundation,
- Supporting tower,
- Nacelle, and
- Rotor blades.

In general, a supporting tower is made from steel and has a thin-walled circular hollow section.

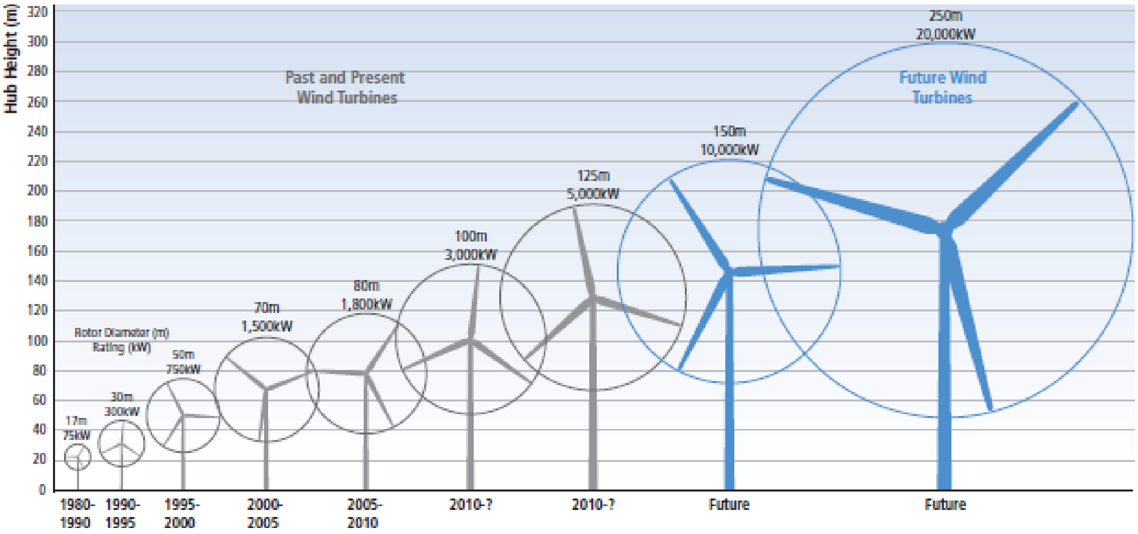


Fig. 3 – Growth in size of typical commercial wind turbines [2]

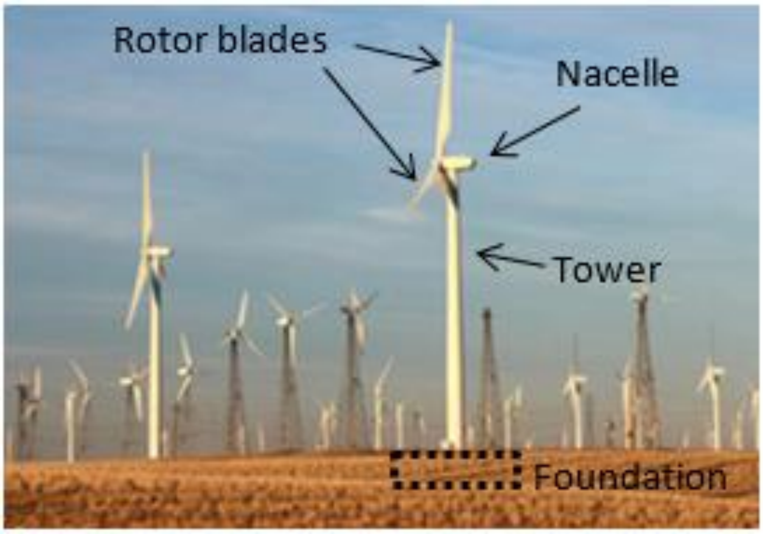


Fig. 4 – Typical wind farm and structure of wind turbines

The design load is controlled by the wind load requirement for turbines. In fact, no severe damage due to earthquakes has been reported in the past, although collapse of wind turbines has been observed due to severe winds during hurricane/typhoon events all over the world. Fig. 5 shows an example of a typical failure mode for wind turbines, in this case during a typhoon event in Japan [4, 5].

Developing an earthquake damage function for wind turbines requires understanding the structural behavior of a supporting tower under lateral load at the top of the tower. Analytical or experimental studies (e.g., [4, 5, 6]) investigated the nonlinear behavior of supporting towers of wind turbines. The authors concluded that the collapse of tower occurs when local buckling occurs as shown in Fig. 6, and the local buckling occurred at around the elastic limit of the tower. The actual collapse of towers occurred in the same failure mode as the buckling.

Fig. 5 – Tower failure caused by local buckling (400 kW capacity turbine, Japan, 2003) [4, 5]

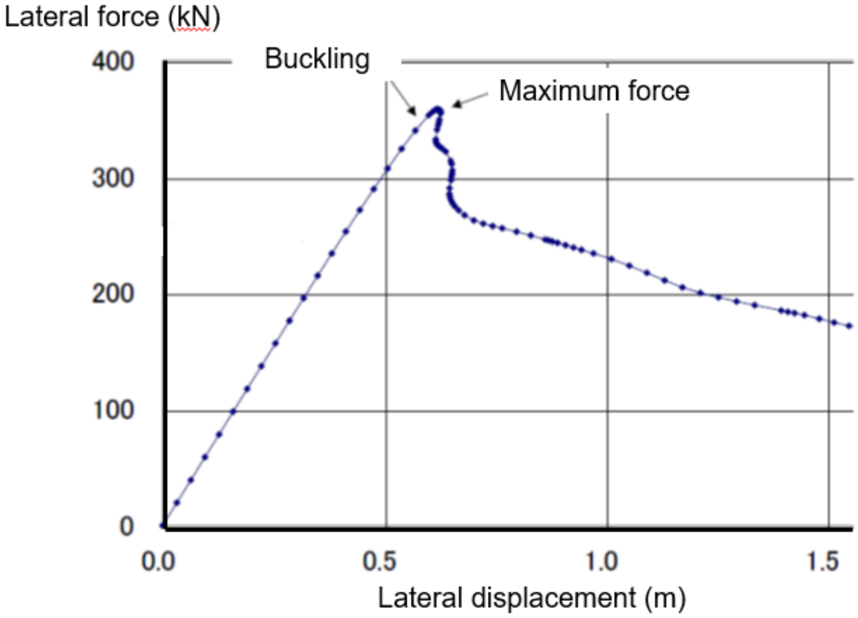


Fig. 6 – Lateral force versus lateral displacement of wind turbine (Capacity: 400 kW, Height: 35m) [4, 5]

Using such considerations, which describe the structural behavior of a tower when subjected to a lateral load, RMS developed unique damage functions for wind turbines, shown schematically in Fig. 7. The initiation of loss is set at the elastic limit of a tower and the mean damage ratio increases very rapidly after exceeding the limit due to local buckling. The yield displacement, which is displacement at the elastic limit, were obtained based on the statistical study of structural properties of 510 wind turbines [7] as shown in Fig. 8, and the yield displacement was set for the model by size category (Large/Mid/Small). Natural periods of wind turbines were estimated by size from the data in [7] as shown in Fig. 9.

Wind farms also include transmission / distribution lines and transformers / substations. For the IFM, RMS determined the contribution of each of these subcomponents to the total value of a wind farm based on the document published by International Renewable Energy Agency [8]. Based on this document, RMS assumes that wind turbines account for around 80% of the overall replacement cost of a wind farm.

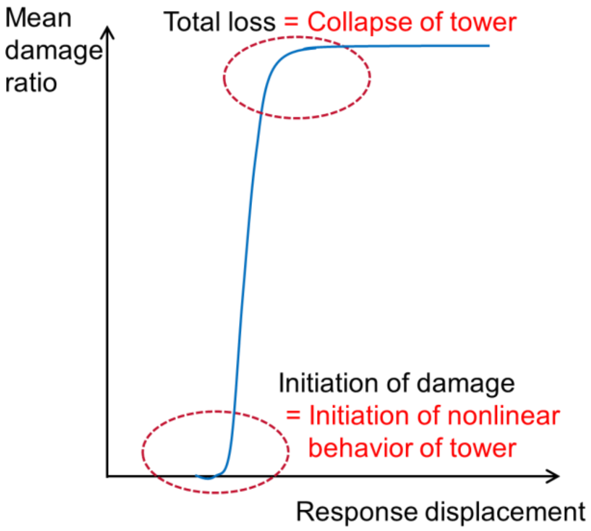
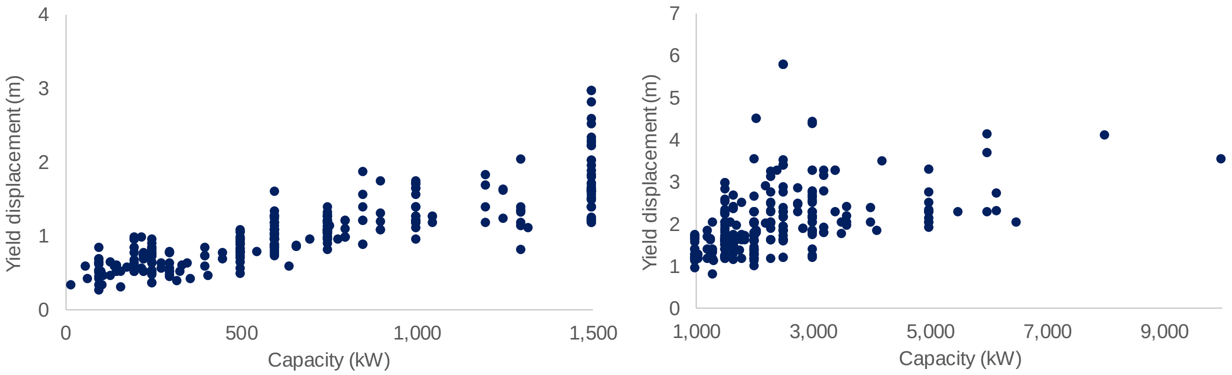


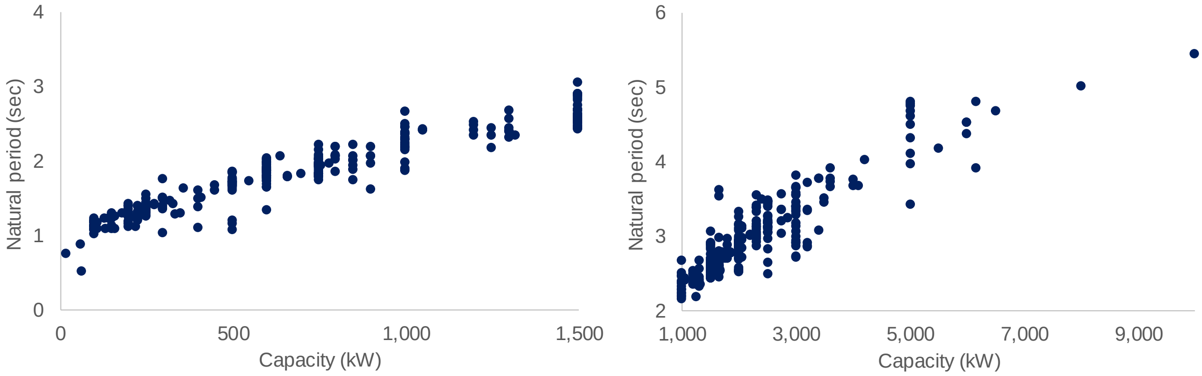
Fig. 7 – Proposed damage function for wind turbine



(a) Small to mid-size

(b) Large size

Fig. 8 – Capacity and estimated yield displacement of wind turbines



(a) Small to mid-size (b) Large size

Fig. 9 – Capacity and estimated natural period of wind turbines

4. Development of Earthquake Vulnerability Model for Solar Farms

Fig. 10 shows images of a typical mega-solar farm. California has nearly half of the nation's solar electricity generating capacity according to U.S. Energy Information Administration [9]. The largest solar farm in the U.S. is in Southern California and its capacity is about 580 MW.

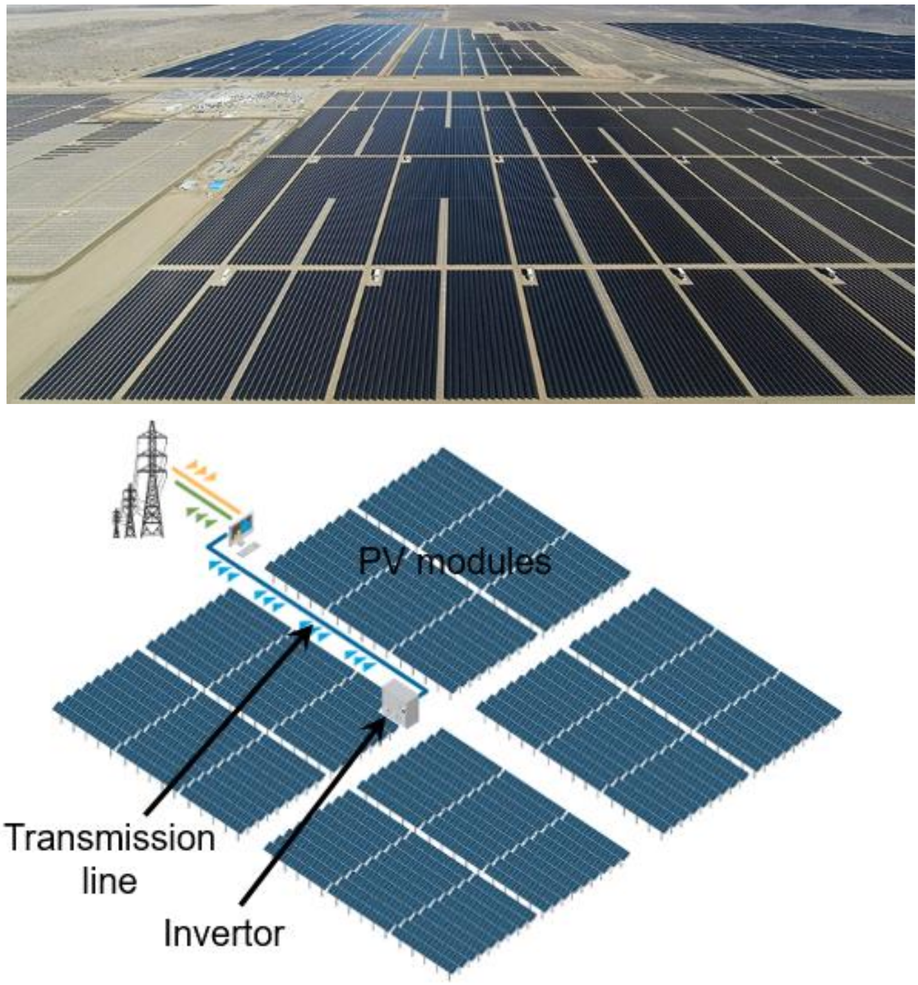


Fig. 10 – Typical mega-solar farm

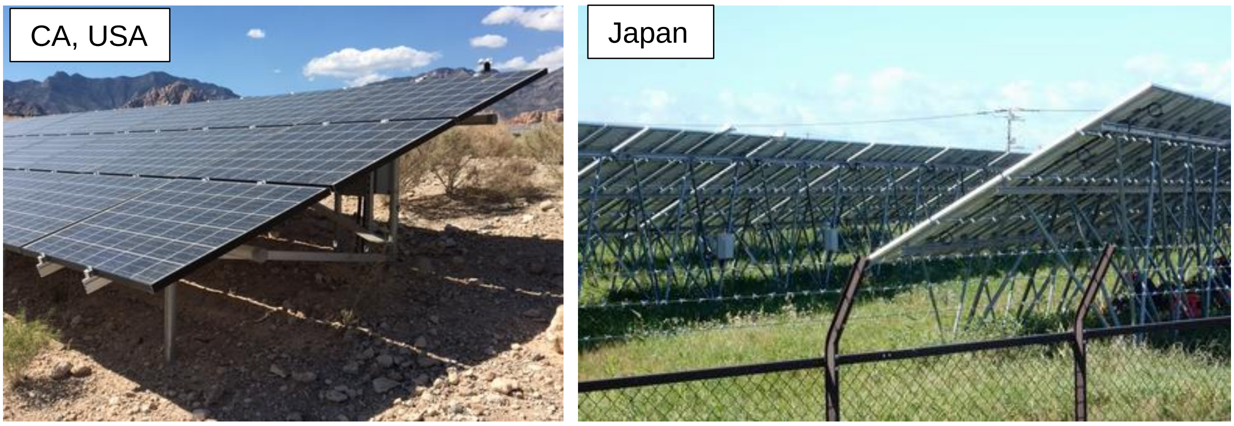


Fig. 11 – Example of PV (photovoltaic) modules and supporting steel frames

(a) No damage to solar farm (b) Severely damaged SFD near solar farm

Fig. 12 – Photos from reconnaissance after 2016 Kumamoto EQ, Japan

Fig. 13– Example of damage to solar farm (2015 Kanto flood, Japan)

The primary component of solar farms are PV (photovoltaic) modules supported by light-weight steel frames as shown in Fig 11. Sub-components include invertors and transmission/distribution lines as shown in Fig. 10.

Similar to wind farms, no severe damage to solar farms due to earthquakes has been reported in the past. An RMS reconnaissance team investigated solar farms after the 2016 Kumamoto earthquake, Japan, finding undamaged solar farms near the hypocenter in close proximity to several severely damaged traditional wooden single-family dwellings were observed as shown in Fig. 12. RMS reconnaissance teams have found catastrophic damage of solar farms due to strong wind, flooding and heavy snow. Fig. 13 shows damage to a solar farm in Joso-shi, Ibaraki, Japan after 2015 Kanto flood event. Similar level of damage was observed near the levee breach point of Chikumagawa-river in Nagano prefecture after 2019 Typhoon No. 19 (Hagibis).

Because PV modules are supported by relatively rigid steel frames and PV panels themselves are not heavy in general, the PV arrays have a very short natural period and relatively small yield displacement.

RMS developed the earthquake vulnerability model for solar farms based on these structural properties combined with a component cost breakdown. RMS used the cost breakdown on solar industry data from Solar Energy Industries Association website [10] as a basis, which indicates that PV modules account for about 70% of the overall replacement cost of a solar farm.

5. Modeled Losses of Wind Farms and Solar Farms

Fig. 14 shows the average annual loss comparison of selected IFM occupancies including wind and solar farms using uniform exposure located in San Bernardino County in Southern California. Compared to the losses of general industrial or fossil fuel electric power stations, loss results of wind/solar farms are significantly lower. This result is consistent with observed limited damage/losses from the recent significant earthquake events.

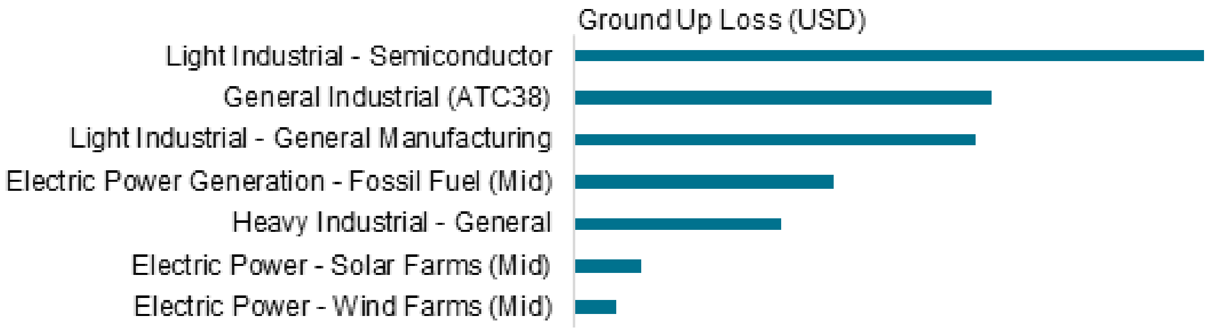


Fig. 14– Modeled losses of wind/solar farms compared to existing IFM models

6. Conclusions

This paper introduces the component-based approach that was employed to develop the earthquake vulnerability models for wind and solar farms. The component-based approach requires understanding the structural behavior under strong ground shaking and the replacement cost breakdown of each structural component. Based on detailed investigation of structural properties of each component of the facilities, the vulnerability models of wind and solar farms were developed. The modeled losses at locations with high seismic hazard in California, USA, of the newly developed wind and solar farm models are significantly lower than those of general industries or fossil fuel electric power stations, which is consistent with observed limited damage/losses from the recent significant earthquake events.

7. References

[1] PowerWeb - A Forecast International Inc. (2019) (http://fi-powerweb.com/Renewable-Energy.html).

[2] Intergovernmental Panel on Climate Change (IPCC) (2011): *Special report on renewable energy sources and climate change mitigation*, Cambridge University Press.

[3] Wiser R, Hand M, Seel J, Paulos B (2016): Reducing wind energy costs through increased turbine size: Is the sky the limit? Electricity Market & Policy Group, Berkeley Lab, USA.

[4] Takahara K, Mekaru T, Shinjo F, Ishihara T, Matsuura, S (2004): Analytical study on collapse of wind turbines in Miyako-jima, Japan, during 2003 Typhoon Maemi. *26th Wind Energy Symposium*, Japan Wind Energy Association (JWEA), (in Japanese).

[5] Ishihara T, Yamaguchi A, Takahara K, Mekaru T, Matsuura, S (2005): An analysis of damaged wind turbines by typhoon Maemi in 2003. *6th Asia-Pacific Conference on Wind Engineering* (*APCWE-VI*), 1413-1428, Seoul, Korea.

[6] Guo L, Yang S, Jiao H (2013): Behavior of thin-walled circular hollow section tubes subjected to bending. *Thin-Walled Structures*, 73, 281–289.

[7] The Wind Power -Wind Energy Market Intelligence –

(https://www.thewindpower.net/turbines_manufacturers_en.php)

[8] International Renewable Energy Agency (IRENA) (2012): Renewable Energy Technologies: Cost Analysis Series Volume 1 Power sector, Issue 5/5 Wind Power. *IRENA Working Paper*.

[9] U.S. Energy Information Administration, U.S. Department of Energy. (https://www.eia.gov/)

[10] Solar Industry Research Data, Solar Energy Industries Association (SEIA).

(https://www.seia.org/solar-industry-research-data)