# SEISMIC AND WIND DESIGN FOR SOLAR PANELS

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**ABSTRACT:**

The Pasadena Water and Power Department and EBMUD are aggressively upgrading their water system infrastructure to withstand earthquakes. As seismic-related upgrades are developed, we consider opportunities for addressing climate change. This paper examines the economics and pros and cons of constructing solar panel systems atop several water reservoirs that also require seismic upgrades. Pasadena and EBMUD serve progressive communities, and opportunities to address climate change and earthquake reliability are actively being addressed. California's Governor Schwarzenegger is requiring that coal power not to be used for base load purposes, and replacing coal with solar for power generation is viewed positively by the public. Given these important reasons to build new renewable electric generation, we examine the economics of installing solar panels atop water reservoirs. Our engineering studies show that the mix of solar and seismic concerns brings up many new engineering issues, having to do with the economics of renewable power as well as high wind speeds. The findings show that the normal code strategy of designing for 475 year earthquakes and 50 year winds is not prudent or cost effective for many installations. The costs for seismic upgrades with concurrent solar panel installations suggest a more prudent design for as much as a 400 year wind.

**KEYWORDS:** Solar, Water, Reservoir, Wind, Pasadena, EBMUD

## 1. INTRODUCTION

Over the past few years, water utilities in the United States have become interested in placing solar panels atop their water reservoir roofs, with the objective of collecting electric power that can be used to operate nearby equipment (wells, pumps, treatment plants) to reduce peak demand or put into the local power grid for resale. At the same time, these same water utilities are investing in seismic upgrades of water reservoir roof structures.

This paper examines a case study as to the seismic and wind loading issues that affect the cost to construct these solar panels atop a water reservoir. We examine reliability and economic issues.

The key conclusions are as follows. First, existing light-weight reservoir roof coverings that are commonly used in California for large water reservoirs can and do fail in 50 year wind events. Second, the economics and reliability of adding solar panels to existing water reservoir roof structures is greatly affected by the style of construction: for low-weight wood and panel-type roofs (by far the most common used in California), wind load affects can be critical in selecting a suitable seismic and wind load retrofit strategy. Third, the common "code" provision for seismic and wind design assumes that some level of damage will occur in 475-year return period earthquakes, or 50-year return period wind storms; these are mutually inconsistent return periods, leading to poor outcomes if only "code" wind loads are adopted. Fourth, the economics of designing for 400-year wind events, given that a seismic upgrade is concurrently adopted, is very cost effective.

## 2. WATER RESERVOIRS

The style of reservoirs (or tanks) used by water utilities for storage of potable water will vary greatly, depending on water demands, site topography, locally available materials, and what the designer felt like doing that day. In California, there are more than 400 water utilities serving communities with populations from 20,000 to more than 4,000,000 people, and cumulatively, they own about 3,500 reservoirs and tanks. By "reservoir" we mean a water storage basin that was built by digging a basin into the soil, laying down an impervious (or so it was hoped) liner, and then filling the basin with water. By "tank", we mean steel, concrete or redwood storage tanks. In California, there are about 200 existing reservoirs and 3,300 existing tanks. For reservoirs constructed prior to about 1950, the most common strategy was to leave the basin open to the air. In the late 1950s, it was mandated that roof structures be placed over the basin, in order to reduce algae growth and prevent bird droppings (or other contaminants) from entering the potable reservoirs. Through the late 1970s, the most common seismic design philosophy (if any at all was used) was to design the roof structures for a lateral load of 10% of its dead weight. Of the existing 200 reservoirs, the most common styles of roof structures are:

- Wood framing with lightweight sheathing (~60%),
- Concrete columns with wood framing and lightweight sheathing (~20%),
- Concrete columns with concrete diaphragm and sheathing (~15%), and
- Steel or aluminum (~5%).

The liner systems in most of these reservoirs are some sort of poured or placed concrete slab / panel system; some with underdrains. The range storage capacity of the reservoirs are between 4 to 30 million gallons (a very few are much larger), with common water depths of 15 to 25 feet. Common roof areas are 200 x 200 feet to 500 x 500 feet (or so).

The most common roof sheathing for water reservoirs is corrugated steel, corrugated asbestos-impregnated panels (weights about 1 pound per square foot), or sometimes plywood with roofing cover. Including the weight of the sheathing, rafters, purlins, beams and columns, the total weight of the roof structures commonly ranges from 8 psf to 10 psf.

For ground-supported tanks constructed using common AWWA codes, in practice, no seismic design provisions beyond keeping the tank leak tight for normal use are done. This is because the seismic design provisions in AWWA D100, D110 essentially provide no extra seismic reliability, owing to their improper assumption that "steel tanks are ductile", etc. and implying "magic R" values of 4 to 6 or higher. Should such a "code designed" steel tank actually experience ground motions much in excess of PGA = 0.3g, they commonly fail (broken side entry pipes, buckled walls, torn welds, etc.) with complete or partial release of water. Concrete tanks will also fail if they slide off their flexible foundations. The actual seismic capability of most existing tanks (there are some exceptions) is largely provided by dead weight resistance and friction, and once these are overcome, bad things happen to the tank. As of 2008, most water utilities in California are seismically upgrading their existing tanks (for example, EBMUD seismically retrofitted more than 60% of their 150 existing steel, concrete and redwood tanks over the past ten years). Due to their smaller size, and often obstructed vies (trees placed around the tank to hide it from the neighbors) placing solar panels on tanks is not usually as advantageous on tanks as that for reservoirs. So for the remainder of this paper, we examine only reservoirs.

## 3. SOLAR POWER AND COSTS

The energy efficiency of existing solar photovoltaic panels varies by manufacturer. For purposes of design, we assume a 5 million gallon reservoir, with a 62,000 square feet roof, if covered with solar panels can produce about 500 kilowatts (kW). For California as a whole, this suggests that it is possible to use these reservoir roofs to generate about 500 kW x 200 reservoirs = 100 megawatts. For the entire state of California, current peak electric load on a hot summer day, (when almost all solar panels would be generating peak power) is about 45,000 to 50,000 megawatts. So, from a state-wide planning perspective, installation of panels on water reservoir roofs is not going to materially impact the use of fossil fuels or change the global environment. Most water utilities are municipally-owned, and some elected members of water utility boards have a "innate" sense of being "ecologically green", and feel that installation of solar panels provides a satisfactory "return on investment" when all factors are considered. Other publically-owned water agencies are keen on "fiscally sound investment" and "keeping water rates low", and have not installed solar panels. So far (as of 2008), economic analyses as to the efficacy of installing solar panels on reservoir roofs, when considering only the capital cost of installation versus the saving of saved electricity (say at $0.10 per kilowatt) consistently shows that the electrical power savings alone does not come close to break even, using any common economic model (like pay back, internal return on investment, benefit cost ratio, etc.) if *only* the capital costs and direct electrical power savings costs are used. These models usually show that if the value of electric power is closer to $0.80 per kilowatt, that it *is* cost effective to install solar panels. Today (2008), the common retail price of electricity in California is $0.10 per kilowatt (where base load is largely served by coal or hydro) to $0.25 per kilowatt (where base load is largely served by natural gas, nuclear and hydro). For many water utilities, no solar panels are being installed unless "grants" from some place are used to offset the capital cost. For other water utilities, where "cost is of not much concern", solar panels are actively being incorporated into contract documents. Today (2008), there is one solar panel installation already in place on a water reservoir (owned by EBMUD, located in El Sobrante, California, about 20 miles from San Francisco, funded in part by a $1,300,000 grant, total cost $3,200,000 to produce 600 kilowatts;

these costs are over-and-above the seismic upgrade costs for the reservoir). Other solar panel installations are being designed and constructed in Pasadena and San Francisco.

## 4. SEISMIC DESIGN ISSUES

Of the ~200 potable water reservoirs in California, about 150 can be currently considered seismic deficient. What we mean by "deficient" is that should an earthquake occur at the reservoir site that produces ground motions with PGA much over 0.35g or so, then moderate to major damage to the reservoir roof can be expected. Various consulting engineers have done detailed seismic evaluations of these existing reservoirs (mostly built pre-1970), and in almost every case, the evaluation shows gross seismic overloads for ground motions much over PGA = 0.40g, such as:

- Lack of continuous diaphragm;
- Undersized interior connections;
- Lack of suitable exterior reaction blocks;
- Non-ductile behavior of interior concrete columns (especially along sloped sides where "short column" effects might dominate);
- Wave induced loading on interior baffle walls; etc.

We have also observed that as the existing structures get older (50+ years) that delamination of glulam beams has resulted in roof collapse (this suggests that glulams should not be used for interior use over reservoirs); ongoing corrosion of steel sheathing requires painting every 20 years or so; corrosion of painted overhead structural steel beams can occur within just a few years in areas adjacent to frothing disinfected water (such as at chemical injection points).

The consequences of roof damage in an earthquake include the following: falling debris into the water basin makes the water "non-potable", and therefore a boil water alert is required; falling debris might clog the inlet/outlet pipes, resulting in loss of water available for fire fighting; post-earthquake repairs will be required, possibly taking weeks to months, at very high cost. In general, there is no "life safety" consequence of a falling / damaged roof, as there is rarely anybody inside the reservoir or walking on the roof of the reservoir; although, in a few cases, the roof area above the reservoir might be dedicated as a park or other public assembly area, in which case life safety becomes a much more critical issue.

Faced with these issues, water utilities are presented with a range of options for seismic retrofit. These include: do nothing (this is known to occur); install heavy grates and low cost modifications to protect the inlet/outlet pipes and valves so that availability of fire water is assured (cost about $1 to $2 per square foot of roof area) (done about 50% of the time); seismic upgrade the roof to current design practices (common design for about PGA = 0.50 to 0.60g, with an importance factor of I=1.25, and ductility limited to conform to the style of retrofit) (done about 30% of the time, costing about $20 to $100 per square foot). In a few cases, the cost for retrofit / maintenance is so high that the water utility abandons (drains) the reservoir, especially true for smaller open cut basins, but is known to sometimes occur for ~5 million gallon basins, especially for areas with too much water storage where water quality issues (lack of turnover) become a paramount consideration.

These seismic upgrades are often done at the same time as various other maintenance activities, possibly including repairs or upgrades to liners to reduce water leakage. For a 5 to 10 million gallon reservoir, it is not uncommon to observe daily leak rates of 1,000 to 5,000 gallons (usually does not warrant action); left unmitigated over time, leak rates for common liner systems sometimes increase to about 40,000 to 100,000 gallon per day rate, at which point the water utility often takes remedial action (usually, fill in leaks with suitable compounds using an underwater diver, costing perhaps $0.17 per square foot to do about once every ten to thirty years or so). In a few instances, water utilities have "relined" the reservoir with new concrete liners or polyethylene bladders, costing about $30 per square foot.

## 5. SOLAR PANELS

As of mid-2008, there are a variety of vendors selling solar photovoltaic panels. For purposes of designing a water reservoir roof structure to support these panels, prior to actual specification and purchase of the panels, we examined the common range of weights for possible panels that might be used, from more than 10 solar panel vendors. The common weights vary from 2.5 to 4.3 pounds per square foot (psf). These weights exclude mounting hardware of the panels, so for design, the range of total installed weight might be between 2.8 and 5.0 psf.

A key design decision is whether or not to mount the panels as "flat" or "sloped" atop the reservoir roof. If the panels are mounted as "flat", then the amount of energy they can produce is compromised. If the panels are mounted as "sloped", then the common assumption (at least in sunny California) is to use a fixed slope equal to the latitude of where the panel is placed (commonly between 32 to 36 degrees latitude in California), which optimizes power generation considering both summer and winter time. Note: for solar panels placed at high latitudes (such as observed in Tanqueray Fjord, Ellesmere Island, latitude 81 degrees), then the correct placement is much steeper to maximize solar input just in the daylight summer months.

For the common case of solar panels in Coastal California at latitude ~32 degrees, the loss of efficiency between placing the panels "flat" atop a reservoir roof with existing slope of under 2 degrees, versus placing the panels on the same reservoir at permanent slope of 32 degrees, is estimated at about 12%. In other words, a "sloped" panel array would produce about 12% more power than a "flat" array.

The capital cost to procure and install a 60,000 square foot solar panel array atop an existing reservoir roof, to produce about 500 kW, is about $3,500,000 to $4,000,000. This cost includes the panels, panel mounting hardware, rectifiers and other associated equipment, and labor to install. This cost does not include the cost of annual maintenance, replacement of the rectifier every 10 years or so, replacement of the panels every 20 years or so, or structural modifications for the reservoir roof that might be needed for either dead, live, seismic or wind loads for the solar panels.

## 6. CASE STUDY

We examine the practical issues and economics of installing solar panels for a reservoir with light wood roof in Pasadena (10 miles from Los Angeles). Figures 1 and 2 show the existing condition of the reservoir in Pasadena. The roof sheathing is corrugated steel, the roof structure is redwood rafters atop redwood beams atop redwood columns, the liner is light reinforced concrete. The columns rest on the liner without positive attachment. Roof dead weight is about 8 psf. The roof was built in 1950, for an original seismic horizontal load of 10% times dead weight. The existing lateral load system is provided by lateral resistance of the roof beams and rafters being resisted by exterior concrete anchors. The current (2008) seismic design criteria is for an earthquake with PGA = 0.60g (475 year return period). Seismic analysis of the roof shows that the interior connections between wood members are undersized for the seismic loads (seismic upgrade by modifying most bolted connections) and the exterior concrete anchor blocks are too small (seismic upgrade with new drilled piers). Accumulated corrosion, repair of the leaking liner and other maintenance items results in a seismic upgrade cost of $32 per square foot (excluding solar panels).

Once the seismic upgrade costs were established, the owner wished to add in solar panels on the roof. Assuming the maximum weight of new panels (about 5 psf), the lateral loads on the roof are increased by 5/8 = 62%. The seismic design is redone using the higher loads, and the additional costs for seismic resistance for the solar panels placed flat on the roof is about $3 per square foot.

We then examined what extra design provisions should be done to accommodate high wind loads on the roof. When the roof was originally constructed (1950), we could find no documentation as to any provision for wind loading on the roof. The common design philosophy in most of California is to design for a 70 mph wind (fastest mile, commonly assumed from 1965 to 2000) or 85 mph wind (3-second gust, commonly assumed post 2000). For exposure B type setting (some surface roughness provided by nearby trees and buildings), this results in a gross wind uplift of about 10 - 12 pounds per square foot. If one counts upon the dead weight of the existing roof (8 psf) plus lowest weight of new solar panels (3 psf), we see that at 70 mph, little or no net roof uplift occurs, and thus no special wind design is required.

We elected to do the wind load design for the roof with solar panels assuming a 100 mph wind (fastest mile), exposure B. This results in a wind uplift on the roof of about 24 psf, or about two times the dead weight. In other words, unless we positively anchored the roof against uplift, we would expect the solar panels ($3.5 to $4 million) to "blow away" in a large wind storm. To upgrade the solar-panel roof for the higher-than-code wind speed requires the extra installation of thousands of "hurricane ties", and the addition of concrete anchors to provide suitable dead weight resistance against uplift at the base of most of the columns, or about $4 per square foot.

We then considered whether or not it was economical to design for this high wind speed. We observed the following. The design wind speed of 100 mph is about 42% higher than code. Using common extreme value analysis for winds, this would imply design for a 400-year return period wind, well in excess of the code-mandated 50-year return wind. Based on calculation, we expect that a 70 mph (exposure B, fastest mile) straight wind should produce just enough turbulence on the roof at its edges and center vents to overcome deadweight, and begin to peel-off the existing roof sheathing.

We next looked for evidence of wind-damage for existing reservoirs. In Pasadena, one of eight reservoirs had its roof peeled off / damaged (moderate repair costs) in a prior wind event. In Fremont, one of six reservoirs (all similar to the one in Figures 1 and 2) had its roof peeled off (very high repair costs) in a recent winter storm. Both these reservoirs were located at or near the base of large mountains (1,500 to 4,000 feet higher than the roof) in exposure C type environments. It is readily apparent that the 50-year return wind speeds in the California code should not be considered "never to exceed" and in fact can be expected to be exceeded one or more times at reservoirs within a 50 year time frame. If the reservoir is strictly used for water retention purposes, then perhaps a $2 to $10 per square foot repair bill, due to high winds once every 50 years is acceptable. However, once a new solar panel array is installed, the repair bill would increase to perhaps $35 to $60 per square foot, and the loss of the power generated might become material to the community if solar power become a material portion of the total base load power generation.

We performed benefit cost analyses to examine if it was cost effective to design the new roof for a 400-year versus the 50-year return period wind, assuming that solar panels are installed. We found that the benefit cost ratio, assuming a 7% discount rate, was over 4 (highly cost effective).

## 7. CONCLUSIONS

It is becoming "in vogue" to install solar panels in California. There are perhaps 150 to 200 water reservoirs in California that have large roofs (1 acre to 6 acres common, a few with 10 to 50 acres) where ecologically-minded owners might want to install solar panels. Given the common style of construction (light weight roof), and concurrent seismic issues, we make the following recommendations.

- Installation of solar panels on these lightweight roofs, to code minimum levels of wind design and without concurrent seismic retrofit, will likely result in partial to complete economic loss of the solar panels due to high winds once every 50 years, and due to earthquake once every 50 to 200 years.

- Assuming the decision is made to seismically-upgrade the roof and to install solar panels, then we recommend that uplift-type wind loads of at least 20 psf be considered for most of coastal California. If the roof is lightweight (commonly about 8 to 12 psf with solar panels), then this will require positive tie down of the roof. The incremental cost to design for a 400-year return period wind, given the concurrent cost for seismic upgrade, and the high valuation of the solar panel installation, makes the extra wind design cost effective. Lacking this level of wind load, the utility owner should not be surprised to lose the solar panel installation once every 50 years or so. For installation on light-weight roofs, we recommend placing the solar panels in "flat" configuration, as if the panels are placed in "sloped" configuration, then the additional lateral wind loads on the sloped panels can result in lateral loads on the roof structure or nearly 1.0 times the dead weight of the roof, well in excess of the design needed for reasonable performance in 475-year earthquakes. Exceptions to these recommendations would be made if the costs of construction vary significantly from those described in this paper.

## UNITS

This paper uses customary units in the United States. The following are the conversions for metrification. Currency. U.S. dollars, benchmarked to the year 2008 except where noted. Approximate exchange rates in mid-2008. $1 U.S. dollar = 5.1 Norwegian kroner = 0.63 Euro = $ 1 Canadian dollar = 107 Yen. Length. Length, width, and height. 1 foot = 0.305 meters. Area. 1 square foot = 0.093 square meters. Pressure. Pounds per square foot (psf). 1 psf = 9.8 kilogram-force per square centimeter. Acceleration. Peak Ground Acceleration. 1 g = 981.45 cm/sec/sec. Acres. 1 Acre = 4,406.873 square meters. Volume. 1 U. S. gallon = 3.785 liters.

*Figure 1. Interior View of Empty Water Reservoir*

*Figure 2. Exterior View of Water Reservoir Roof*