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WHEN TO TURN OFF THE POWER?
COST/BENEFIT OUTLINE FOR PROACTIVE DE-ENERGIZATION

Abstract:

Examination of historical weather, fire, and outage data reveals that there is a distinct possibility that events such as those of October 2007, in which multiple power large power line fires were ignited, may be expected to recur. Furthermore, if even more extreme Santa Ana wind conditions are possible these could lead to Katrina-like damage throughout Southern California. While this contingency might be prevented by hardening of the electrical grid, it can also be prevented by de-energizing areas in which extreme winds occur. However, turning off the power exposes the public to a number of additional hazards and costs. Any estimation of the "trigger point" for pro-active de-energization must take these costs and risks into account. This document outlines a method that can be applied to estimate the trigger point for which maximum public benefit is achieved, and lists a number of the factors that need to be included. Since some of these are currently unknown, this draft outline also lists areas of investigation that should be undertaken to form the foundation of any-de-energization plan. Due to the severity of potential damage from catastrophic wildland fires ignited by power lines however, the setting of trigger points that take into account a best estimate of ALL hazards should not wait until all factors are known with certainty, but should be an iterative process that is refined over time as estimates and calculation methods are improved.

A1. Context: The risk of catastrophic power line fire

In October 2007, Southern California was hit by what could be described as a "powerline firestorm" – a strong Santa Ana event that was characterized by having almost half of its 20 fires being due to the ignition of vegetation by power lines. The most destructive of these was caused by the Witch and Guejito fires, which merged to become the fourth largest fire in California's recorded fire history[1]. Total estimated damage for all fires was $1.6 B[2], most of which could be attributed to power line fires by virtue of the fact that these fires were responsible for most of the structure losses.

The fact that this event occurred raises the question of whether such an event is likely to recur, or whether an even more extreme event with more severe damage is possible. With this in mind, an analysis was done of historical fire and weather data for all of Southern California, and the results were presented in January 2009 at the Fire and Materials Conference in San Francisco[3]. Key results of this analysis included:

- Power line fires are, on average, 10X larger than fires from all causes.
- Power line fires are similar in size distribution to fires that start under Santa Ana weather conditions.
- Suppression of fires by fire agencies is over 97% effective under normal conditions, but only 80% effective under Santa Ana conditions with wind gusts over 30 mph.
- The number of outages and line faults increase rapidly when wind gusts exceed 30 mph.

Also, some general review of the physical principles leading to power line fire ignitions were examined, and it was shown that there was a distinct possibility of a very rapid rise in the number of ignitions as the wind speed rises to or beyond the design limits, as illustrated in the figure below:

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[1] California Department of Forestry and Fire Protection; 20 Largest California Wildland Fires (by Acreage Burned / by Structures Destroyed)
http://www.fire.ca.gov/communications/downloads/fact_sheets/20LACRES.pdf
http://www.fire.ca.gov/communications/downloads/fact_sheets/20LSTRUCTURES.pdf

[2] California Department of Insurance; Insurance Commissioner Poizner Hosts Insurance Recovery Forum to Assist San Diego Wildfire Survivors with Recovery Efforts.
http://www.insurance.ca.gov/0400-news/0100-press-releases/0060-2007/release120-07.cfm

[3] Mitchell, Joseph W; Power Lines and Catastrophic Wildland Fire in Southern California; Fire & Materials 2009, San Francisco CA, Jan 26, 2009
http://www.mbartek.com/FM09_JWM_PLFires_1.0fc.pdf
http://www.mbartek.com/FM09_Mitchell_ppt.pdf

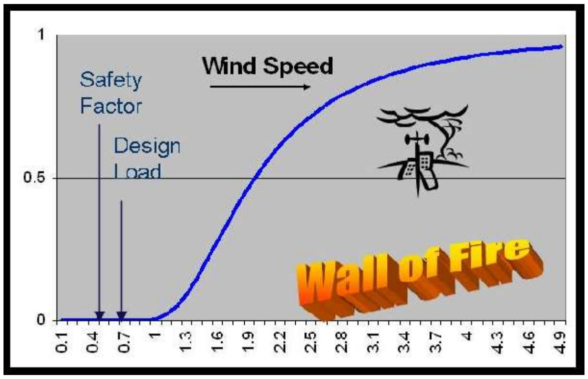

Figure 1 – Anticipated outage/ignition dependence on wind speed

A large number of ignitions under extreme Santa Ana conditions could not be successfully suppressed, and would spread rapidly. There is a potential for Katrina-like damage throughout Southern California.

Support for the hypothesis of a rapid rise in the number of faults / failures as the wind speed increases is provided by hurricane data collected by Florida Power and Light[4]. The figures below show data on faults and pole failures, respectively, as a function of wind speed. Note that the rapid increase in failure rate has the same general shape as Figure 1.

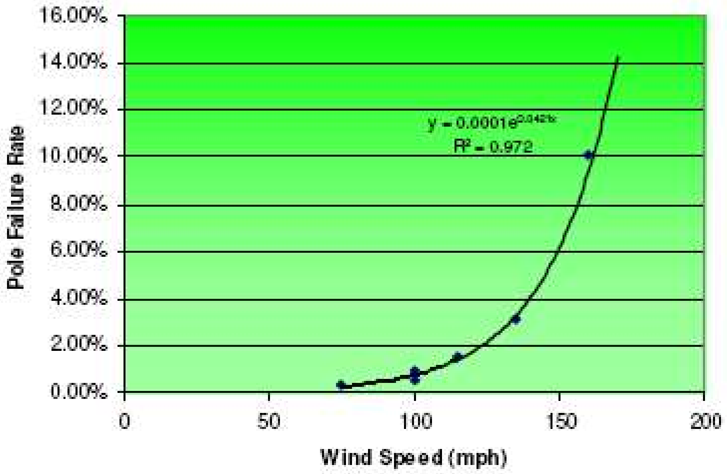

Figure 5-1. Pole Failure Rate vs. Average Wind Speed in Affected Area

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[4] Quanta Technology, "Undergrounding Assessment Phase 3 Final Report: Ex Ante Cost and Benefit Modeling." Prepared for the Florida Electric Utilities and submitted to the Florida Public Service Commission per order PSC-06-0351-PAA-EI. Contacts: Le Xu, Richard Brown. May 21st , 2008. http://www.cba.ufl.edu/purc/docs/initiatives_UndergroundingAssessment3.pdf
Phase 1 and Phase 2 reports are at: http://www.floridapsc.com/

Figure 2 - FPL/Quanta Pole Failure Rate - reprinted by permission

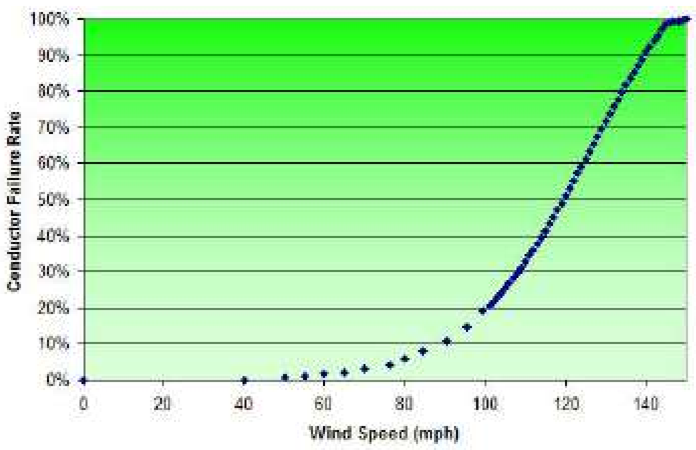

Figure 5-2. Florida Power & Light Span Failure Rate Data

Figure 3 - FPL/Quanta Span Failure Rate - reprinted by permission

Due to the extensive exposure of the electrical grid to flammable vegetation occurring throughout Southern California, a failure of even a very small fraction of the components in the network would be capable of causing the catastrophic scenario mentioned above. Case in point – the October 2007 wind event did not cause failure of a significant portion of the distribution grid, but was still capable of igniting enough power line fires to be in sum catastrophic. The hurricane data plots show just how rapid the rise in number of faults and failures with wind speed can be, so it is not difficult to visualize how a Santa Ana event of extreme but foreseeable intensity could induce enough power line fires to wreak havoc upon Southern California.

The importance of preventing such a scenario from happening can not be overstated.

A2. Methods to reduce catastrophic fire risk

The California Public Utilities Commission convened Rulemaking R.08-11-005 in order to study measures to reduce the fire risk in light of the October 2007 fires and the results arising of its investigations into these fires[5]. This state-wide effort is aimed at identifying and codifying measures that will significantly reduce the risk to California residents.

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[5] California Public Utilities Commission; R.08-11-005; Order Instituting Rulemaking To Revise and Clarify Commission Regulations Relating to the Safety of Electric Utility and Communications Infrastructure Provider Facilities; November 6, 2008.

A2.1. Hardening of the distribution and transmission network

Most of the methods that have been or will be discussed in R.08-11-005 have had to do with "hardening" the electrical transmission and distribution network, or making it less likely to fail under extreme wind conditions. Among the measures that have been suggested for investigation in the course of this proceeding are:

- Replacing wood with steel poles
- Undergrounding of distribution and transmission lines in high-risk areas
- Putting spacers on conductors to prevent mid-line slap
- Reducing the length of spans
- Adopting a higher wind speed for wind-load design requirements
- Removal of trees and vegetation anywhere near electrical equipment/conductors

This is not an exclusive list.

One of the problems utilities face in engineering sound solutions to the problem of wildland fire ignition by power lines is that it is not clear what the maximum strength of the winds during a Santa Ana event would be. This is an area requiring investigation. It is possible, using statistical methods and assumptions about the recurrence intervals for extreme events, to estimate what the maximum expected wind speed would be in a specified interval. This method is used to devise wind loading standards, such as the ASCE 7 standard[6] which calculates an 85 mph estimated maximum 3 second gust with a 50-year recurrence time.

Due to the extremity and inevitability of damage from power line fires caused by extreme Santa Ana events, however, a 50-year recurrence time is not sufficient. A more cautious approach would be to apply the same methodology used for seismic design requirements to the design of the electrical network. The IEEE Recommended Practice for Seismic Design of Substations[7], for instance, suggests a 2% probability of exceedance within a 50 year time interval – corresponding roughly to a 1000 year recurrence time.

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[6] American Society of Civil Engineers (ASCE); (1995); ASCE Standard 7-95, New York.

[7] Institute of Electrical and Electronics Engineers; 2006; IEEE recommended practice for seismic design of substations / sponsor; Substations Committee of the IEEE Power Engineering Society.

Acceptance of a recurrence interval of hundreds of years would be appropriate for guaranteeing the safety of the public from the consequences of an anomalously intense wind event. However, doing so raises a number of difficult issues:

- Since even the 50-year expected 85 mph gust is far in excess of the current GO 95 wind loading of 54 mph, applying an even higher standard would require more extensive adjustments to the network.
- Statistical data on Santa Ana wind event intensities in the high risk areas is poor, and currently not possible to extrapolate accurately out to 50 years, much less 1,000 years.
- ASCE recurrence times depend only on wind speeds and do not differentiate "wet" storms from Santa Ana events, so it is not clear to what extent the ASCE standards are appropriate to this problem.
- Effects of climate change are likely to affect this estimate, and this would require additional modeling and study
- The expense required to upgrade the electrical distribution and transmission network up to a standard significantly in excess of that required for a 50-year recurrence interval will be very high.

In order to deal with these issues, the adoption of performance-based requirements rather than prescriptive measures for dealing with extreme events is attractive because it allows operational countermeasures instead of specific engineering design requirements. In other words, it allows for proactive de-energization under the most extreme conditions.

A2.2. Proactive De-energization: Turning off the power

The possibility of turning off electrical power in response to an extreme weather event was raised in SDG&E's original petition for a rulemaking, P.07-11-007. It is also central to their current application A.08-12-021. However, since this is a currently active application, no details of current SDG&E activities in this area will be included in this section. Instead, we review only some of the generic points that do or might apply to pro-active de-energization as a strategy to reduce the risk of catastrophic power line fires.

In a generic de-energization model, areas of significant fire risk would be divided into areas in which electrical power can be independently controlled. Risk factors applying to wildland fire – wind speed, humidity, slope, vegetation conditions and others, can be independently evaluated in each segment. If risk factors that make a catastrophic power line fire likely occur in any segment, then the electrical power to that area would be removed. This does not necessarily prevent damage to the electrical infrastructure, but it would effectively remove the risk of a catastrophic fire developing as a result of damage to power lines.

Removing power, though, brings on a number of societal costs and risks. Among these are:

- Other utilities, such as water districts and telcos, may not be able to provide service
- Vulnerable customers may be put at risk
- Disruption to vulnerable facilities, such as schools
- Wildland fire risks will be increased by lack of notice or communications, inability to report fires or danger to people, and hampered evacuation due to loss of traffic signals.
- Large number of private generators may increase overall the fire risk due to defects, poor maintenance or improper use.
- General costs of lost power: disruption to businesses, loss of public convenience.
- Moral hazard: Utilities are given an economic incentive to postpone or cancel needed maintenance and system upgrades.
- Ratepayer issues vis a vis cost discrepancies and reliability concerns among customers within the same service region.

Any analysis of the appropriate trigger point to cut off power must take these costs and risks into account. Any strategy aimed solely at reducing utility liability risk due to power line fires will not optimize the general public benefit.

A3. Proactive De-energization Cost/Benefit Outline - Overview

The following section lays out a general form for a cost-benefit analysis. By cost-benefit, we show how the costs of de-energization balance against the benefit of avoided power line fires, with the goal of obtaining the lowest overall cost and risk for residents and ratepayers. The purpose is primarily illustrative, in that it shows how the various factors relating to de-energization relate to each other in terms of cost and risk.

This is a draft outline and discussion, not the cost/benefit analysis itself. More elaborate or refined frameworks may be devised to carry out the actual cost/benefit analysis. This draft outline is intended as a starting point. As each aspect is explored, unknown variables and fields of investigation should be addressed.

It is unlikely that all uncertainties will be resolved in a short timeframe. Hence, any initial cost/benefit analysis will contain subjective inputs – even guesswork. This should not deter utilities and the Commission from using this approach, because the potential that an event equaling or exceeding the October 2007 power line firestorm can occur is established, and any measure taken that will reduce the commensurate damage is worthwhile even if it is not complete or fully optimized. An iterative approach, in which the estimation is refined over time as new information and analyses become available, would best solve this problem. This is particularly true because it is relatively easy to change the trigger point for de-energization, as opposed to changing design engineering standards and wind-load requirements. ***However, any initial estimate must make an effort to take into account the potential societal risks and costs associated with this approach if is to succeed in reducing overall risk to the public.***

Use of cost benefit analysis to determine electrical grid survival strategies for extreme events is already an established practice. For instance, the Florida Public Utilities Commission recently engaged a study to gauge the cost/benefit relationship for undergrounding of distribution lines in hurricane-prone regions[8].

Many of the costs to be estimated will be based on amortized risk calculations and arguments based on probabilities. This will be shown in the remainder of this section. In order to accurately represent the relationships involved, we've had to adopt a mathematical treatment. Enough description will also be provided so that the basic ideas are explained without referring to the math.

Despite this, one could argue with some justification that the models that are used to represent costs and risks are overly simplistic. We assert that with the current lack of knowledge in this field, it is best to start with simple models and relationships, and to refine these with time if future data shows that they are inadequate.

We define the terminology for some of these costs as follows:

v: This specifies a maximum annual wind speed in the service area.

v_T: This specifies the trigger threshold for de-energization.

$P(v)$: This specifies the probability that wind speed v_0 will be exceeded in any given year. $dP(v)$ is the probability that the maximum wind speed in any given year would be v.

$C_x(v)$: This is the average cost of an event in which the maximum annual wind speed is equal to v_0 or greater. Types of cost (each having its own identifier, shown as 'x' above) will be specified.

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[8] Quanta, 2008.

$R_x(v)$: This is the cost amortized using risk. In general risk is calculated as *P X C*, or the probability of an event multiplied by the cost of the event. Mathematically, we express this as[9]:

$$R_x(v) = \int_0^{v_t} d\overline{C}_x(v)dP(v)dv$$

A3.1. Total Cost of De-energization

The total cost of de-energization includes a large number of factors. However, many of these different contributions can be lumped together into pieces that will vary in similar ways with respect to the input variables (such as wind speed trigger-point). Taken together, these form the total cost equation, below:

$$C_{TOT}(v_T) = R_{WLF}(v_T) + C_M(v_T) + R_{PLF}(v_T) + R_{DEF}(v_T, C_M(v_T))$$

Each of these functions is defined below, and described in more detail in a later section. This equation can be used to determine the *minimum cost* – inclusive of all hazards and risks that the public will be exposed to as a function of the de-energization trigger point v_T.

$R_{WLF}(v_T)$: This is the additional risk to the public from wildland fire arising from turning off the electrical power.

$C_M(v_T)$: This is the mitigation cost that communities and persons will have to spend to mitigate the risk of losing power.

$R_{PLF}(v_T)$: This is the risk from power line fires from winds less than the cut-off threshold v_T.

$R_{DEF}(v_T, C_M(v_T))$: These are the costs of de-energization, some of which can be mitigated by taking countermeasures.

A3.2. Maximum Wind Speed Probability

A3.2.1. Description

The probability that the wind speed will be greater than a given trigger threshold v_T in any given year can be specified as $P(v_T)$. While there is considerable historical data regarding "average" years, our knowledge of the behavior for high-wind "anomalous"

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[9] More properly, this is expressed as an integral. A summation sign is used for the sake of simplification.

years is lacking. Various statistical tools can be used to extrapolate into the low-probability region.

A3.2.2. Equations

Functions that have been used to estimate maximum wind speeds include Extreme Value Type I distributions[10] and reverse Weibull distributions[11].

A3.2.3. Expected Shape

A typical Weibull type distribution is plotted below.

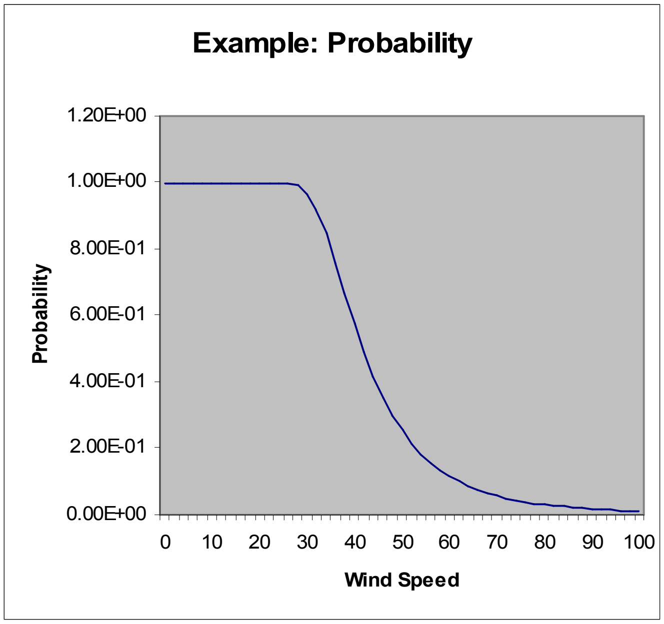

Figure 4 - Example wind speed distribution

A3.2.4. Parameters

The parameters will be based on the type of probability function assumed.

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[10] Simiu, Wilcox, Sadek, and Filliben, 2003, “Wind Speeds in ASCE 7 Standard Peak-Gust Map: Assessment”, Journal of Structure Engineering, 129(4):427-439

[11] Minciarelli, Gioffre, Grigoriu, and Simiu, 2001. “Estimates of extreme wind effects and wind load factors: influence of knowledge uncertainties”, Probabilistic Engineering Mechanics, 16(4): 331-340

A3.2.5. Areas of Study

The primary issue is to determine what the expected maximum values of Santa Ana wind speeds are expected to be. This is currently not known. Investigations that would be useful include:

- Use of historical data to determine maximum values. This can use both recent high-precision measurements (such as RAWS data) coupled with long-term historical data.

- Determination of maximum Santa Ana wind speed based on climate and weather modeling. This would require mesoscale analysis and simulation using supercomputers by climate scientists.

- Determination of how climate change might be expected to cause these maximum speeds to change with time.

A3.3. Affected Area

A3.3.1. Description

An optimal strategy for de-energization will only affect the areas that are subjected to the highest winds and have a significant fire risk. Wind strength would not be uniform over this area – it will vary on both coarse scale due to the specifics of the Santa Ana event and on finer scales due to topography. One proposal that reduces the overall impact is to divide the affected region into independently sectionalized distribution segments and then to monitor winds in each of these segments individually, and shut them off only if conditions in that particular segment exceed the trigger points.

For cases in which the wind conditions barely exceed the trigger point, only a few segments would be affected. In the case of very high winds that significantly exceed the trigger point in the worst events more of the segments (or even all of them) would be affected.

For the sake of most risk and cost assessments, it would also be proper to weight the geographic areas that will be de-energized by their populations.

This whole strategy is highly dependent on the hypothesis that geography is the best predictor of nearby wind speeds.

A3.3.2. Equations

For winds below the trigger point, no areas would be affected. For winds very far beyond trigger, all will be affected. Let $F(v)$ be the fraction of the service area subject to shut-off that will be de-energized for a wind speed v.

Then:

$F(v) = 0$ for $v<v_T$

$F(v) = 1$ for $v>>v_T$

The relation between area affected and threshold is not known, but might be parameterized as a simple empirical function based on historical weather data. For instance:

$F(v) = A(v - v_T) / v_T$ where A is an empirical constant and $F(v) < 1$.

A3.3.3. Expected Shape

An example of the non-uniformity of the wind distribution can be seen below in the distribution of winds as predicted by the National Forecast Data Center on October 21, 2007[12]:

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[12] A.06-08-010 Sunrise Power Link – Mussey Grade Road Alliance Phase 2 Testimony, Appendix 2G.

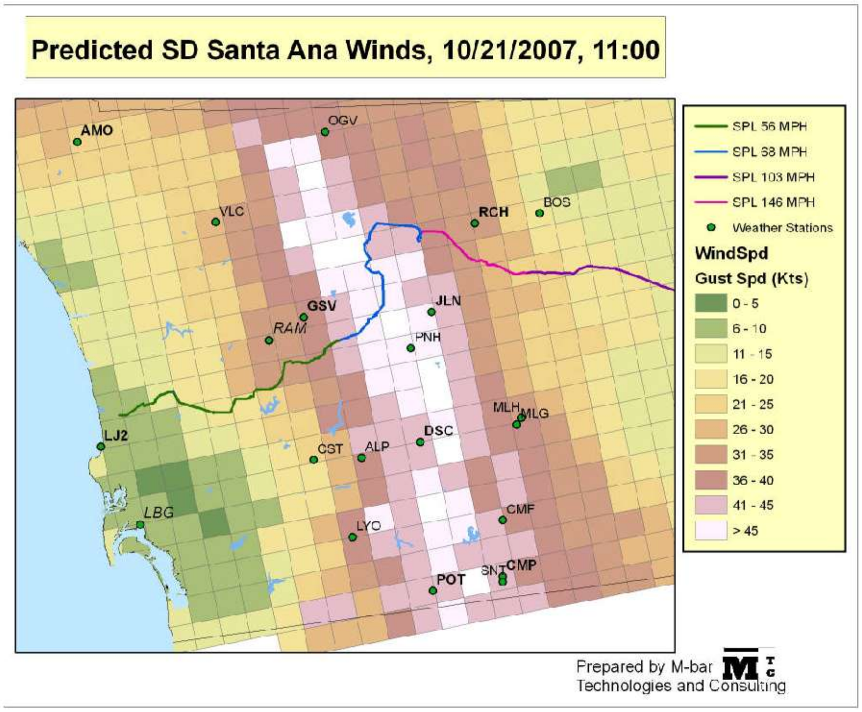

Figure 5 - October 21, 2007 San Diego Winds

The NDFD predicted wind gust speeds for 11 a.m. on October 21, 2007, roughly two hours prior to the start of the Witch Creek Fire. Superimposed is a proposed power line route. Weather station locations are also shown, with those used in the MGRA analysis indicated in bold face, and those used only on the SDG&E analysis in italics.

A3.3.4. Parameters

Relative variation of weather station wind speeds can be obtained from historical wind data under Santa Ana conditions.

A3.3.5. Areas of Study

- The relationship between maximum and minimum winds for Santa Ana events can be studied by looking at weather history data for existing weather stations.

- The hypothesis that geographic location is a good predictor of wind speed can be tested by looking at correlations between different weather station wind data under Santa Ana conditions.

- It might be that finer scale topographic considerations can strongly affect local wind conditions. As noted by SDG&E in its wind analysis provided in its Sunrise Powerlink application: "*Winds can be strong and gusty near the* *mouths of canyons oriented parallel to the direction of airflow. Funneling of airflow through mountain passes and along deeper valleys can cause unusually high wind speeds… valleys with persistent down slope winds associated with strong pressure gradients.*"[13] Computer modeling with a goal of generating a wind-speed correction map to augment weather station data would be potentially useful.

A3.4. Wildland Fire Risk

A3.4.1. Description

Wildland fire risk can be divided into two components: those caused by power lines and those not caused by power lines. Power lines make up less than 3% of ignitions throughout California (only about 1% in Southern California), so under normal conditions one would expect them to contribute a similar fraction to the time-averaged cost of wildland fires. However, under Santa Ana wind conditions, two things happen: First, when gusts exceed 30 mph, the efficiency of fire suppression drops, and fires become much larger – on the average ten times larger. This is true for all wildland fires, regardless of source[14]. Second, the number of ignitions due to power line faults will increase very steeply, as described in the introduction. This section describes these two effects as they relate to the cost of wildland fire and the risk of wildland fire as a function of wind speed.

A3.4.2. Equations

Both power line and non-power line components would be expected to have a threshold at 30 mph according to the analysis in Mitchell 2009. This analysis does not show a correlation between size and wind speed above 30 mph. This is counter-intuitive, since one might expect fires to get more destructive with increasing wind speed. The result might imply that there is actually a problem in using weather stations to make generalizations about conditions in their immediate geographical surroundings. This bears further investigation.

The functional form for the rapid increase in ignitions is unknown. Application of some basic principles suggests that a Weibull distribution would be appropriate guess[15], which is of the same general form as the Florida hurricane data[16]. The maximum cost

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[13] A.06-08-010; Sunrise Powerlink Project; SDG&E's 3/3/08 Responses to MGRA Data Request No. 6; MGRA-50. Quoted in MGRA Phase 2 Testimony, Appendix G, p. 9.

[14] Mitchell, 2009.

[15] Ibid.

[16] Quanta Technologies, 2008.

used to normalize the distribution would be the cost if *all* electrical components failed and caused fire under Santa Ana conditions.

For the risk, the cost is multiplied by the probability of the wind being that strong. While a 110 mph Santa Ana would be extraordinarily damaging, we do not currently know if this wind intensity is even physically possible. As stated in the section on probability, this is an area that needs additional investigation.

A3.4.3. Expected Shape

The cost of wildland fires, using an arbitrary cost scale, is shown below. The wind speed should be interpreted as "if a year has a Santa Ana event of wind speed X in it then the average cost of wildland fires would increase by Y".

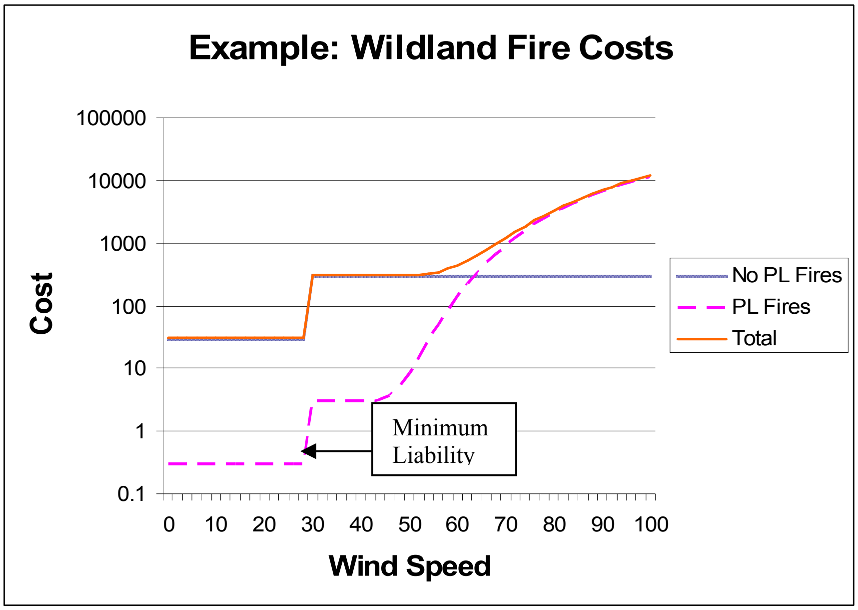

Figure 6 – Wildland Fire Costs

Note the "knee" at 30 mph, where the fire suppression efficiency drops off. If reduction of total power line fire costs (a utility liability) were the only consideration, this would be the trigger point to be chosen. Shape of the Weibull distribution was adjusted to get cross-over of the power line fire and "normal fire" curves around 60 mph, corresponding to what was observed during the 2007 fire siege.

Below is the risk curve, which is obtained by multiplying the costs in Figure 6 with the probabilities from Figure 4. Note the "double hump" from "normal fire" and "power line fire" contributions. The way to interpret the risk is "what is the average cost we can expect to have from wildland fires as a function of Santa Ana event wind speeds during the year the cost is incurred."

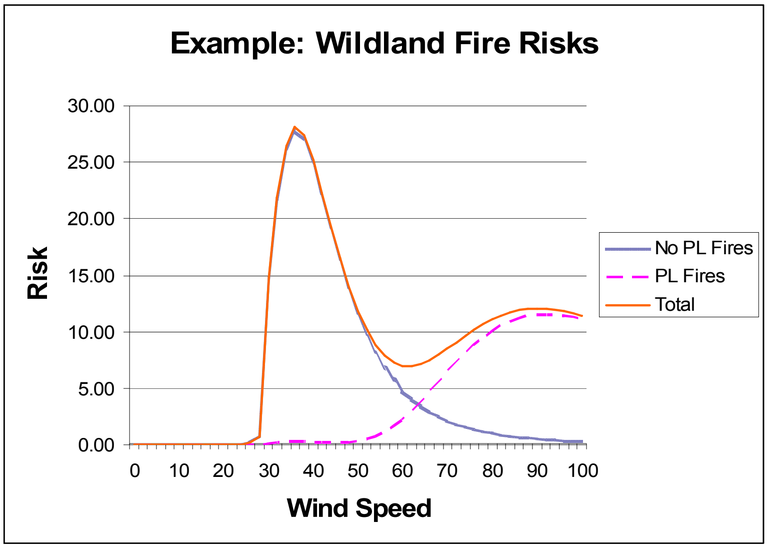

Figure 7 - Wildland Fire Risks

Note that for years in which Santa Ana events are mild, the primary contribution to fire costs will be from "normal" fire ignitions. As noted in Mitchell 2009, the October 2003 fire storm (the largest and most expensive on record) had average wind speeds of 33 mph, versus 59 mph in October 2007. The second peak relates to very rare but very destructive events – power line firestorms. Understanding the underlying physical mechanisms and the probability distributions that represent them is critical to accurately assessing this risk.

Bear in mind that these plots are simply examples of how an analysis would be done for a true cost/benefit analysis, and are dependent on the types of distributions chosen and the input parameters.

A3.4.4. Parameters

For this example, data from Mitchell 2009 was used to 1) obtain the 1% fraction of power line fires under low wind conditions 2) set a knee at 30 mph for wildland fire costs and 3) set the cost differential to 10X between the low and high wind domains. The shape and normalization of the Weibull distribution used to show the increase in ignitions as a function of wind speed was tuned to get a cross-over between "normal" and "power line" costs at around 60 mph, which was a typical wind gust speed peak measurement during October 2007.

As stated above, the total normalization for the power line costs should be the cost of the "maximum possible event" - igniting the entire Southern California WUI under Santa Ana conditions. Normalization in the figures shown above is arbitrary.

A3.4.5. Areas of Study

The following things need to be studied in order to model wildland fire costs and risks:

- The overall "maximum" cost of an extreme event needs to be assessed. This can be determined from looking at at-risk assets in the Southern California WUI, and applying a typical loss rate under extreme conditions.
- Maximum wind speed probability needs to be assessed, as stated in the previous section on this topic
- Ignition rate versus wind speed needs to be estimated. The Florida hurricane data can serve as a starting point.
- The hypothesis that wind speed at a location can be accurately estimated based on the data from a weather station that is several miles away needs to be examined.

A4. Proactive De-energization Cost Impacts

The goal of proactive de-energization is to remove the potentially catastrophic costs to Californians of wildland fires ignited by power lines under high wind conditions. However, de-energization itself imposes many costs upon the public that under some conditions will exceed those posed by the power line fire threat. By "costs", we mean not only economic losses and the threat of property damage, but also threats to the health, safety and even lives of residents living in the affected areas.

Therefore, any attempt that solely focuses on eliminating power line fires as a way of reducing liability risk will invariably tend to set a trigger point that is too low to take into account other costs. As can be seen in Figure 6, the set point for threshold optimized for liability reduction would be at the first knee in the curve, where suppression efficiency breaks down, with gust speeds around 30 mph. As shown in the figure below, there are many factors that need to be taken into account other than power line fire ignition when setting a trigger point. These will be discussed in turn throughout the remainder of this section.

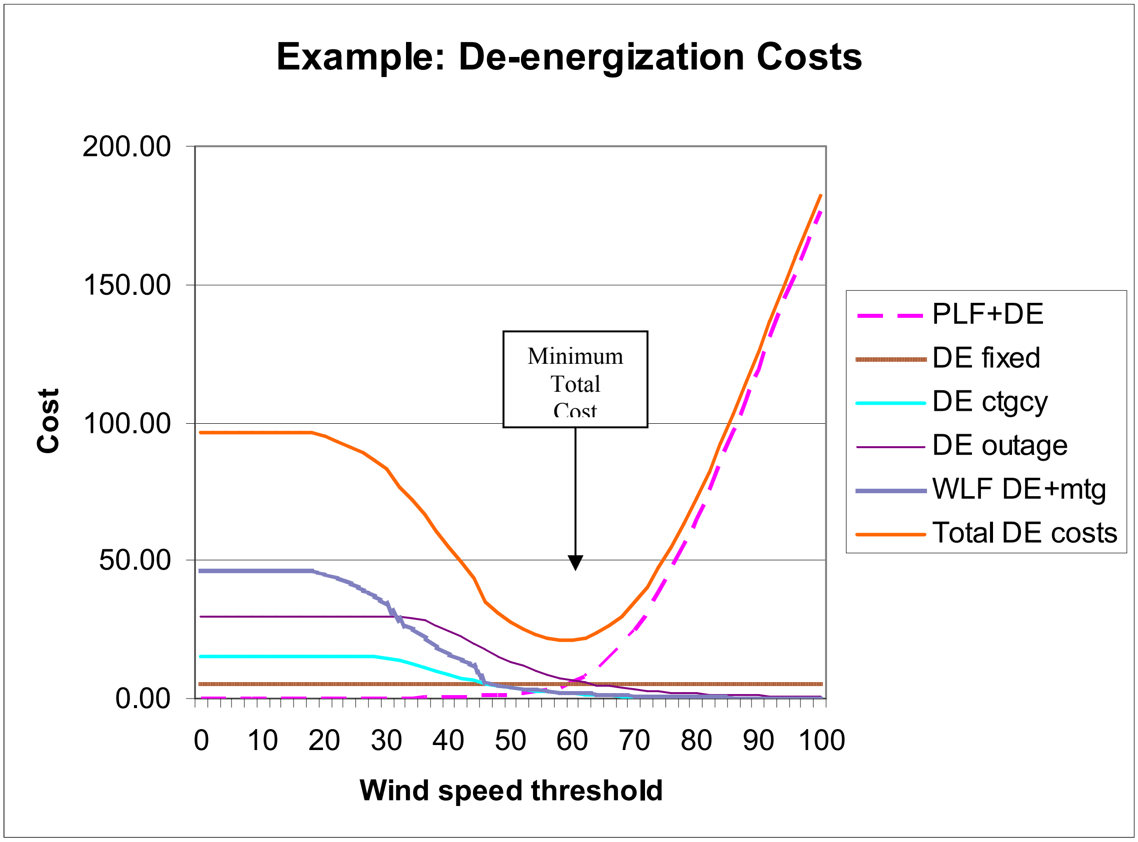

Figure 8 - De-energization cost curves

Abbreviations used in Figure 8 are "PLF" = Power Line Fire, "DE fixed" = Fixed costs of de-energization, "DE ctgcy" = Contingency costs of de-energization (dependent on threshold), "DE outage" = Outage costs of de-energization, "WLF DE+mtg" = wildland fire increased risk due to de-energization, including mitigation. These are described separately in the following subsections. Note, however, that with anticipated shapes of these curves with respect to reasonable assumptions regarding their relationship to threshold, there is a minimum in the overall cost. ***Note that the values in the figure above are illustrative only. Actual values must be determined by a concerted effort, as described below, to take these costs into account.***

A4.1. Wildland Fire Risk – Power Line Fires

A4.1.1. Description

Even with de-energization in place, there is a risk that power line fires can start if the threshold is set too high. This will be a very small risk for low thresholds, but will increase dramatically as the threshold enters the domain where catastrophic losses can be expected.

A4.1.2. Equations

If we have an estimated probability distribution of power line fire damages as described in Section A3.4.2, this can be turned into a risk estimate by looking at the probability that a power line fire starts for wind values less than the threshold. This would be given by the equation:

$$R_{PLF}(v_T) = \int_0^{v_T} C_{PLF}(v)dP(v)dv$$

A4.1.3. Expected Shape

Expected shape is shown by the magenta dashed line in Figure 8. It would be expected to be near zero for low thresholds, have a slight bump at 30 mph, and reach very large values that dominate the total at large values of $v_{T.}$

A4.1.4. Parameters

The inputs used will be the shape of the cost curve. These might be expected to be of Weibull or other rapidly increasing form, consistent with FPL pole and span failure data.

Differential wind speed distribution probability $dP(v)$ is also an input.

A4.1.5. Areas of Study

See Section A3.4.5.

A4.2. De-energization – Flat Costs

A4.2.1. Description

There may be set costs associated with the de-energization program. By “flat” we mean costs that do not depend on where the threshold is set for de-energization, but instead are applied to the program as a whole.

These may include:

- Startup costs
- Installation of infrastructure to support de-energization
- Cost of hearings, informational mailings, etc.

A4.2.2. Equations

This is a constant in v_T, and is shown by the brown diffuse line in Figure 8.

A4.2.3. Expected Shape

This is a constant in v_T, and is shown by the brown diffuse line in Figure 8.

A4.2.4. Parameters

All flat costs should be summed together into this category.

A4.2.5. Areas of Study

All costs associated with starting up and maintaining a de-energization program should be included.

A4.3. De-energization – Mitigation Costs

A4.3.1. Description

Many costs that would be incurred by a de-energization program would be incurred in order to mitigate the disruption that anticipated outages would cause. Among these would be:

- Purchase or rental of backup generation or energy storage equipment
- Contracting with medical services to arrange for evacuation of at-risk utility customers
- Purchase of emergency equipment and supplies by customers

Mitigation costs will tend to scale with the anticipated probability of an outage. For instance, if a customer anticipates they will have long outages occurring every year, they are far more likely to arrange for alternative power sources than if they are anticipating one outage every 10 years. It will therefore be a function of the trigger threshold for de-energization.

A4.3.2. Equations

The maximum mitigation cost would that which would be incurred if there were no reliable external power source. Call this C_M^0.

Mitigation cost is then:

$$C_M(v_T) = C_M^0 P(v_T)$$

A4.3.3. Expected Shape

The expected functional form is shown by the thick solid aqua line labeled “DE – ctgcy” in Figure 8. For low shut-off thresholds, the mitigation costs will be near the maximum. As the threshold is raised, the risk of outage goes down, and the amount spent on mitigation would also be expected to be reduced.

A4.3.4. Parameters

C_M^0 : Maximum mitigation cost

$P(v_T)$: Integral wind speed probability

A4.3.5. Areas of Study

All cost implications that will be applied to an area-by-area basis (as opposed to overall fixed program costs) should be summarized in this contribution.

Elements needed to understand the wind speed probability distribution are described in Section A3.2.5.

A4.4. De-energization – Outage costs

A4.4.1. Description

There are many ways in which loss of power can lead to economic losses and increased risk by residents of the affected areas. These do not include wildland fire risks, which are handled by a separate calculation. Among the impacts are:

- Loss of water supply
- Loss of telephone communication
- Loss of cellular networks
- Loss of internet connectivity
- Disruption of traffic circulation with loss of traffic signals
- Economic losses due to cessation of business
- Delayed or disrupted response to medical emergencies
- Transportation of at-risk individuals to care centers
- Relocation costs for residents leaving the area

- Loss of refrigerated perishables
- General loss of public convenience

Many of these impacts are mitigable through the provision of backup power supplies. Hence the overall impact will be directly dependent on the amount spent on mitigation measures. The impacts will also be proportional to the area affected by outages. Both of these effects are taken into account by the calculation below.

A4.4.2. Equations

The expected relationship between outage costs and shut-off trigger threshold can be expressed as:

$$R_{DEF}(v_T) = \int_{v_T}^{\infty} R^0_{DEF} F(v, v_t) \left[1 - \alpha \frac{C_M(v_t)}{C^0_M} \right] dP(v) dv$$

This contains terms expressing an overall normalization (R^0_{DEF}), fraction of area shut off ($F(v,v_t)$), fraction of costs mitigated by countermeasures $\left[1 - \alpha \frac{C_M(v_t)}{C^0_M} \right]$, and probability that wind speed will exceed threshold ($dP(v)$). This model makes the simple assumption that the effect of mitigation will be proportional to the cost of mitigation performed.

A4.4.3. Expected Shape

The expected shape of this curve is shown by the thin purple curve labeled "DE – outage" in Figure 8. Like other cost curves, it is at a maximum for low values of shut-off (since these will usually be triggered), dropping to zero as the threshold becomes large[17]. This contribution has a longer tail (dropping off more slowly than other contributions) because as mitigation contributions decrease due to lower probabilities, the impacts of any outage will increase.

A4.4.4. Parameters

R^0_{DEF} : Maximum value for outage costs.

$F(v,v_t)$: Fraction of the area de-energized. See section A3.3.

α : Maximum fraction of outage cost that is mitigable, assuming a very simple model where a fraction of outage costs are inversely proportional to the amount paid for mitigation.

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[17] The figure is a "toy-model", and does not contain the full numerical integration including fractional area.

$C_M(v_T)$: Mitigation costs for turn-off threshold v_T.

C_M^0 : Maximum mitigation costs.

$dP(v)$: Differential wind speed probability.

A4.4.5. Areas of Study

The possible significant effects of power outages on residents and communities must be quantified. Other factors included in the calculation have been identified elsewhere in the document.

A4.5. De-energization and Wildland Fire Risk

A4.5.1. Description

The motivation for turning off the power is to prevent power line fires under high wind conditions. However, power line fires under low and moderate wind conditions have historically constituted only 1% of ignitions leading to significant fires (greater than 100 acres). Certain consequences of de-energization will actually increase the wildland fire risk that residents face. Hence, a shut-off trigger threshold that is set too low could actually increase overall wildland fire risk by exposing residents to additional danger from non-power line fires. Among these unintended consequences are:

- De-activation of communications may delay the reporting of fire starts and allow fires to escape initial attack.
- De-activation of communications reduces the effectiveness of reverse 9-11 emergency notices.
- Loss of electrical power to residences will hamper night-time evacuation and fire preparations.
- Lack of radio and television communications reduces the effective communication of fire safety and evacuation information to fire areas.
- The start-up of a large number of resident-owned electrical generators, some of which may be unmaintained or poorly maintained, may result in fires that spread to wildland fuels.
- Loss of power to traffic signals and street lights may cause disruption of evacuations or traffic accidents under wildland fire conditions.
- Loss of water pressure due to loss of power to both private and municipal pumps may hamper fire suppression efforts by both fire fighters and private citizens.

This risk will be proportional to the cost of wildland fire as it depends on wind speed. This is explored in section A3.4. This risk will be proportional to the area affected by the outage, and may also be partially mitigated by countermeasures taken in anticipation of power loss.

A4.5.2. Equations

A relation that expresses the risk level due to wildland fire is:

$$R_{WLF} = \int_{v_T}^{\infty} C_{WLF}^{0}(v) F(v, v_t) \left[1 - \beta \frac{C_M(v_t)}{C_M^0} \right] dP(v) dv$$

This contains terms expressing a cost function for wildland fire as a function of wind speed ($C^0_{WLF}(v)$), fraction of area shut off ($F(v,v_t)$), fraction of costs mitigated by countermeasures $\left[1 - \beta \frac{C_M(v_t)}{C_M^0} \right]$, and probability that wind speed will exceed threshold ($dP(v)$). This model makes the simple assumption that the effect of mitigation will be proportional to the cost of mitigation performed.

A4.5.3. Expected Shape

The expected shape of this curve is shown by the diffuse blue curve labeled "WLF DE + mtg" in Figure 8. Like other cost curves, it is at a maximum for low values of shut-off (since these will usually be triggered), dropping to zero as the threshold becomes large[18]. This contribution has a longer tail (dropping off more slowly than other contributions) because as mitigation contributions decrease due to lower probabilities, the impacts of any outage will increase.

A4.5.4. Parameters

$C_{WLF}(v)$: Cost function for wildland fires. We use a step function with the step at 30 mph, as described in section A3.4.

$F(v,v_t)$: Fraction of the area de-energized. See section A3.3.

β : Maximum fraction of wildland fire cost that is mitigable, assuming a very simple model where a fraction of wildland fire costs are inversely proportional to the amount paid for mitigation.

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[18] The figure is a "toy-model", and contains only a rough approximation of the full numerical integration that includes fractional affected area.

$C_M(v_T)$: Mitigation costs for turn-off threshold v_T.

C_M^0 : Maximum mitigation costs.

$dP(v)$: Differential wind speed probability.

A4.5.5. Areas of Study

The risks due to the unanticipated consequences of de-energization as they relate to wildland fire must be quantified to the extent possible. Other factors included in the calculation have been identified elsewhere in the document.

A5. Conclusions

A5.1. Total cost minimization

The total cost is given by the sum of all risk-amortized costs due to de-energization (and the lack thereof), as described in section A3.1, and is shown as the thick orange curve representing the sum in Figure 8. We expect that it will have a characteristic U shape as a function of shut-off threshold. At low shut-off threshold, all of the various costs associated with de-energization, including mitigation costs, fixed costs, outage costs, and wildland fire costs will dominate, though the risk of power line fires will be greatly reduced. At high thresholds, the risk that power line fires will be ignited by wind damage occurring below the threshold becomes significant. Finding the minimum – the bottom of the U – allows us to determine the optimal shut-off point that minimizes overall costs and maximizes overall benefit.

While the models used are simplistic, and many factors will require further study before reasonable estimates can be obtained, we argue that an educated guess is far superior to inaction. Inaction leads on the one side to the possibility of catastrophic fires with Katrina-like damage potential, and on the other that residents will be subjected to greater risks due to thresholds that are determined only to minimize utility liability from power line fire damages.

A5.2. De-energization versus hardening

Additional study needs to be done to compare the cost/benefit of a de-energization plan to that of hardening the electrical network by adopting more robust wind loading standards. To some extent, these programs should be regarded as complimentary. Without knowing maximum possible wind strengths of Santa Ana events, it is difficult to establish standards that will completely preclude a “power line firestorm” scenario. Adopting and applying more robust wind loading standards, however, would allow adoption of a higher threshold for triggering electrical shut-off, thus reducing many of the costs associated with de-energization.

A5.3. Immediate steps

It should be anticipated that adopting a shut-off plan that best serves the interest of ratepayers will be an iterative process, particularly since there are so many unknowns. However, the "knowns" that we currently have provide significant motivation to move forward. Among initial steps would be:

- Require utilities that wish to implement shut-off plans to do a full cost-benefit analysis that attempts to quantify the unknown inputs. Such analyses have been performed by other utilities to measure the cost/benefit for measures such as undergrounding in areas with significant hurricane risk[19]. The analysis models should be of such a form that interested parties can enter their own inputs if they disagree with those chosen by the utility.

- Fund, or encourage utilities to fund, research into areas necessary to quantify the key risks underlying a de-energization plan, particularly in the areas of Santa Ana winds, climate change, effect of topography on winds, and wildland fire as it relates to power lines.

- Do not permit de-energization plans that have trigger points which do not adequately take into account the consequential costs and risks to ratepayers and communities.

- Require that utility systems be capable of withstanding extreme wind events with long recurrence times (300-1000 years) without starting numerous wildland fires. Whether they use engineering standards or de-energization to accomplish this would be up to the utility. This measure, if implemented, would effectively protect the public against unanticipated extreme events and the widespread damage that they would cause.

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[19] Quanta Technology, 2008.