Risk Analysis for Incorporating Photovoltaic Solar Panels into a Commercial Electric Power Grid

Andrea Chaves and A. Terry Bahill
Systems and Industrial Engineering
University of Arizona
Tucson AZ 85721-0020
achaves@email.arizona.edu
terry@sie.arizona.edu

ABSTRACT

This paper compares two popular risk analysis techniques and uses them to analyze the risk of incorporating photovoltaic (PV) solar panels into a commercial electric grid. It integrates methodologies from both techniques such as Hierarchical Holographic Models (HHMs), risk frequency and severity normalization, and avoidance of the bias of extreme events. The paper describes the benefits and limitations of these techniques for the PV solar case study. Then, this paper summarizes the main risks associated with incorporating PV panels into a commercial electric grid, presents a what-if analysis for extreme scenarios, and explains mitigation strategies to ameliorate these risks. Finally, the paper points out some possible unintended consequences of developing large-scale solar PV farms.

KEYWORDS: Risk analysis, risk management, renewable energy resources, photovoltaic solar systems.

1. PURPOSE

Economically viable harvesting of renewable energy is one of the most profound challenges of the 21st century. To help meet this challenge, Tucson Electric Power is incorporating photovoltaic (PV) solar panels into their commercial electric power grid. However, evolving such a big complex system is risky. Therefore, a risk analysis is a mandatory part of this system design. This paper compares two risk analysis techniques: the first by Bahill et al.(1,2) which is based on Failure Modes and Effects Analysis (FMEA), and the second by Haimes et al.(3,4,5,6) The goal is to compare these two techniques and apply them to the risk analysis of a large-scale grid-tied photovoltaic (PV) system for Tucson Electric Power (TEP), the electric service provider in for the Tucson metropolitan area.

TEP has experience operating a 4.6 megawatt solar array at their Springerville Solar Generating Station; however, this capacity represents only about a 0.2% of their total generating capacity. TEP needs to significantly increase their renewable energy capacity in order to comply with Arizona Corporation Commission's (ACC) Renewable Energy Standard (RES). The RES requires that by the year 2025, 15% of the utility companies' retail sales must be served from renewable energy sources and that 30% of the renewable energy of this fifteen percent requirement must come from distributed generation (DG).

This risk analysis was conducted under the assumption that a large percentage of this RES requirement will be satisfied with photovoltaic solar energy. It identifies risks and complications associated with incorporating large-scale solar systems (distributed and those concentrated in solar farms) from the utility company's perspective.

2. DEFINITION OF RISK

The world is full of uncertainty, therefore, risk is an inherent component of any project or system, and risk analysis is an important part of project management. Risk is an expression of the potential harm or loss associated with an activity executed in an uncertain environment. However, there are different ways to quantify risk. Haimes' technique quantifies risk as the product of probability and severity of adverse effects as in equation (1) while Bahill's technique quantifies risk in terms of frequency of occurrence rather than probability, as in equation (2).

$$risk = severity * probability \quad (1)$$

$$risk = severity * relative\ frequency \quad (2)$$

These definitions are quite similar. Equation (2) would be equivalent to (1) if we divide the risk by the total number of the frequency observations. However, Bahill's technique uses frequency instead of probability, because humans evaluate probability poorly: it argues that the frequency approach helps humans to partition a set of cases into exclusive subsets, which is a mental operation that is performed quite well. Although the definitions are similar, the two risk analysis techniques differ. Haimes' technique uses both quantitative and qualitative risk analysis methods, while Bahill's technique is more qualitative. These techniques are discussed in the following section.

3. SYSTEM DEFINITION

In order to conduct a risk analysis, it is important to understand how the system works. Bahill's Eight Wymorian Documents are a good source of documentation for systems that are being developed [(7)]; however, for an existing system, the best alternative may be to read the documentation of the system (if any) or talk to system experts. Understanding how the system works and clearly defining the system are the two most important steps for beginning a risk analysis.

For the system definition and risk identification phase, Haimes' technique recommends the use of a Hierarchical Holographic Model (HHM) in order to give a full (and visual) description of the system, classified into main system categories and subcategories (see Figure 1). These HHM charts are presented to teams or individuals that possess enough system knowledge (system experts) in order for them to identify potential risks.

Although it is evident that Bahill's technique requires extensive system knowledge for the risk analysis, it does not prescribe specific documentation or description. In the Pinewood Derby[(2)] case study, the system is described extensively before moving into the risk analysis phase, but a visual depiction of the system is not included : however, they recommend the identification of various risk categories (system, project, business, safety, environmental, etc), which is analogous to the top-level components of Haimes' HHM technique.

The system definition of the photovoltaic solar system is as follows: "A grid-tied photovoltaic system consists of photovoltaic (PV) solar panel arrays and the hardware that connects these panels to the electric grid. It includes both small grid-connected solar systems as well as utility-scale projects. These systems may be located on residential or commercial property, on rooftops, or in open-land. Net-metering[1] is allowed; permitting customers to sell excess energy back to the grid (when supply is greater than demand) and buy electricity from the grid when their production is short. The utility company uses this solar output to meet part of their electric

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[1] Net metering allows customers with grid-connected electric generating systems (e.g. grid-connected solar PV systems) to buy electricity from the electric provider (utility company) or sell it back to the electric grid at a pre-determined price when they produce less or more energy than consumed respectively.

demand, and must be capable of meeting electric demand during the night and during days with lower than expected solar power output. All these systems shall comply with local and federal laws."

The HHM that describes the above system is depicted in Figure 1.

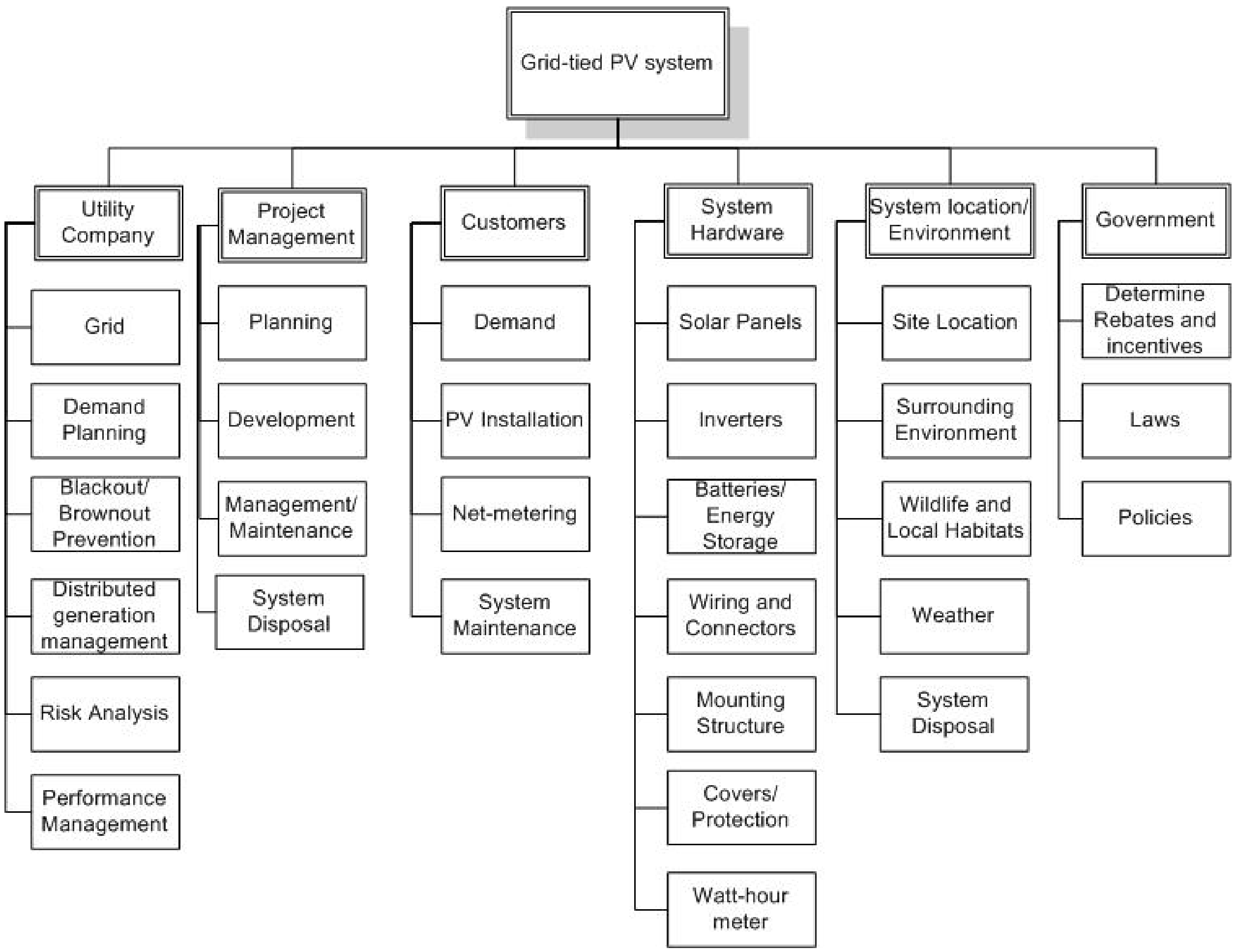

Figure 1. HHM of grid-tied solar powered system

4. RISK IDENTIFICATION AND QUANTIFICATION

Both techniques use a similar approach for risk identification: they try to obtain significant input from system experts and outsiders to help generate, quantify, and verify risks. Bahill's technique uses risk tables and Haimes' technique uses HHMs and risk matrices to generate and summarize risks. Risk identification is an iterative process. Once a risk table or matrix has been obtained, the resulting risks must be discussed with professionals, academics, or other system experts that can help verify, quantify, and add or eliminate risks. The risk tables summarized in this paper required many iterations. As time goes by and risk management strategies are implemented, risks and risks severities will have to be revised in order to verify that they are a true representation of the existing system.

Both techniques measure the probability or frequency of occurrence of each risk based on observations, statistical analyses of historical events, or expert opinion. Bahill's technique quantifies the risk as the product of frequency and severity and emphasizes the importance of normalizing the values of both frequency and severity so they are quantified on the same scale. This normalization guarantees that both frequency and severity are given the same weight when calculating the final risk. This technique also recommends the use of log-log plots so that extremely rare events can be tracked without distorting the risk analysis.

Haimes' technique places significance emphasis on not using expected risk (equation 1) to determine the total risk of a system since this would give the same weight to a risk with high probability of occurrence but low severity and one with a low probability of occurrence but high severity (extreme events). Instead, he uses the Partitioned Multiobjective Risk Method (PMRM) and develops risk functions for each one of these risks. In order to obtain these risk functions, the first step is to obtain the distribution function of the damage of a particular risk and then define the lower tail region:

$$P(x < \beta) = \alpha \qquad (3)$$

Next, the lower tail conditional expectation is calculated:

$$E[x \mid -\infty \leq x \leq \beta] = \frac{\int_{-\infty}^{\beta} x f(x)}{\int_{-\infty}^{\beta} f(x)} \quad (4)$$

Where β is the upper limit on x and α is the cumulative probability. The lower tail region with upper limit β is the zone with low probability of occurrence but high severity.

When trying to apply the PMRM to our TEP case study, there was one major drawback: most of our risks have been quantified in terms of time, and unless each failure mode was broken down into the frequency of failure of each of the system's individual components, there was no precise way to accurately estimate the possible damage and map this damage to the probability of failure. In order to avoid biasing the expected system reliability due to the risk of extreme events, we took a different approach: events with low probability but high severity, such as human accidents and human deaths, were eliminated from the numerical risk calculations and have been marked in the risk tables with a "$0\times\infty$" symbol. It is important to note that we only eliminated those risks on the lower tail of the distribution (very low probability of occurrence) since we believe that risks that have a high probability of occurrence but low severity should be kept for analysis purposes because, although the severity is low, ameliorating these risks would have a significant impact on the overall system reliability.

5. RISK SEVERITIES

The severity of a risk is the perceived damage due to its occurrence. Determining severities is an important step, because it allows us to calculate the risks and rank them in order to identify the most critical elements. Severities are subjective and depend on the perception of the analyst; however, it is possible to reduce analyst-induced bias by sharing the resulting severities with system experts or other analysts in order for them to validate the severity values.

Analyzing risk severities is a very common practice. Over the decades, insurance companies have developed tables to quantify risk so that different risks can be compared. They assess policy holders' risk in order to estimate the total risk of their insured pool and calculate the expected insurance cost in dollars. Understanding risk severities allows them to quantify the risk and act appropriately: by estimating expected insurance costs and they are able to determine the cost of insurance premiums so that, with a very large probability of occurrence, they will generate a profit. In a similar manner, if the utility company understands the severity of each failure, they will be able to prioritize risk mitigation strategies.

Both techniques have different methodologies for determining risk severities. Bahill's technique normalizes the severity scale so that it has the same range as the frequency scale. This guarantees that the risk does not depend only on the frequency or the severity. If the frequency and severity scales were different (e.g. frequency had five orders of magnitude, but severity had only one), it is possible that the severities would have no impact on determining the highest risk; risk could be dependent only on the frequency values. When the risk and severity scales are normalized, they will have the same weight in the quantification of risk and this problem is eliminated. For example, if the frequency scale goes from 0.01 to 100, then there are five orders of magnitude and thus the severity scale must also have a range of five orders of magnitude (i.e. from 1, very low, to 10^5, very high).

Haimes' technique uses various methods for quantifying severity. In the PMRM (Haimes, 1998, Reyes & Haimes, 2002), severity is typically quantified in terms of dollars (monetary losses generated by that failure mode), which may be easier to interpret than Bahill's technique's approach (a unit-less value). Haimes' technique uses the PMRM to partition the probability axis into various severity or damage ranges and uses the conditional expected value of damage (the expected value of the damage given that the damage is within a specific range) in order to avoid extreme event bias and obtain a better estimate of risk[3,6].

Haimes' technique also describes the Risk Filtering and Ranking Method (RFRM), where he uses a linear scale from 1 (very low) to 5 (very high) to quantify severities on both quantitative and qualitative probability scales. Based on the normalization discussion in Bahill's technique this could have major drawbacks; however, given the methodology and purpose of the RFRM, the selection of the severity scale is not important. The RFRM places emphasis on finding risks that are above a certain severity threshold and filtering the rest in order to reduce the number of risks that will be analyzed in depth. Similarly to the PMRM, each failure mode is divided into several probability ranges and each range is assigned a severity. The filtering is only conducted based on a qualitative basis determined by the severity of each risk (and not the product of probability and severity). In essence, the problem described by Bahill's technique is avoided since the focus is placed on finding the failure modes that exceed a certain severity threshold rather than in determining the actual value of the risk (the product of frequency and severity).

For the purpose of identifying the most severe risks, either Bahill's technique's or Haimes' PMRM technique would be appropriate; however, depending on the audience of the risk analysis, a quantification in terms of dollars (if possible) may be better, particularly if the risk analysis if intended for management decision-making.

5.1 **Algorithm for computing severity values[2]**

The following algorithm is used in Bahill's technique for computing values for the severity of the consequences

1. Assign a frequency of occurrence (F_i) to each failure mode.

2. Find the failure mode that has the most severe consequences, Call its value S_{worst}.

3. For each other failure mode, ask: "How many of these failures would be equally painful to the Worst?" Call this $N_{i.}$ This can be rephrased as, "Cumulatively, how many of these failures would have an equal impact to the Worst?"

4. Compute the severity for each failure mode as $S_i = S_{\text{worst}} / N_i$

5. Normalize the severity values so that their range equals the range of the frequency values.

6. Compute the estimated risk using a combining equation.

7. Prioritize the risks to show which are the most important[348].

Both techniques emphasize that after completing a risk analysis, you should look at (1) the high risk events, (2) the high consequence events (no matter how unlikely) and (3) estimates that have a large uncertainty. In the next iteration you should focus resources on these three items.

6. CASE STUDY: RISK ANALYSIS OF THE PV SYSTEM

When analyzing all the possible risks associated with incorporating solar energy generation into an electric power grid, there were two clear categories: risks related to uncontrollable factors such as weather, and risks related to software, hardware, or human error. Although many papers do not consider uncontrollable factors or acts of God, because there is no risk management alternative to deal with them, we deem them important given that weather risk is one of the greatest sources of uncertainty for solar power production.

Risks were initially analyzed in several different tiers: risks related to the utility company or grid, project management/development risk, customer risk, hardware risk, environmental risk, and government risks. The tiers described in Table I correspond to the main categories of the HHM depicted in Figure 1 .

Table I. High-level risk categories

Risk-tier	**Description**
Utility company or grid	Risks related to operations: not meeting demand, brownouts, blackouts, etc.
Project Management/Development	Risks that may be encountered throughout the development of the PV project: changes in costs, design issues, permit issues, etc.
Hardware	Risks related to the hardware components of the system: reliability
Environmental	Risks related to the location and surrounding environment of the project: effect on local habitats, weather, environmental opposition, etc
Government	Risks related to changes in governmental policies

The risk-tiers were analyzed from various stakeholder perspectives. For example, the first tier, “utility company or grid” is clearly a risk to the utility company; however, it can also be a risk to the customer because brownouts or blackouts can affect their daily activities and may damage their property. All these tiers will most likely have risks that affect various stakeholders (utility company, customers, environment, etc); however, the risk tables below summarize the risks from the utility company’s perspective.

In order to identify as many risks as possible, interviews were conducted with various people including high-level TEP managers and directors, academics, and experts in project management related to renewable project. The information provided by them was summarized and analyzed to determine the possible risks. After identifying the risks following Bahill’s technique, risks frequencies were derived or estimated based on the available information. It is important to note that the HHM was generated ex-post facto and was not shown to system experts. Therefore, we cannot compare the effectiveness of the two risk identification methods.

6.1 Description of identified risks

In our preliminary risk analysis, the greatest risk for a PV system was weather risk, the risk of the panels receiving less sunlight than expected. This is a critical factor for a self-sustaining PV system, but for a large-scale system composed of both renewable (solar) and non-renewable capacity, as it will be discussed in section 6.3, this risk can be mitigated by introducing either storage capabilities, or increasing the availability of backup generating capacity. In consequent iterations, this risk was modified in order to encompass output variability: large changes in power output (±60 MW) which would correspond to a solar power output variation of ±3 sigma. This change in power output could introduce transients onto the grid and may result in brownouts.

Grid related risks are the second greatest risk category. These risks include the grid frequency going out of the ±0.5 Hz limit, feeder circuit disconnects, and shorts to ground. The first two risks are expected to increase as solar PV generation increases, because the solar panels may introduce transients or voltage that is out of phase with the grid. The frequency of occurrence of these failures was obtained from TEP.

Hardware risks have been ranked at the bottom of the performance risk table and include failures due to component malfunction or external events such as lightning or dust. The frequency of failures of PV system hardware such as inverters, data acquisition systems, junction boxes, PV modules, and general failures due to lightning strikes was estimated based on a 2005 report of

TEP's experience with the Springerville Generating Station[5]. These failures were categorized as low to medium risk based on the expected consequences, which ranged from a simple system restart to more complex maintenance requirements[9]. In addition to the hardware failures reported by TEP, we included storage system failures because storage technologies are currently being considered by TEP and may be implemented in the future. A storage system failure may result in a loss of stored energy and will eliminate the possibility of using this stored energy to meet electric demand. The failure of a backup generator will affect the capability of meeting demand during peak or low power production hours. These failures have been categorized as medium severity failures, and their frequency was estimated based on hardware-specific reliability rates (assuming an expected lifetime of 30 years).

Accidents and human mistakes are the risks with the highest severities given that they can harm people; however, based on TEPs record, the occurrence of such accidents is extremely low, and thus their frequency is almost negligible. These risks are located at the lower tail of the probability distribution (very low probability), and thus were not factored into the total numerical risk analysis. Other extreme events such as terrorist attacks on the Western Power Grid, and volcano eruptions were also considered; however, it can be seen in Table II that the estimated risk for these extreme events was filled with our null symbol $0\times\infty$. This is expected to reduce the bias that would be included by considering these extreme events[3,6].

Economic risks include a change in interest rates. Changes in interest rates were deemed to be very low-severity risks since TEP engages in interest rate swaps, hedging their interest rate exposure and minimizing the impact from future interest rate changes.

Environmental risks include immediate risks to the environment such as habitat destruction, as well as deferred risks (such as the disposal after the system's lifecycle or after irreparable failure). Large scale solar farms could have a negative impact on local habitats and could modify animal migration paths. The disposal risk is very low since PV panels (as well as the rest of the system hardware) do not contain dangerous or extraneous materials that would complicate system disposal. However, this risk could increase if stronger recycling policies were passed that required that most system components be recycled to reduce environmental impact and maintain the green motivation of the solar PV system. The other environmental risk is unknown hazards and is related to the possibility of discovering that the system contains elements that may be cancerous agents or that could cause potentially deadly illnesses, or that the system could result in any other unknown events.

Finally, government risks include any changes in regulations, such as carbon emissions policies that would have a direct or indirect impact on the viability and size of PV systems. Any policy changes may result in the obsolescence of TEP's renewable energy portfolio plan, and may require total re-planning of the strategies to follow. The early elimination of rebates is another government risk. It has a medium (and potentially high) severity since this would affect customer incentives to convert to solar-powered generation. Any reduction in consumer incentives to adopt solar energy would have a significant impact in distributed generation. According to Denise Richerson-Smith[9], Director of Energy Efficiency and Renewable Programs at TEP, in 2009, about 70% of the distributed generation (7 GWh) came from residential customers, and by the year 2025, about 50% of the distributed generation is expected to come from residential solar arrays. Distributed generation must comprise 30% of the 15% ACC renewable energy requirement (4.5% of total capacity) and eliminating customer incentives may make this target difficult to attain.

Table II thru Table V contain a failure modes and effects analysis (FMEA) with both PV system-specific risks as well as Tucson Electric Power's (TEP) AC electric power distribution grid risks. The input data for the distribution grid risks was given to us by Tom Hansen, former vice president of TEP, in October 2008, and Bahill derived the rest of the distribution grid data by changing the frequency into events per month and calculating the range of these frequencies: about six orders of magnitude. Since the range for frequency and severity must be the same(1), numerical values were assigned to the severities as follows

Description	**Metric**
Extreme	1,000,000
Very High	100,000
High	10,000
Medium	1,000
Low	100
Very Low	10
Minuscule	1

Table II summarizes performance risks for PV solar systems and TEP's distribution grid. These risks are those related to the functionality of the system. Failure modes in the performance category typically result in partial system downtime and will affect the quality and reliability of system operations.

!!!!!<INSERT RISK TABLES HERE>>

Table II. Performance FMEA for TEP's distribution grid with PV solar systems.

Failure Mode	Potential Effects	Frequency of Occurrence in the TEP control area (events per year)	Severity of Failure	Estimated Risk
Performance				
Terrorist attack on the Western Power Grid	Power supply would be interrupted, severe hardware damage	0	1000000	0×∞
A volcano erupts	Large clouds of ash and smoke would cover Tucson, blocking sunlight to solar panels and significantly reducing solar PV output	0	100000	0×∞
Solar panel output fluctuates by more than 60 MW in a 15 minute interval due to clouds, thunderstorms, etc.	Not enough power is produced. This could trip breakers and leave customers without electric power. Voltage on the grid could drop and frequency of coal-fired generators could change: big electric generators do not like transients. TEP would have to initiate a controlled brown-out with load shedding. The local community could lose trust in TEP. To ameliorate these possibilities TEP must buy and operate backup generators and negotiate purchase agreements with other suppliers. Presently this is not much of a problem, because solar power comprises only a few percent of the load. But when solar power approaches one-fourth of the peak power, TEP will need backup systems.	94.6	100	9460
Feeder circuit disconnects from substation	Feeder circuit voltage gets out of phase with the grid. This failure has a medium severity for existing equipment, but it will get worse with PV solar panels. It may require synchronized reclosers.	365	1	365
Short to ground on the distribution grid	This could damage TEP's equipment particularly transformers and capacitor banks. The system should be back up within two hours. This is unlikely to damage our customers' equipment.	24	10	240
Western Power Grid fails.	TEP must have backup generators and plans for controlled brown-outs with load shedding.	0.01	10000	100
Lightning strikes the system	Components may be damaged, system may stop working, partial production loss	0.3935	100	39.347
Inverter fails	Loss of generated power output	0.4925	50	24.625

Voltage Stability	Voltage stability is the ability of a power system to maintain steady acceptable voltages during normal operating conditions and after being subjected to a disturbance. This failure has a low severity based on the current levels of renewable generation given the existing infrastructure. However, potential failures will increase with higher penetrations of distributed generation.	24	1	24
Transient Stability Response	Outage events on the utilities transmission or distribution system have the potential to trigger a widespread shutdown on PV systems. This failure has a low severity based on the current levels of renewable generation given the existing infrastructure. However, potential failures will increase with higher penetrations of distributed generation.	24	1	24
Solar panels accumulate layers of dust or other particles	Efficiency of the solar panels will decrease and energy output will be lower than expected.	2	10	20
Junction Box Fails	Loss of generated power output	0.2688	50	13.439
Data Acquisition System Fails	Data cannot be read from the solar farm, loss of monitoring	0.1449	50	7.2444
PV module fails	Loss of production capacity	0.3855	10	3.8551
Grid frequency goes out of ±0.5 Hz limits	Transients caused by PV panels might perturb the big generators tripping them off line, perhaps overloading transmission lines and may result in fines. This failure has a low severity with existing equipment. However, it will increase with distributed generation.	0.07	10	1.25
Other System failures	Potential capacity loss,	0.0991	10	0.9909
Electric storage system fails	Stored energy is lost. Infrastructure might be damaged.	0.0003	2000	0.5757

Table III summarizes the environmental risks. These risks are related to the environment surrounding the system and affect various stakeholders (utility company, wildlife, humans, and environment). The first three risks were analyzed from both an environmental and utility company perspective, while the latter two were analyzed strictly from the utility company's perspective due to the possibility of large financial repercussions.

Table III. Environmental FMEA for TEP's distribution grid with PV solar systems.

Failure Mode	Potential Effects	Frequency of Occurrence in the TEP control area (events per year)	Severity of Failure	Estimated Risk
Environmental				
More stringent siting requirements by city, county, and state zoning jurisdictions	Obstructionist activities and law suits would significantly delay all aspects of the project	10	100	1000
Modification of animal migration paths	Migrating species might be affected. Loss of public support, project may require additional environmental studies.	1	100	100
Destruction of natural habitats	May be accompanied by strong opposition from environmental groups	1	100	100
Unsuspected hazards	Fines, lawsuits, loss of public confidence	0.01	500	5
Higher than expected disposal or recycling cost	Budget overrun, loss of profit	0.01	100	1

Table IV summarizes project management risks. These risks are associated with the operation and management of grid–connected solar PV farms (either by the utility company, or by a third party).

Table IV. Project Management FMEA for TEP's distribution grid with PV solar systems.

Failure Mode	Potential Effects	Frequency of Occurrence in the TEP control area (events per year)	Severity of Failure	Estimated Risk
Project Management				
Accidents	Injury to humans requiring medical attention	0.1	10000	$0 \times \infty$
Drastic human mistakes	Death of humans. With 1500 employees, TEP has had no fatalities in 25 years of operation.	0	1000000	$0 \times \infty$
The project's cost becomes higher than projected	The project may have to be delayed or cancelled.	0.1	1000	100

The maintenance costs become higher than expected	Budget overrun, reduction of profits	0.1	1000	100

Table V summarizes economic and government risks. These risks are associated with any economic policy changes or changes in government regulations. Although the third risk directly affects customers by increasing the cost of renewable energy systems, the risks in this table were analyzed only from the utility company's perspective.

Table V. Economic and Government FMEA for TEP's distribution grid with PV solar systems.

Failure Mode	Potential Effects	Frequency of Occurrence in the TEP control area (events per year)	Severity of Failure	Estimated Risk
Economic				
Interest rates changes	NPV calculations may become invalid, may affect interest payment on floating rate loans, etc.	2	10	20
Government				
Carbon emissions regulations are different than expected	TEP would need to revise their projections and alter their renewable energy acquisition plans	1	100	100
Early elimination of rebates	This would increase the net cost of the DG systems to the consumer and may jeopardize TEP's ability to meet the DG requirements.	0.1	1000	100

Motor generator sets (MG sets) are used as a backup generator to mitigate unplanned contingencies such as unexpected demand peaks or decreases in power output. The backup generators that are being considered for future PV projects have a start time of approximately 10 minutes. The FMEA for the quick-start natural gas motor-generator set (MG set), which is described in Table VI and Table VII, was conducted in the same manner as the FMEA for the distribution grid with PV solar systems; however, the severities for this table used the following scale:

Description	Metric
Very High	1000
High	100
Medium	10
Low	1
Very Low	0.1
Minuscule	0.01

!!!!!<INSERT MG SET RISK TABLES HERE>>

Table VI. Performance FMEA for a backup quick-start natural-gas motor-generator set.

Failure Mode	Potential Effects	Frequency of Occurrence in the TEP control area (events per year)	Severity of Failure	Estimated Risk
Performance				
Backup power generation is unavailable in a timely manner	Natural gas motor-generator sets are big complicated machines. It is planned that they will start up in less than ten minutes, but it could take an hour or two.	2	200	400
Unforeseen unit outages	Backup generation capacity is subject to unforeseen operating problems due to reliability issues. Given TEP's seasonal capacity requirements, this is only critical during peak summer months	1	200	200
The MG set introduces transients on the power grid.	This would be bad, because big electric generators (like those at the Palo Verde plant) do not like transients.	0.5	100	50
Software failure	Software failures are ubiquitous, but hard to diagnose, particularly when they involve interaction of systems. Redundancy and built in self test help reduce the severity. Therefore, every software routine in this MG backup system shall have built in self test. Software failure is causing the uncontrolled acceleration of millions of Toyota cars.	0.25	100	25

Backup generator connects to the grid at the wrong frequency.	The MG set would be damaged.	0.5	10	5
Human error could result in system override and may result in backup generation interconnecting out of phase or at the wrong frequency.	The system would disconnect the MG set as quickly as possible. But it may be too late to avoid damage to the MG set.	0.5	10	5
Lack of fuel source	TEP would lose backup capability.	0.1	50	5
The system connects the MG set out of phase with the grid.	The MG set could be damaged.	4	1	4
The MG set breaks.	TEP would lose backup capability. Then, if the sun were blocked, TEP could not provide full capacity. This would result in initiating a planned phased brown-out and load shedding program.	0.2	10	2
A gas turbine MG set requires ten minutes for start up. Therefore, TEP must have a system that will predict cloud cover ten minutes in advance. This system could fail.	TEP would lack backup capability for ten minutes. Voltage on the grid could decline and the frequency of coal-fired generators could drop.	0.2	10	2
The grid frequency changes abruptly.	This would harm the MG set.	0.01	100	1
These values were estimated by Terry Bahill, February 23, 2010, based on Tom Hansen's data.				

Table VII. Operations FMEA for a backup quick-start natural gas motor-generator set

Failure Mode	Potential Effects	Frequency of Occurrence in the TEP control area (events per year)	Severity of Failure	Estimated Risk
Operations				
Drastic mistakes	Death of humans	0.000001	1000000	$0\times\infty$
Accidents	Injury to humans requiring medical attention	0.1	200	20

Infrastructure damage from violent storms	TEP would be without backup for a month.	0.01	200	2

In addition to the risks described above, some risks that we identified for the PV system had already been mitigated by either the electric utilities or the government:

Table VIII. Risks that have already been addressed

Failure Mode	**Potential Effects**	**Solution**	**Problem Solver**
Home Owners Associations (HOAs) could prohibit or strongly discourage PV systems	HOAs could prevent residents from installing PV systems or could penalize them for doing it.	The state of Arizona passed laws making it illegal for HOAs to impose rules against photovoltaic systems.	State of Arizona
Accidents or deaths due to installation of PV systems by homeowners	Homeowner could get electrocuted when installing the system. High voltages are involved and any mistake could result in death or severe injuries	In order to qualify for TEP's rebate program (which pays for about one third of the installation cost), the system needs to be installed by a *certified* professional; this discourages people from installing the system themselves since they would forego the rebate.	TEP and the green incentives program
Electric companies refuse to buy electricity from homeowners	Homeowners would not benefit from net-metering on days when power output is higher than power consumption	Federal rules requires electric companies to buy electricity from their consumers[2]	Federal Government, State Governments
The panels contain toxic chemicals or heavy metals.	Smashing or crushing a panel would release toxic gases could create a short circuit.	No toxic chemicals or heavy metals are contained on the final product	Manufacturers

6.2 What-if Analysis

Both techniques point out the importance of considering all (or most) possible states of the system and the impact they might have on the output. They require defining hypothetical situations and examining the consequences and implications on the current system. Both

[2] Source: http://irecusa.org/wp-content/uploads/2009/10/IREC_NM_Model_October_2009-1.pdf
http://images.edocket.azcc.gov/docketpdf/0000089952.pdf

techniques recommend mathematical sensitivity analyses[14], as well as a more qualitative method (a what if analysis) by exploring and describing possible outcomes and consequences. This section contains a what-if analysis for the PV system described herein.

6.2.1 Early elimination of rebates

The early elimination of rebates would affect customer incentives to convert to solar-powered generation. As mentioned before, any reduction in consumer incentives to adopt solar energy would have a significant impact in distributed generation. In 2009, energy from residential PV arrays was equivalent to 7 GWh[9] and total distributed generation (DG) equaled 10 GWh. If the rebates were eliminated in 2010 or 2011, there might be no growth in commercial or residential DG systems and thus by the year 2025 DG would be one-hundredth of the projected 1,000 GWh. Failure to meet the ACC's distributed generation requirements may result in fines to TEP and may force them to either acquire additional renewable energy generation capacity or purchase Renewable Energy Credits (RECs) in order to meet the ACC standards.

6.2.2 Cloudy days

Weather is the most uncontrollable factor for a PV system. When clouds appear between the solar panels and the sun, there is an immediate and significant drop in power output. What would happen if there were a total blockage of the sun (due to total cloud coverage) and the system peaked above capacity at exactly the same time? There are two important factors to consider: first, peak loads typically occur in the late-afternoon, around 5 to 6 pm, and second, during these late afternoon hours, output from PV panels has fallen to approximately 24% of peak output. Based on TEP projected demand loads for 2010, obtained from TEP's Resource Planning Group, and on the percentage of cloudy days in Tucson, we estimated the probability of this event happening within a year to be 0.79%.

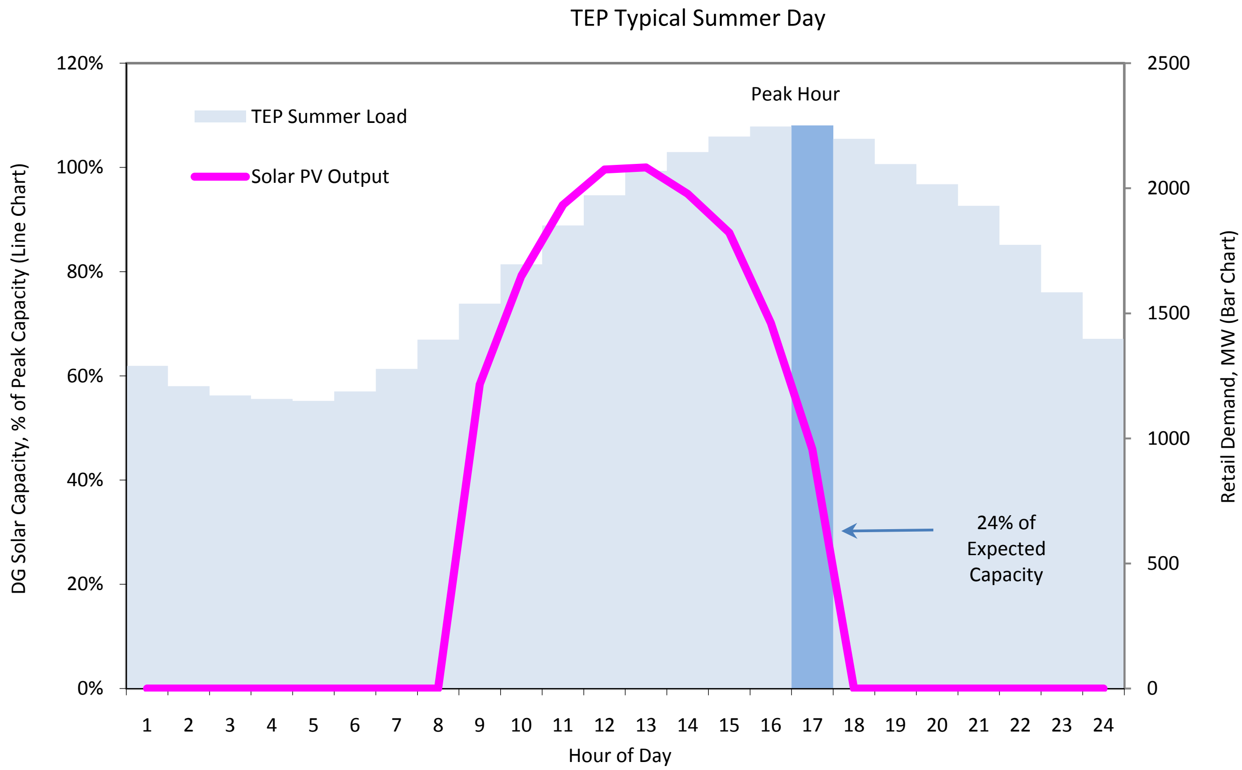

Figure 2. Electric load and typical PV solar panel output on an average summer day

In order to meet these RES requirements, TEP projects that by 2025 its system will have about 400 MW of utility scale renewable capacity and approximately 200 MW of distributed generation capacity. For planning purposes, TEP's Resource Planning group uses a 24% capacity contribution factor for flat panel solar photovoltaic resources. If we assume that TEP's utility scale and distributed generation capacity is made up of 100% flat PV systems, under the best-case weather scenarios, renewables would only contribute approximately 5% or 150 MW of capacity during peak summer load conditions in 2025.

TEP Power Projections for 2025	
Projected levels	Power, MW

Solar Nameplate Power Generating Capacity	600
Solar Power Generating Capacity at noon	600
Solar Power Generating Capacity at 5 PM	150
Peak Retail Load Obligations	3,100
Planning Reserves	375

Under the worst weather conditions (zero solar power output) during peak summer load conditions at 5 PM, TEP would lose 150 MW of solar power generation, but their 375 MW planning reserve would provide adequate backup. If the worst weather conditions occurred at noon, the 375 MW planning reserve would be less than the 600 MW solar power loss, but load demand would not be as high. The load demand at noon is projected to be about 2,000 MW. So TEP would have 3100 -2000 -600 = 500 MW of spare capacity, without dipping into the reserves.

6.2.3 Hardware reliability

Another significant source of risk is the reliability of power generators. Power generators (renewable or non-renewable) could fail during peak load hours. Depending on the total capacity loss and the availability of reserves, it may or may not be possible to meet demand. Given that the incident is not planned, there may be a lag between the time when a generator trips offline and the time when back-up or reserve capacity is available to cover this shortfall. Under rare circumstances, a large unit outage during peak load conditions could result in a temporary capacity shortage that requires TEP to shed load. In most cases, when generating units trip offline, TEP is able to call on backup capacity from the Southwest Reserve Sharing Group (SRSG). SRSG enables TEP to rely on regional utilities for backup capacity for short periods of time (intra-hour). TEP then uses a combination of its own units (if available) and market resources to replace the needed capacity for the next dispatch hour.

6.2.4 Economic factors

There are also economic factors that could affect the PV penetration on TEP's system. For example, the cost of solar panels could suddenly drop. This price drop may make solar panels more accessible, which could result in increased demand. If a large number of households acquired these panels and located them at their homes, during the day, they would stop depending (at least partially) on electricity supplied by TEP. If this happened throughout the city of Tucson, it could affect TEP's bottom line: TEP would have a lot of unutilized capacity during the day since they wouldn't be selling as much electricity to residential customers, and thus their revenues would drop. Unless residential PV adopters installed some kind of energy storage technology, TEP may not be able to significantly reduce generating capacity since it would be necessary to meet demand during night-time, during the afternoon (low PV output and high demand hours), and during cloudy days. Additionally, if all of these residential PV systems are grid-tied and customers are taking advantage of net metering, during sunny days, TEP may be required to buy all the excess electricity produced by residential customers and two things could happen: TEP could start losing money from decreased revenues and increased net-metering costs, or, TEP could substantially reduce net-metering payments, eliminating one of the incentives for residential customers to acquire PV systems.

6.3 **Risk Management**

Both techniques emphasize that a risk analysis is not an isolated step that should be conducted in order to understand the risks associated with the system. Instead, they recommend that a risk analysis should be an integral iterative process that is accompanied by a risk management initiative. After most of the risks inherent to a system have been identified, several risk management or risk mitigation strategies may be implemented in order to try to improve the system. The following section describes some risk management strategies that have already been implemented and suggests additional alternatives.

6.3.1 Demand Risk

TEP's Resource Planning group factors in the variable demand exposure associated with renewable generation resources. Currently, TEP targets a 15% planning reserve margin to ensure adequate system capacity. This planning reserve margin is used to cover peak load obligations and to mitigate unforeseen system contingencies. According to Mike Sheehan, Director of Resource Planning, TEP is aware of the increased demand risk associated with renewable resources and is considering the potential of customer demand response programs, energy storage technologies, and the need for additional quick-start combustion turbines as possible mitigation strategies.

Additionally, output variability may also be explored. The possibility of designing curtailment options around both utility-scale and DG resources may provide system dispatchers with another tool to maintain system reliability on days with adverse weather conditions. TEP's most recent strategy is to implement a diversified utility-scale renewable portfolio based on a wide range of technologies dispersed over a number of geographical locations. This diversification strategy is a means to reduce the magnitude of output variations and to mitigate simultaneous solar curtailments from cloud cover .In order to maintain future system reliability standards, both TEP and other regional utilities should revise their backup capacity and operating reserve policies as their renewable energy portfolio increases.

We expect that as the percentage of renewable capacity increases, demand forecasting models and real-time weather monitoring and forecasting software will be implemented in order to identify risky dispatch scenarios that may require higher levels of back-up generation. These real-time monitoring systems would take the system to a "prevention" state that would enable system dispatchers to bring on additional generating resources as required.

6.3.2 Environmental Risks

The U. S. Department of Energy, Energy Efficiency and Renewable Energy Program is working on the "Solar Energy Development Programmatic Environmental Impact Statement"[(10)] (PEIS) to analyze the environmental impact that solar projects might have and to develop and implement programs that would facilitate a responsible solar energy development. According to Bob Dame, owner of ERG Green, any project has to undergo several detailed assessments to comply with governmental and environmental regulations. These studies include, architectural studies, environmental studies, and biological studies (all managed by the EPA) and are conducted to ensure that the project's environmental impact is below the acceptable levels. Once the U. S. Department of Energy develops solar-specific environmental guidelines, the risks associated with developing solar farms in open-land will be reduced given that the project will have to comply with a series of requirements that minimize environmental impact.

Once solar PV panels are installed, no carbon emissions are produced as a consequence of power generation; however, the solar panel manufacturing process is not a zero emissions process. We were concerned that solar energy generation (considering the manufacturing, installation, and operating phases) could have a net positive carbon foot print; however, this is not the case. A. Study conducted by Solar Hydrogen Education Program[(5)] found that the Springerville Solar Generating Station reduces the carbon footprint by 36.5 tons of CO_2 per kW DC installed, which is 91% less than a comparable fossil fuel powered plant. Additionally, the total energy used to manufacture the hardware of the Springerville Solar Generating Station is 12 MWh AC per kW

DC (88% of which corresponds to solar panel manufacturing). Based on expected power production for the Springerville Solar Generating Station, the energy payback time would be 2.8 years, which is less than the 30 year expected life of the solar-powered plant(9). According to the United Kingdom's Parliamentary Office of Science and Technology(12), the carbon foot print of solar panel manufacturing is expected to be reduced with the development of thin film technologies and the implementation of new, less energy intensive, semi-conductor materials.

There are many technologies available that simplify the project planning process and may be used to design environmentally friendly projects. One example is geographic information systems (GIS), which may aid the planning of solar panel location. The GIS analysis may be conducted in various ways in order to reduce environmental impact. For example, the GIS may be used to identify solar-feasible greyfields[3] and sites such as roofs or buildings(15) that would not require the modification of open-land in order to locate the PV system, sites that can be easily connected to the grid, and sites that receive enough solar radiation to make the project viable. TEP's current environmental risk mitigations strategy is to construct utility-scale projects on greyfields such as reclaimed landfills and previous mining sites.

6.3.3 Financial Risks

Solar energy is currently at a developmental state and capital prices are expensive. Depending on the price characteristics of energy and the inherent financial characteristics of the company, developing a solar farm may not be financially viable. However, in some cases, the financial penalty of implementing a solar powered plant may be reduced by introducing renewable energy tariffs, such as TEP's Renewable Energy Standard Tariff (REST), in order to use these funds to

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[3] Greyfields are underutilized real estate assets or lands. These sites have previously had other uses, such as old mines, mine waste tailings, landfills, mud slide zones, low level radiation sites, frequently flooded zones, and perhaps as buffer zones for wildlife reserves and wilderness areas.

promote the use of renewable energy. Revenues generated by these tariffs are passed on to customers who incorporate renewable-energy solutions to their homes, incentivizing them to switch to greener energy technologies.

It is important to note that utilities cannot pass-on their increased costs directly to their customers since, in most cases, they have a cap on the rate they can charge for electricity. In the case of TEP, they cannot file for a rate increase until after June 30, 2012, with the earliest effective date being January 1st, 2013 (TEP 2009 Annual Report). Therefore, this is not a viable risk management alternative for mitigating the higher power costs from renewable energy sources.

According to Bill Henry, Principal Engineer at TEP, at the time that the Springerville Solar Generating Station was built, there were no federal incentives or rebates to help subsidize the project, and at the moment, TEP does not have any federal incentives that can be used to lower the investment cost of a solar farm. For this reason, another alternative for mitigating financial costs is creating special purpose entities (SPE) to develop and own the solar farms, and develop a lease agreement with them. A SPE is a legal entity (typically a company or partnership) that is created to serve a particular purpose, in this case, owning the solar farm. This SPE may be owned by one or more entities which may not to be related to TEP and may qualify for federal or state rebates that are not available to TEP. This may help reduce the investment cost and would reduce the energy generation cost for this facility or any future facilities that employ this strategy.

Another financial risk is interest rate risk: the risk of interest rates increasing and affecting the interest payments on PV project loans. However, the interest rate risk may be mitigated by conducting interest rate swaps. When companies enroll interest rate swaps, they swap floating debt for fixed rate debt (or vice versa) in order to either exploit their competitive advantage in the fixed or floating rate market, attempt to match the characteristics of their assets and liabilities, or reduce their exposure to interest rate risk. According to TEP's 2009 Annual Report, TEP already enrolls in such interest rate swaps and thus it shouldn't be a problem for them to determine what is on their best interest for loans derived from any type of renewable energy projects.

6.3.4 Government Risks

There is no good way to mitigate the impact of government risk; however there are several measures that may be taken to be prepared in case of changes. TEP could conduct various what-if analyses to try to understand what would happen if carbon emission regulations changed and how this would impact their strategies. It is probably not financially viable or necessary to develop a plan for each particular scenario, but by understanding the possible impact it would have, TEP would be able to react faster to any changes, thus reducing the lead-time between finalizing the plan and deploying the new strategies.

6.4 **Unintended consequences**

Implementing new systems, strategies, laws, or controls, has had additional consequences (not necessarily positive) to the desired ones (unintended consequences). These unintended consequences sometimes defeat the purpose of the new implementation, thus making it important to think outside the box and try to predict what these consequences may be. The systems engineer is responsible for the big picture of system development. Hence, the system engineer must search for unintended consequences of the system under design.

Incorporating photovoltaic solar panels into a commercial electric power grid has one interesting possible unintended consequence: global cooling. Solar panels do two things: they absorb sunlight energy and transform it into electricity, and they also reflect some of the sunlight back into the atmosphere. PV panels prevent sunlight from hitting the ground and being absorbed by the Earth, reducing the amount of energy absorbed by the Earth in the form of heat and therefore contributing to global cooling. These effects could be significant if the whole planet was covered by solar panel; however, given the small percentage of the Earth's surface that will be covered by solar panels, if this effect occurred, it is expected to be negligible.

7. SUMMARY

Bahill's and Haimes' risk analysis techniques have both differences and similarities. The main difference is that Bahill's technique uses a more qualitative approach to risk analysis whereas most of Haimes' techniques are quantitative. Both methods are equally effective for conducting risk analysis; however, in order to apply Haimes' PMRM technique, one must have significant knowledge of the probability-damage relationship, which, depending on the system, may not always be available or easy to derive.

Based on their analysis, there are two things that should be kept in mind. The first is normalizing the frequency and severity scales in order to give equal weight to both factors(1), and the second is to beware of the risk of extreme events and to avoid basing conclusions on the expected value of risk since this will give equal weight to events with high probability of occurrence and low severity and events with low probability of occurrence and high severity.

Regarding the PV system risk analysis, as expected, the risk of clouds blocking the sun and introducing output variability is the biggest non-grid related risk for a PV system. Additionally, as PV solar becomes a larger component of TEP's energy portfolio, it is important for them to revise their back-up capacity policies and consider alternative storage methods in order to reduce the risk of reduced power output on periods with high demand. It is important to note that in order for TEP to meet the distributed generation requirements, rebates and federal tax incentives are a very important.

After conducting the what-if analysis, even under the worst case scenario of total sunlight blockage and demand peaking, with appropriate planning, it is possible to develop strategies that will prevent brownouts and demand shortage. Based on how much PV solar energy TEP has, it may be important to develop and implement state-of-the-art weather forecasting, which combined with their current demand forecasting methods, will help them identify risky scenarios and act appropriately.

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Bio Sketches

Andrea Chaves earned a B.S in Industrial Engineering in 2008, an M.S in Management with emphasis in Finance in 2009, and an M.S. in Industrial Engineering in 2010, all from the University of Arizona in Tucson. In 2008, she received the Wayne Wymore award for excellence in Systems and Industrial Engineering and was named outstanding senior for her graduating class. During her graduate studies at the University of Arizona, she worked as a teaching and research assistant in areas such as production planning, forecasting and optimization; probability and statistics; and systems engineering. In her spare time she enjoys triathlon, engaging in races that include swimming, biking, and running. She currently works as a Business Technology Analyst at Deloitte Consulting LLP in Denver, CO. She may be reached at achaves@email.arizona.edu .

Terry Bahill is a Professor of Systems Engineering at the University of Arizona in Tucson. He received his Ph.D. in electrical engineering and computer science from the University of California, Berkeley, in 1975. Bahill has worked with BAE Systems in San Diego, Hughes Missile Systems in Tucson, Sandia Laboratories in Albuquerque, Lockheed Martin Tactical Defense Systems in Eagan MN, Boeing Information, Space and Defense Systems in Kent, WA, Idaho National Engineering and Environmental Laboratory in Idaho Falls and Raytheon Missile Systems in Tucson. For these companies he presented seminars on Systems Engineering, worked on system development teams and helped them describe their Systems Engineering process. He holds a U.S. patent for the Bat Chooser, a system that computes the Ideal Bat Weight for individual baseball and softball batters. He received the Sandia National Laboratories Gold President's Quality Award. He is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), of Raytheon, and of the International Council on Systems Engineering (INCOSE). He is the Founding Chair Emeritus of the INCOSE Fellows Selection Committee. His picture is in the Baseball Hall of Fame's exhibition "Baseball as America." You can view this picture at http://www.sie.arizona.edu/sysengr/.