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Comparison of Risk Analysis Approaches and a Case Study of the Risk of Incorporating Solar Photovoltaic Systems into a Commercial Electric Power Grid

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ABSTRACT

This paper compares two common risk-modeling approaches and then uses them to analyze the risk of incorporating solar photovoltaic (PV) systems into a commercial electric power grid. It uses procedures from both approaches such as Hierarchical Holographic Models, frequency and severity normalization, and avoiding numerical skewing by rare but serious events: It describes the benefits and limitations of these approaches. Then, this paper summarizes the main risks associated with incorporating Solar PV panel systems into a commercial electric power 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 incorporating Solar PV systems into a commercial electric power grid. © 2013 Wiley Periodicals, Inc. Syst Eng 17: 89–111, 2014

Key words: risk analysis; risk management; renewable energy resources; solar photovoltaic systems; unintended consequences

1. INTRODUCTION

Economically viable harvesting of renewable energy is one of the most profound challenges of the 21st century. The most promising renewable energy source in the southwest United States is photovoltaic. However, incorporating solar photovoltaic (PV) subsystems into an existing electric power grid presents a significant challenge because of the intermittent and diurnal characteristics of the environment. This, and the uncertainty of dealing with the unknown, mean that evolving such a big complex system is risky. Therefore, a risk analysis is a crucial part of system design. This paper compares two common risk-modeling approaches: The first is based on a popular industry approach [Bahill and Karnavas, 2000; Bahill and Smith, 2009; Smith, Siefert, and Drain, 2009], and the second is mainly based on statistics [Asbeck and Haimes, 1984; Kaplan, Haimes, and Garrick, 2001; Reyes Santos and Haimes, 2002; Haimes, Kaplan and Lambert, 2002; Henry and Haimes, 2009; Haimes, 2009; Yan and Haimes, 2011]. The goal is to compare these two approaches and then apply them to the risk analysis of a large-scale grid-tied solar PV subsystem for Tucson Electric Power (TEP), the electricity service provider for the Tucson metropolitan area.

TEP has been operating a 4.6-megawatt (MW) Solar PV panel array at their Springerville Solar Generating Station for

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the last 6 years. However, this facility provides only 0.2% of their total generating capacity, and they need to increase their renewable-energy generating capacity significantly in order to comply with the Arizona Corporation Commission's [2008] Renewable Energy Standard. This Standard requires that, by the year 2025, 15% of the utility companies' retail sales must be supplied from renewable-energy sources.

The risk analysis of this paper was conducted under the assumption that most of this Renewable Energy Standard will be satisfied with solar photovoltaic energy. It identifies risks and complications associated with incorporating large-scale photovoltaic-solar systems from the utility company's perspective.

2. DEFINITION OF RISK

The world is full of uncertainty, and this makes risk an inherent component in the design of any system. Risk is an expression of the potential harm or loss associated with an activity executed in an uncertain environment. Starting in 1662, Arnauld and Nicole, French Catholic priests, wrote that risk had at least two components: "Fear of some harm ought to be proportional not only to the magnitude of the harm, but also to the probability of the event" [Arnauld and Nicole, 1996: 274]. This is the first use of these phrases *magnitude of harm* and *probability of the event*. Some ancient Greek, Chinese, and biblical sources express the concept of risk; but they do not have these phrases. It is unlikely that any older source had these phrases, because Arnauld's friend Blaise Pascal only invented probability in 1654 and the *Oxford English Dictionary* cites the earliest use of the word *risk* as a few years after that.

This paper will primarily examine two risk-modeling approaches.[1] They use different methods to design the system, to model the system, to identify risks, and to quantify risk. Haimes' [2009] process for quantifying risk uses the following equations:

$$E[x] = \int_a^b x \cdot p(x)dx, \tag{1}$$

$$E[x] = \Sigma\, p_i x_i. \tag{2}$$

The expected value of risk, $E[x]$, can be represented with Eq. (1) for the continuous case or Eq. (2) for the discrete case, where X is a random variable representing the severity of consequences (often called damage), $p(x)$ is the probability density function of X, and a and b are the lower and upper range limits of the severity of consequences. In Eq. (2), the probability mass function is used for the expected value of risk. The frequency of occurrence of the threat scenario is implicit, meaning it does not appear in Eqs. (1) or (2). However, Haimes [2009] cautions that risk is a multidimensional function and it cannot be expressed through a single metric. Some of these other dimensions will be revealed as this paper progresses.

Bahill [2010] quantifies risk as the product of the relative likelihood (or frequency of occurrence) of a failure event and the severity of consequences for each occurrence of that failure event, as in

$$risk = relative\ likelihood \times severity\ of\ consequences. \tag{3}$$

This process uses the *product combining function*.

Risk as the product of relative likelihood (or frequency of occurrence) and the severity of consequences is the definition usually used in American industry. It is the only approach that Bahill has seen government contractors use. This may be the result of US government guidance and professional standards. For example, the US Food and Drug Administration [FDA, 2006: 1] wrote: "It is commonly understood that *risk* is defined as the combination of the probability of occurrence of *harm* and the *severity* of that harm." The Department of Defense [DoD, 2006: 1] stated: "Risks have three components: A future root cause (yet to happen), which, if eliminated or corrected, would prevent a potential consequence from occurring, A probability (or likelihood) assessed at the present time of that future root cause occurring, and The consequence (or effect) of that future occurrence." The Defense Systems Management College [DSMC, 2001: 10], which is based on DoDI 5000.2 and DoD 5000.2-R, states: "*Risk* is a measure of the potential inability to achieve overall program objectives within defined cost, schedule, and technical constraints and has two components: (1) the *probability/likelihood* of failing to achieve a particular out-come, and (2) the *consequences/impacts* of failing to achieve that outcome." The Institute of Risk Management [IRM, 2012] states: "Risk can be defined as the combination of the probability of an event and its consequences (ISO/IEC Guide 73)." By design, the CMMi [2012] is broad: It states what must be done, never how it should be done. Here it states what is needed to quantify risk: "Parameters for evaluating, categorizing, and prioritizing risks include the following: Risk likelihood (i.e., probability of risk occurrence) Risk consequence (i.e., impact and severity of risk occurrence) Thresholds to trigger management activities." The INCOSE *Systems Engineering Handbook* [INCOSE, 2011: 225] states: "Level of risk depends upon both likelihood and consequences … [R]isk is expressed as: Risk = Probability of failure (Pf) * Consequence of failure (Cf)." There are differences between these definitions, but for the most part they all state that risk should be quantified as a combination of relative likelihood (or frequency of occurrence) of a potential failure event and the severity of the consequences of that event.

Besides the product combining function, there are other functions for combining data [Daniels, Werner, and Bahill,

[1]This paper will use the following dictionary definitions: they are listed from high-level abstract terms to low-level concrete terms. *Approach* is a plan of attack, or a means to accomplish a goal. It is high level and abstract. *Methodology* is a toolbox of methods, processes, and procedures for achieving a goal. *Method* is a regular orderly way of doing something, e.g., a teaching method, the scientific method. *Process* is a chain of related activities that transforms inputs into outputs, e.g., a Markov process, a system design process. *Procedure* is a sequence of steps conducted in a prescribed manner to attain a goal, e.g., a medical procedure. *Technique* is a concrete application of a method: it is a single operation. *Checklist* can be used to ensure that all of the prescribed steps were actually performed.

2001]. For example, the *linear combining function*, which is the simplest and most common, is defined as

$$f = \sum_{i=1}^{n} w_i \cdot x_i,$$

where n is the number of data elements to be combined, w_i represents the weight of importance (scaled from 0 to 1) assigned to the ith data element and x_i represents the score for the ith data element. Second, the *product combining function* is defined as

$$f = \prod_{i=1}^{n} x_i^{w_i},$$

In Eq. (3), both of the weights are usually 1.0. Third, the *exponential combining function* is defined as

$$f = 1 - e^{-\sum_{i=1}^{n} k w_i x_i}.$$

where k is a scaling constant used to tailor the output to match the requirements necessary for accurate evaluation [Cooper, 1999]. Fourth, the *sum minus product combining function* is defined as

$$f = w_1 x + w_2 y - w_3 xy.$$

The sum minus product combination function [Kerzner, 2002] has its origins in probability theory: it is appropriate for computing probabilities of unions for independent events. It also is the function used in Mycin-style decision support systems for computing certainty factors when two or more rules with the same conclusion succeed [Buchanan and Shortliffe, 1984]. But this formula has drawbacks. For example, if you set the severity to 1 (assuming a range of 0–1), then the relative likelihood could be reduced from say 10^{-1} to 10^{-6} without changing the risk, which we do not want. Furthermore, if either the relative likelihood or the severity is 0, then the risk should be 0, but this equation does not produce that result. Fifth, the *compromise combining function* is defined as

$$f = [(w_1 x)^p + (w_2 y)^p]^{1/p}.$$

The variable p is a scaling factor explained in detail in [Daniels, Werner, and Bahill, 2001].

Sixth, Ben-Asher [2006] writes that people do not equally weigh relative likelihood and severity of the consequences. For example, people buy collision insurance for their cars, but they seldom insure their tires against premature wear. Therefore, he computes risk as

$$risk = relative\ likelihood \times (severity\ of\ consequences)^2$$

Seventh, the Failure Modes and Effects Analysis (FEMA) process also includes the *difficulty of detection* in the product [Carbone and Tippett, 2004], so that

$$risk = relative\ likelihood \times severity\ of\ consequences \times difficulty\ of\ detection.$$

Eighth, terrorism risk can be viewed as having three components: the *threat* to a target, the target's *vulnerability* to the threat, and the *consequence* should the target be successfully attacked [Willis et al., 2005]. The threat is defined as the probability that a specific target is attacked in a specific way during a specific time period. Vulnerability is defined as the probability that damages occur, given a specific attack type, at a specific time, on a given target. The consequence is defined as the expected magnitude of damage given a specific type of attack, at a specific time, that results in damage to a specific target. Terrorism risk is defined as the expected consequence of an existent threat (for a given target, attack mode, and damage type) which can be expressed as

$$risk = threat \times vulnerability \times consequence.$$

"Rather than seek an optimal method for estimating risk, we seek a method that leads us to make the least egregious errors in decision making across the range of possible scenarios that might develop in the future" [Willis et al., 2005].

Bahill's [2010] process for quantifying risk uses the *product* of relative likelihood (or frequency of occurrence) and the severity of consequences. This *product combining function* of likelihood and severity makes intuitive sense. People are familiar with multiplying data; for example, multiplication is used in computing a benefit to cost ratio. (A ratio is just multiplication by the reciprocal.) The product combining function is used in many different realms; for example, a person buying a lottery ticket should care about the size of the pot *divided* by the number of people buying tickets; insurance rates on a Corvette are higher than for a typical automobile, because the frequency of accidents is higher and it is an expensive car so the monetary loss in an accident is higher: It seems intuitive to *multiply* the frequency times the monetary loss. The product combining function can also have weights of importance, like this:

$$risk = (relative\ likelihood)^{w_{rl}} \times (severity\ of\ consequences)^{w_{sc}} \quad (4)$$

Of course, a risk analyst would never give a decision maker a single number and say, "This is the most important risk." The risks must be prioritized and discussed with the decision makers. Risk management progress must be understood. Figure 1 presents a risk plot, using the definition of Eq. (3), that can facilitate these discussions. It is similar to the DoD Risk Reporting Matrix [DoD, 2006] and [INCOSE, 2011: Figs. 5–10].

Each row in a risk table (like Table I) describes particular risk. It contains a *potential failure event*, the *consequences* of that failure event, the *frequency of occurrence* (or *relative likelihood*) of the event, the *severity of consequences*, the *estimated risk*, and perhaps a short *identification tag.* The *frequency of occurrence* (or *relative likelihood*) of the event

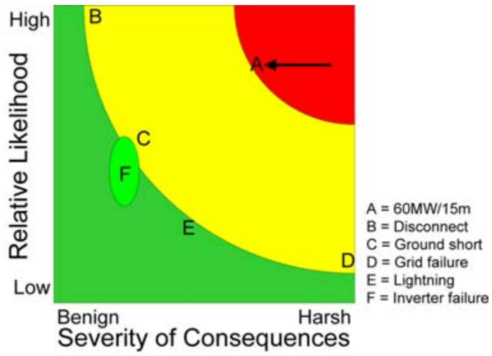

Figure 1.

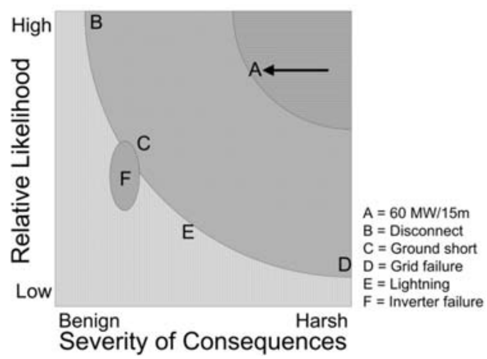

Figure 1. A linear risk chart for some failure events explained in Table I. The arrow shows that the biggest risk, risk A, has dropped in severity since the last review, due to risk mitigation action. Uncertainty in the likelihood and severity numbers can be shown with ellipses, as is illustrated with risk F. Risks in the red (darkest grey) region are high risk and must be managed. Risks in the yellow (medium grey) region are medium risk and should be managed if it fits within the budget. Risks in the green (lightest grey) region are low risk and need only to be monitored. The curves are iso-risk contours. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

occurring can be derived from historical data or it can be estimated based on expert opinion. Likewise, the severity of consequences of a potential failure event can be based on historical data or expert opinion. The estimated risk is usually defined as the product of relative likelihood and severity of consequences.

However, the terms relative likelihood and frequency of occurrence are not quite synonyms. If there are historical data for an event, then we use the term frequency of occurrence. Otherwise, if we are guessing the future, then we use the term relative likelihood. The word *relative* emphasizes that it is the relationships between risks that are being illustrated. The word *likelihood* is not used in a probabilistic sense, but rather in its dictionary sense to indicate the events that are likely to happen. Frequency is used instead of probability, because humans evaluate probability poorly: The frequency approach helps humans to partition a set of cases into exclusive subsets,

Table I. Selected Risks for Incorporating Solar PV Subsystems into a Commercial Electric Grid

Potential Failure Event	Consequences	Frequency of Occurrence in the TEP control area (events per year)	Severity of Consequences	Estimated Risk, defined as frequency times severity	Identification Tag
Solar panel output drops by 60 MW in a 15-minute interval.	Breakers could trip leaving customers without electric power. Voltage on the grid could drop and frequency of coal-fired generators could change.	95	200	19,000	A
Feeder circuit disconnects from substation	Feeder circuit voltage could get out of phase with the grid.	330	1	330	B
Short to ground on distribution grid	Equipment could be damaged, particularly transformers and capacitor banks.	24	10	240	C
Western Power Grid fails	The western United States would be without electric power.	0.03	1,000	300	D
Lightning strikes the system	Components could be damaged and electric generating capacity would be reduced.	0.4	100	40	E
Failure of DC to AC inverters	The customer can no longer sell electricity to TEP	240	0.1	24	F

This is an abridgment of Table IV. These data come from TEP managers, TEP documents, academics, and project managers of renewable energy projects.

which is a mental operation that is performed quite well [Gigerenzer, 2002; Bahill and Smith, 2009].

These two types of uncertainty are sometimes called aleatory and epistemic. Aleatory uncertainty describes inherent variability or randomness in the physical system: It would be reported as frequency of occurrence. Epistemic uncertainty is due to a present lack of knowledge or data about how the system behaves or interacts with its environment: Epistemic uncertainty would be estimated by domain experts and reported as relative likelihood.

The events in Table I have uncertainty in both the relative likelihood of occurrence and the severity of consequences. However, sometimes we know *when* an event will occur, so the likelihood that the event will occur is 1.0 and we only need to estimate the severity of the consequence. For example, assume that you have bet on tails in a coin flipping event and you are about to flip the coin. The likelihood that the event will occur is 1.0 and the severity of the consequence is that you will lose half the time. Therefore, the risk of losing your bet in the next moment is 0.5. Most gambling games are of this nature.

On the other hand, sometimes there is no uncertainty in the consequence, only uncertainty that the event will occur in the specified time interval. For example, assume that you are performing an experiment with radium and an alpha particle would ruin your experiment. In radioactive decay of radium-226 into radon-222, we can estimate the likelihood of the event as 3.7×10^{10} decays/s-g. When the event occurs, we know with absolute certainty that the consequence will be an alpha particle; therefore, the severity of this consequence is 1.0. Therefore, the risk of getting an alpha particle is 3.7×10^{10}/s-g. If there is 1 g of radium (about 10^{22} atoms) and the experiment lasts 1 s, then the risk is 3.7×10^{10}.

We can compare these three types of events and consequences (1) uncertainty in both the event and the consequences, (2) uncertainty in only the consequences and (3) uncertainty in only the occurrence of the event as long as the time interval is the same. In a fourth case, the likelihood of the event occurring cannot be estimated, for example, when dealing with terrorist attacks on population centers. For these cases, Haimes' approach replaces the difficulty of estimating the likelihood of occurrence with the difficulty of obtaining data to compute probability density functions for the severity of consequences given that the failure has occurred.

In a risk table, a failure event might have multiple consequences, as in Table II. In this case, each consequence will have an expected frequency of occurrence, which will be the product of the frequency of the failure event times the frequency of each consequence.

A particular consequence might cause a different amount of damage, depending on the specific event that caused it and the environment in which it occurred. If data are available for such events, then the severity of the occurrence and the frequency of occurrence can be described with a probability distribution instead of a single value.

It is difficult to get good frequency of occurrence data for physical and cyber infrastructure. For example, terrorism is an asymmetric nonzero sum game with spotty and weak intelligence. The frequency of occurrence of an initiating event (e.g., act of terrorism or a natural disaster) is fraught with epistemic and aleatory uncertainties. On the other hand, the probability distribution of the severity of consequences is easier to assess by experts, using modeling and simulation tools. Indeed, Haimes' approach develops scenarios of future failures; then simulations and expert evidence are used to assess the severity of consequences as functions of different failures.

For the severity of consequences, Haimes' risk quantification process uses the expected value of a probability density function: whereas Bahill's process uses a single value. Although the definitions are similar, the two risk analysis processes differ. Haimes' process is statistical, whereas Bahill's process is quantitative. Bahill's process uses the relative likelihood of the failure event times the severity of consequences. Haimes' process does not use the frequency of occurrence of the failure event itself. Instead, he uses the expected value of the severity of consequences and the probability of the consequences, given the event. These processes are discussed in the following section.

Table II. A Failure Event with Multiple Consequences

Failure Event	Consequences	Frequency of occurrence (events per year)
Lightning strikes, the number of lightning strikes per year in Arizona = 10^6	Electrical devices are destroyed, frequency per lightning strike = 10^{-3}	1,000
	A house burns down, frequency per strike= 10^{-4}	100
	A person is injured, frequency per strike= 3×10^{-6}	3
	A person dies, frequency per strike= 10^{-6}	1

These annual data are for the state of Arizona.

3. SYSTEM CHARACTERIZATION

There are many methods for breaking down a system into smaller parts. To design and model a large or complex system, the system can be decomposed using a hierarchy of physical or functional components. Functional decomposition decomposes the system according to the functions that the system must perform. The top-level function is decomposed into subfunctions, and the subfunctions are decomposed into sub-subfunctions. When should this decomposition stop? When a function is found that can be satisfied by a commercial off the shelf (COTS) component [Bahill et al., 2008].

The Zachman framework is a classification method used to organize descriptive representations of an enterprise. Each row represents a different stakeholder's perspective of an enterprise, while each column depicts a different area of interest within those perspectives. The forte of the Zachman framework is that it provides an even coverage of important topics without redundancy, repetition, or lacuna. Each cell in the matrix contains at least one model or artifact [Bahill, Botta, and Daniels, 2006].

Haimes' system analysis method starts with a hierarchical holographic model (HHM) that is comprised of many system models: some models overlap; some do not [Haimes, 1981, 2009; Agrawal, Barker, and Haimes, 2011]. Typical perspectives of an HHM include business models (with aspects of purchase orders, invoices, costs, schedules, and return on investment); architectural models; use case models; behavioral/functional models; requirements models [Bahill and Dean, 2009]; physical structure/component models; and performance/parametric models. Each of the models in an HHM requires determining its properties, constructing relationships among its inputs and outputs through its state variables, and quantifying dependencies and interfaces between its components and subsystems [Haimes, 2012]. Figure 2 shows an HHM for our solar power system. The top-level box is the

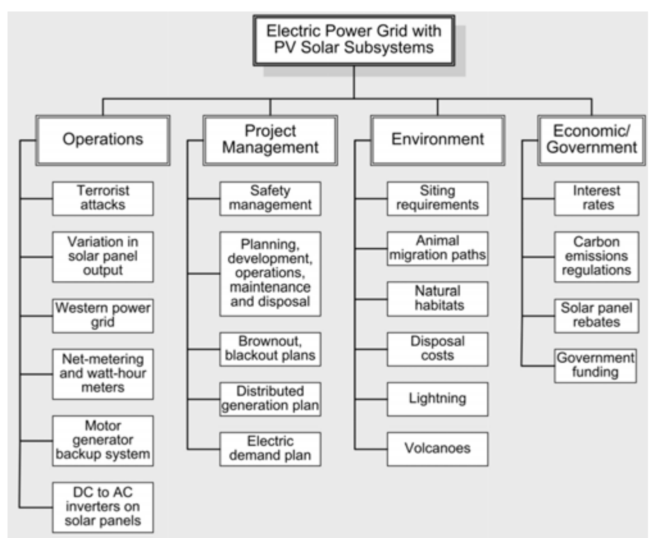

Figure 2. An HHM for an electric power grid with Solar PV subsystems.

system that we are analyzing, the electric power grid with Solar PV subsystems. The next level shows some overlapping perspectives (or views) of this system, namely, operations, the environment, project management, and economic/government. Each of these perspectives is analyzed using various aspects. For example, some aspects of the operations perspective are terrorist attacks, variation in solar panel output, the Western Power Grid, etc. Each entity in this figure would typically have a model and a risk analysis.

Bahill's system design process is a use-case-based iterative process [Bahill, 2010, 2012]. It starts with a problem statement. Next, we make a rough schedule of who does what and when. Those were brief activities. Now we write the use cases that describe the behavior of the system. While we are writing the use cases, we develop functional and nonfunctional requirements: These are large documents. Design of tests can start as soon as the use cases are written. The systems engineers then derive the technical requirements and the test engineers create the test requirements. Now that we have some requirements, we can form evaluation criteria that will be used in the tradeoff studies. Design engineers create the design model containing UML and SysML diagrams that show the behavior (with state machine diagrams, sequence diagrams, and activity diagrams) and structure (with block diagrams) of the proposed system. This system design process is iterative and hierarchical. Creating these documents is not a serial process. There must be many iterations, and there are many opportunities for parallel processing. This process recommends identifying various risk aspects (such as cost, schedule, performance, project, business, safety, environmental, etc.). Defining the system and explaining its behavior are the two most important tasks at the start of a risk analysis. Communicating with the decision makers and explaining the risks are the most important tasks near the end of a risk analysis.

An electric power grid with solar PV subsystems, is defined as follows. "An electric power grid with solar PV subsystems consists of photovoltaic (PV) solar panel arrays, DC to AC inverters and the hardware that connects them to the electric power 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 allows customers with grid-connected electric generating systems to buy electricity from the utility company when they need more electricity than they are generating and to sell electricity to the utility company (at a predetermined price) when they generate more electricity than they need. The utility company uses this solar-generated electricity to meet part of their electric demand, and it must be capable of meeting electric demand during the night and during days with reduced solar power output. These systems shall comply with all local and federal laws." An HHM that describes a small portion of such a system is depicted in Figure 2. This figure is used to help identify system risks.

In this paper, we show the risk analysis of the top-level system, the electric power grid with Solar PV subsystems. The risk analysis for operating performance is shown in Table IV. The risk analysis for the environment is shown in Table VII. The risk analysis for project management is shown in Table VIII. The risk analysis for economic/government is shown in Table IX. As a further decomposition example, the risk analysis for a motor-generator backup system is shown in Tables X and XI.

4. RISK IDENTIFICATION AND QUANTIFICATION

The two risk analysis approaches use similar methods for risk identification: First, they obtain significant input from system experts and outsiders to help identify potential failure events and their consequences. Bahill's approach uses brainstorming and risk tables, whereas Haimes' approach uses HHMs and risk matrices. The term risk usually describes risks to the system being designed or its primary users, not to unintended consequences in systems outside the scope of the system being designed. Risk identification is an iterative and hierarchical process. Once a risk table or matrix is obtained, the resulting risks must be discussed with professionals, academics, and other system experts that will help verify, quantify, add and eliminate risks. The risk tables summarized in this paper required multiple iterations. As time goes by and as risk management strategies are implemented, risks and risk severities will have to be revised in order to be a true representation of the existing system.

Next, the effects of these failures should be explained. These failures could affect cost, schedule, performance, operations, the environment, safety, etc. Then the likelihood of each risk occurring should be estimated. If the project has plentiful statistical data, then the frequency of each event might be calculated. But typically such data are not available, so the likelihood of occurrence in some given time interval is estimated.

Haimes' process does not use the frequency of occurrence of each failure: it focuses on the probability of the severity of consequences, given the events. Bahill's process estimates the frequency of occurrence of each failure event based on observations, statistical analyses of historical events, and expert opinion. Bahill's process quantifies the risk as the product of frequency of occurrence and severity of consequences and emphasizes the importance of normalizing the values of both frequency and severity on the same scale. This normalization guarantees that both frequency and severity are given the same weight when calculating the final risk. This process also recommends the use of log-log plots so that rare events can be tracked without distorting the risk analysis.

Haimes emphasizes **not** using *only* the expected value of the risk to determine the total system risk: because this could give a risk with a high-frequency and low-severity the same weight as a risk with a low-frequency and high-severity. Instead, he uses the Partitioned Multiobjective Risk Method (PMRM) [Asbeck and Haimes, 1984; Haimes, 2009] and develops a risk function for each risk. It is important to note that for extreme events, the conditional expected value of the risk supplements and complements the expected value of the risk; it does not replace the expected value of risk. Indeed, all figures in Haimes [2009] depict the tradeoffs between the expected value of risk and the conditional expected value of risk. The conditional expected value of the risk is defined as

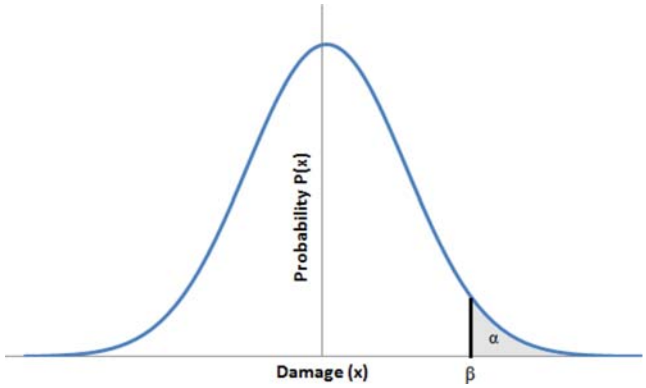

Figure 3. Typical normal distribution curve. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the expected value of a random variable, given that this value lies within some pre-specified range. The conditional expected value of risk, $f(x)$, for severity of consequences between β and ∞ (where β represents an extreme value of severity of consequences) is given in

$$f(x) = E[x|x > \beta] = \frac{\int_{\beta}^{\infty} xp(x)dx}{\int_{\beta}^{\infty} p(x)dx}, \tag{5}$$

As shown in Figure 3, this upper-tail region, with lower limit β, is the zone containing rare but serious events. On the other hand, when analyzing return on investment [Reyes Santos and Haimes, 2002] (or profit or another *more-is-better* metric) the lower-tail would be the region of interest, and Eq. (5) would be rewritten accordingly. These statistics for frequency and severity are used for calculating risk as well as for reliability analysis, sensitivity analysis and the search for unintended consequences. So we do not want them skewed by outliers in these tail regions.

Applying the Partitioned Multiobjective Risk Method (PMRM) to our TEP case study was difficult because there were no data with which to calculate probability density functions. Therefore, to avoid skewing the statistics with extreme events, events with low-frequency but high-severity (such as category 5 hurricanes, volcanic eruptions, acts of war and terrorist attacks) were removed from the numerical computations and have been marked in the risk tables with a "0×∞" symbol. These rare but potentially catastrophic events would have been in the lower-right corner of Figures 1 and 4. The upper-left corners of these figures could have contained events with high-frequency but low-severity (such as birds and airplanes casting shadows on the solar panels, solar corona mass ejections and solar PV customers connecting to and disconnecting from the electric power grid), but they were removed from the statistics.

5. RISK SEVERITIES

The severity of consequences of a risk event 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. Severity values can be derived using brainstorming, group decision techniques, modeling, and simulation. However, severity values are subjective and depend on the perception of the analyst. Fortunately, it is possible to reduce analyst-induced bias by sharing the resulting severity values with system experts and other analysts so that they can validate the severity values.

Analyzing risk severities is a common practice. Insurance companies have developed tables to quantify risk so that different risks can be compared. They assess policyholders' risk in order to estimate the total risk of their insured pool and derive the expected payout costs. Understanding risk severities allows them to quantify the risk and act accordingly. By estimating expected payout costs, insurance companies are able to set the price of insurance premiums so that they almost always generate a profit. (It is only the rare but catastrophic events that bankrupt them.) Utility companies also routinely analyze risk severities. If the utility company understands the severity of consequences, they will be able to prioritize risk mitigation strategies.

The two risk approaches being compared in this paper have different processes for determining risk severities. Bahill's process normalizes the severity of consequences scale so that it has the same range as the likelihood scale. This guarantees that the risk does not depend *only* on the likelihood or the severity. If the event's likelihood and severity scales were different (e.g., likelihood had 5 orders of magnitude, but severity had only 1), it is possible that the severities would have no impact on determining the highest risks; risk would be dependent only on the likelihood values. When the likelihood and severity scales are normalized, they will have the same weight in the quantification of risk and bias is eliminated. For example, if the likelihood scale goes from 10^{-6} to 10^{-1}, then the range has 5 orders of magnitude, and thus the severity scale must also have a range of 5 orders of magnitude (e.g., from 1, very low, to 10^5, very high).

Table III. The Problem with Different Ranges for Likelihood of Occurrence and Severity of Consequences

Example 1				Example 2			
Likelihood	Severity	Risk	Rank Order	Likelihood	Severity	Risk	Rank Order
10^{-1}	1	1×10^{-1}	1	10^{-1}	6	6×10^{-1}	1
10^{-2}	2	2×10^{-2}	2	10^{-2}	5	5×10^{-2}	2
10^{-3}	3	3×10^{-3}	3	10^{-3}	4	4×10^{-3}	3
10^{-4}	4	4×10^{-4}	4	10^{-4}	3	3×10^{-4}	4
10^{-5}	5	5×10^{-5}	5	10^{-5}	2	2×10^{-5}	5
10^{-6}	6	6×10^{-6}	6	10^{-6}	1	1×10^{-6}	6

Risk = Likelihood × Severity

The examples in the left and right halves of Table III have the same likelihood of failure, but the severity column in the right half has been turned upside down. The risk columns are different, but the rank order columns are identical. Severity has no effect. We can generalize this idea by letting F_i, S_i and R_i and F_j, S_j and R_j be, respectively, the frequency, severity and risk data for any two rows of Table III. Clearly $R_i > R_j$ if and only if $F_i \times S_i > F_j \times S_j$, that is, when $F_i/F_j > S_j/S_i$. For the data of Table III, the smallest possible value of $F_i/F_j = 10$, for $F_i > F_j$. The largest possible value of $S_j/S_i = 6$. Since 10 > 6, the ratio F_i/F_j will always dominate S, regardless of the order of the rows.

In general, if two items are being multiplied and they have different ranges, the one with the bigger range has more weight, perhaps secretly. To explicitly weight frequency and severity, weights of importance can be used as exponents, as in Eq. (4).

5.1. Data Range is Proportional to the Weighting Exponent

Assume that the frequency (F) data for a particular risk analysis extend from 1 to 100, but the severity (S) data only extend from 1 to 10. We would then need a function that would transform the S data so that they would have the same range as the F data. First, let's try an exponential function like $f(S) = S^{w_S}$, where the weight of importance for severity $w_s \geq 1$. If $w_s = 1$ then the S data will extend from 1 to 10. If $w_s = 2$ then the S data will extend from 1 to 100. Generalizing, if we need the S data to extend from 1 to α, then we need $f(S) = S^{w_s} = \alpha$. The original maximum value of S was 10 and now we need it to be α. So we need $f(10) = 10^{w_S} = \alpha$, ∴ $w \approx 0.43 \ln \alpha$. In contrast, for a different set of F and S data, we might need to *compress* the data range of S, which we can do using a logarithmic transform, $f(S) = \ln S$. Obviously, both of these transforms are nonlinear. In summary, for an equation in the form of two exponential functions being multiplied together, the exponents are proportional to the data ranges and therefore the function with the bigger exponent has more weight.

5.2. An Algorithm for Computing Severity

The following algorithm is used for computing values for the severity of consequences [Bahill and Smith, 2009].

1. Assign a relative likelihood of occurrence to each potential failure event.
2. Find the failure event that might have the most severe consequences, call its value S_{worst}.
3. For each other failure event, 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 of consequences for each failure event as $S_i = S_{\text{worst}}/N_i$.
5. Remove the low-frequency and high-severity failure events and the high-frequency low-severity failure events.
6. Normalize the severity values so that their range equals the range of the likelihood values.
7. Compute the estimated risk using a combining function [Bahill and Smith, 2009].
8. Prioritize the risks to show which are the most important [Botta and Bahill, 2007].

Because step 3 is subjective, numerical values for severity and estimated risk cannot be directly compared from one table to the next.

Another technique for step 6 is to use the likelihood of occurrence of the failure event, which is restricted to values of 0–1, and then for each row, assign a scoring function [Daniels, Werner, and Bahill, 2001] for the severity of consequences. Scoring functions also produce outputs in the range of 0–1. Therefore, the range for both likelihood and severity will be between 0 and 1. On the other hand, if you use the probability of occurrence and the dollar value of the loss, you are certain to create confusion.

Haimes' approach uses various methods for quantifying severity. In the Partitioned Multiobjective Risk Method (PMRM) [Asbeck and Haimes, 1984; Reyes Santos and Haimes, 2002; Haimes, 2009], severity is typically quantified using measurement units relevant to the event (dollar losses, acres of flooded land, etc.), which may be easier to interpret than Bahill's approach (a unitless value). However, to avoid unwanted hidden weighting of severity and likelihood, the range for each must be the same. This makes it hard to use natural units. Haimes' approach uses the PMRM to partition the frequency axis and the severity (damage) 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.

Haimes' Risk Filtering and Ranking Method (RFRM) uses an ordinal scale from 1 (very low) to 5 (very high) to quantify severities on both quantitative and qualitative frequency scales. Based on the normalization discussion in Bahill's approach, this could have drawbacks; however, given the purpose of the RFRM, the selection of the severity scale is not that 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. Each failure mode is divided into several frequency 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 frequency and severity). In essence, the problem described by Bahill's approach is avoided since the focus is placed on finding the failure events that exceed a certain severity threshold, rather than in determining a numerical value of the risk.

Decision makers should be interested in rare but serious events. Over the last decade, we have witnessed a series of such events. In April 2010, a British Petroleum oil well in the Gulf of Mexico exploded and leaked 5 million barrels of oil. The terrorist attacks on the World Trade Towers September 11, 2001 caused severe physical and emotional damage. Hurricane Katrina of August 2005 was the costliest natural disaster in the history of the United States; because so many properties were built below sea level: Total property damage was $81 billion. These three events are mentioned because they indicate that the probability density function for the severity of consequences is not Gaussian. The right tail (and perhaps the left tail containing Microsoft, the Internet, Google, and Social Networking) has far more occurrences than a Gaussian distribution would have. Insurance companies and politicians have a hard time dealing with such rare but serious events.

5.3. Minisummary

Risk is a multidimensional function, representing the affected multidimensional states of a system, and thus it cannot be measured with a single number [Haimes, 2009]. Therefore, many additional attributes, such as difficulty of detection and vulnerability, have been included in the risk definition. If a problem is difficult to detect (in testing, verification, etc.), then we should worry more about it and increase its contribution to risk [Bahill and Karnavas, 2000]. If we know that we are vulnerable in a certain area, then we should worry more about that area and increase its contribution to risk. When quantifying risk, Haimes [2009] has used the following attributes: frequency, severity, safety, efficiency, reliability, vulnerability, and resilience.

The biggest difference between the two approaches is the scale. Haimes' approach is a statistically based risk-management process that includes risk analysis, risk modeling, risk assessment, and risk communication and is explained in dozens of papers and several books. In contrast, Bahill's approach might be considered a subset of Haimes' approach in that it only covers risk analysis, risk prioritization, risk modeling, and risk communication. It is described in a couple of papers and is easier to implement, furthermore, it is the approach commonly used in American industry.

Both approaches work on existing systems as well as on new systems being designed. However, we believe that Haimes' approach of the 1980s and 1990s was optimized for existing systems where plentiful statistical data either existed or could be collected. On the other hand, Bahill's approach was designed to be an integral part of the system design process; although in this paper, it is being applied to an existing system.

Both approaches emphasize that after completing a risk analysis, you should look at (1) high-risk events, (2) high-severity events (no matter how unlikely), and (3) estimates that have a large uncertainty. These should be discussed with the decision makers. In the next iteration, you should focus resources on these items.

6. RISK ANALYSIS OF POWER GRID WITH SOLAR PV

There are two categories of risk for incorporating solar photovoltaic subsystems into a commercial electric power grid: risks related to uncontrollable factors such as weather and risks related to software, hardware, and human error. Although many papers on risk do not consider uncontrollable factors or acts of God, because they cannot be predicted, 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 different tiers or levels [Bahill et al., 2008]: (1) risks related to the utility company and the power grid, (2) operations, project management, environment, and economic/government, and (3) components of these. The risk tiers correspond to the perspectives of the HHM depicted in Figure 2.

Risk-tier	Description
Electric Power Grid with Solar PV Subsystems	Risks related to not meeting demand, brownouts, blackouts, customer dissatisfaction, etc.
Operations	Risks related to the hardware, software, and bioware of the components of the system during operation: reliability
Project Management	Risks that may be encountered throughout the development of the PV project: changes in costs, design issues, permit issues, etc.
Environment	Risks related to the location and surrounding environment of the project: effect on local habitats, weather, environmentalist's opposition, etc.
Economic/Government	Risks related to changes in governmental policies or economic conditions

The risk-tiers were analyzed from various stakeholder perspectives. For example, the first tier, "Electric Power Grid with Solar PV Subsystems," 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. Each tier will have risks that affect various stakeholders (utility company, customers, environment, regulators, etc.); however, the risk tables in this paper summarize the risks *from the perspective of the utility company.*

Our project started with a search for risks of using renewable energy resources in an electric power grid [Bahill, 2010, 2012]. Then, to help expand and solidify the risk descriptions, we interviewed TEP managers and directors, academics, and project managers of renewable energy projects. The information provided by them was summarized and analyzed to determine the possible risks. After identifying the risks, risk frequencies were calculated or estimated based on the available information. Finally, the risks were prioritized and discussed with the decision makers.

6.1. Description of Identified Risks

We will now describe the most important risks, which are in Tables IV–XI. Our preliminary risk analysis indicated that the greatest risk for an electric power grid with Solar PV subsystems was weather causing the solar panels to receive less sunlight than expected. This is a critical factor for a self-sustaining PV system, but it is less important for a large-scale system comprised of both renewable (solar) and nonrenewable resources. As will be discussed in Section 6.3, this risk can be mitigated by using energy storage systems or increasing backup generating capacity. In consequent iterations, this risk was modified in order to encompass output variability:

Table IV. Operating Performance Risks for Incorporating Solar PV Subsystems into a Commercial Electric Power Grid

Potential Failure Event	Consequences	Frequency of Occurrence in the TEP control area (events per year)	Severity of Consequences	Estimated Risk, defined as frequency times severity	Identification Tag
Physical or cyber terrorist attack on the Western Power Grid	Load shedding, brownouts, blackouts, transportation gridlocks, hardware damage, chaos and cessation of commerce	0	10^6	$0 \times \infty$	
Nearby volcanic eruption	Clouds of ash and smoke could cover the sky blocking sunlight to solar panels and reducing solar PV output.	0	10^5	$0 \times \infty$	
Solar panel output fluctuates by more than 60 MW in a 15 minute interval due to clouds, thunderstorms, etc.	Power production plummets tripping breakers and leaving customers without electric power. Voltage on the grid could drop and frequency of coal-fired generators could change: transients are harmful to big electric generators.	94.6 This number represents the $\pm 3\sigma$ points for data collected every 15 minutes for an entire year.	200	18,920	A
Feeder circuit disconnects from substation	Feeder circuit voltage gets out of phase with the grid. solar PV	330	1*	330	B
Short to ground on the distribution grid	Equipment is damaged, particularly transformers and capacitor banks.	24	10	240	C
Western Power Grid fails (due to other than terrorist activities)	The western United States would be without electric power.	0.03	10^4	300	D
Lightning strikes the system	Components may be damaged and electric generating capacity would be reduced.	0.39	100	39	E
Grid voltage exceeds ±5% limits	Customer service deteriorates. solar PV systems trip off-line.	24*	1*	24	G
Transient local outages	Outages on transmission or distribution lines trigger shutdown of PV systems.	24	1	24	H
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	I
Junction box fails	Loss of generated power output	0.27	50	14	J
Data acquisition system fails	Data cannot be read from the solar farm, loss of monitoring	0.14	50	7	K
PV module fails	Loss of production capacity	0.38	10	3.8	L
Grid frequency goes out of ±0.5 Hz limits	Small PV subsystems and big generators trip off-line, perhaps overloading transmission lines. TEP might be fined.	0.2	50*	10	M
Software failure	Software failures are ubiquitous and insidious. They can cause a myriad of problems.	2	50	100	N
Electric storage system fails	Stored energy is lost. Infrastructure might be damaged. This failure event will become more severe as more batteries are used to smooth the load.	0.7	20*	1.4	O

*These values will increase with an increasing number of solar PV subsystems.
Tables IV and XI estimates are represented with integers or decimals with only one significant figure. Decimal numbers with two or more significant figures were calculated from TEP databases.
These data are also plotted in Figure 4.

large changes in solar power output (±60 MW) that would correspond to a solar power output variation of ±3 sigma in a 15-min period. This change in power output could introduce transients onto the grid and could produce load shedding.

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

Hardware risks include failures due to component malfunction or external events such as lightning or dust. The frequency of failures of PV system hardware such as data acquisition systems, junction boxes, PV modules, and general failures due to lightning strikes was based on a report of TEP's experience with the Springerville Generating Station [Moore et al., 2010]. Severity for hardware failures ranged from a simple system restart to more complex maintenance requirements [Moore et al., 2010]. In addition to the hardware failures reported by TEP, we included storage system failures, because storage technologies are 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. Failure of a backup generator will affect the capability of supplying enough power during peak demand or low power production hours. The severity values and frequencies were estimated based on hardware-specific reliability rates (assuming an expected lifetime of 30 years).

Environmental risks of Table VII include immediate risks to the environment such as habitat destruction, as well as deferred risks (such as the disposal after the system's design life or after irreparable failure). Large-scale solar farms could harm local habitats and modify animal migration routes. Disposing of the solar subsystems at the end of their design life is low risk, because 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 regulations were passed. The other environmental risk is unknown hazards and is related to the possibility of discovering that the system contains elements that may become suspects for causing cancer or illnesses, or that the system could produce other unknowns.

Tables VIII and XI shows that accidents and human mistakes are the risks with the highest severities given that they can harm people; however, based on TEP's historical record, the occurrence of such events is extremely low and thus their frequencies are almost negligible. Other extreme events such as terrorist attacks on the Western Power Grid and volcanic eruptions were also considered; however, as can be seen in Table IV, the estimated risks for these extreme events were filled with our null symbol, 0×∞, which means that they were excluded from our numerical calculations. This is expected to reduce the skewing of numerical calculations that would result by including these rare but serious events [Haimes, 2009].

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

Finally, government risks in Table IX include changes in government funding and regulations, such as carbon emission policies and carbon taxes that would have a direct or an indirect impact on the viability and size of PV systems. Government policy changes concerning impacts on wildlife habitat, lands and water [http://solareis.anl.gov/documents.index.cfm] could make TEP's renewable energy portfolio plan obsolete, and could require total replanning of strategies. The early elimination of rebates is another government risk: It would affect customer incentives to convert to solar-powered generation [Richardson-Smith, 2010].

Tables IV–IX contain risk analyses with both PV system-specific risks as well as risks associated with Tucson Electric Power's AC electric power distribution grid. The data for the distribution grid risks were given to us by Tom Hansen, vice president of TEP in 2008, and Bahill derived the rest of the distribution grid data by normalizing the frequency of occurrence and calculating the range: about 6 orders of magnitude. Since the range for frequency and severity should be about the same [Bahill and Smith, 2009], numerical values were assigned to the severities as follows:

Severity Description	Numerical Value
Extreme	1,000,000
Very High	100,000
High	10,000
Medium	1,000
Low	100
Very Low	10
Minuscule	1

Is it really mandatory to give frequency and severity the same range? Like most systems engineering questions, the best answer is, "It depends." If your customer does not want you to normalize frequency and severity, then don't do it.

Table IV summarizes the operating performance risks for Solar PV systems and TEP's distribution grid. These risks are related to the functionality of the system. Failure events in the performance category typically result in system downtime and will affect the quality and reliability of system operations.

Tables IV–XI have five or six columns describing a *Potential Failure Event*, the *Consequences* of that failure event, the *Frequency of Occurrence* (or *relative likelihood*) of the event in the relevant environment, the *Severity of Consequences* for each failure event, the *Estimated Risk*, and perhaps a short *Identification Tag*. The *Frequency of Occurrence* was based on historical data and expert opinion. *Estimated Risk* was defined as the product of the *Frequency of Occurrence* and *Severity of Consequences*.

Mitigation strategies must be written for all risks. Here are a few examples for Table IV.

Risk: Solar panel output fluctuates by more than 60 MW in 15 min. *Mitigation Strategy:* To ameliorate these

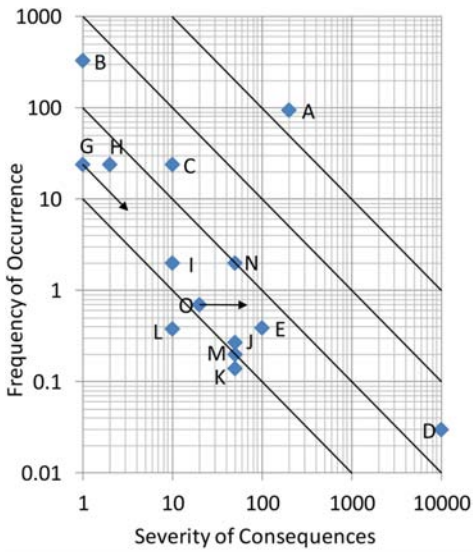

Figure 4. A log-log risk chart for Table IV. The arrows show that in the next few years risk G is expected to move down and to the right and risk O is expected to move to the right. The straight lines are iso-risk contours. This process uses log-log plots so that rare events can be tracked without distorting the risk analysis. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

possibilities, TEP will buy and operate backup generators and negotiate purchase agreements with other suppliers. TEP will plan controlled brownouts with load shedding. 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 extensive backup systems.

Risk: Feeder circuit disconnects from substation. *Mitigation Strategy:* TEP will use synchronized reclosers.

Risk: Western Power Grid fails (to other than terrorist activities). *Mitigation Strategy:* TEP will have backup generators and plans for controlled brownouts with load shedding.

Risk: Software failure. *Mitigation Strategy*: Every software module in the system shall have redundancy and built in self-test to help reduce the severity.

The range of magnitudes for Frequency of Occurrence and Severity of Consequences must be the same. In Table IV, the frequency of occurrence covers 4 orders of magnitude (from 10^{-15} to 10^{25}), and the severity of consequences also covers 4 orders of magnitude (from 10^0 to 10^4). Low-frequency high-severity risks, such as terrorist attacks and volcanic eruptions, are not included in these calculations.

The most interesting points of Table IV are plotted in Figure 4: (1) risk A, that the "solar panel output fluctuates by more than 60 MW in a 15-min interval," is the riskiest, (2) risk D, that the "Western Power Grid fails," is in the rare but severe corner, and (3) risk B, that a "feeder circuit disconnects from its substation," is in the common but benign corner. Therefore, our overall advice is to (1) apply risk mitigation to risk A, (2) keep an eye on risk D, and (3) ameliorate risk B. Although Risk B is not high risk, inexpensive mitigation would improve the overall reliability of the system. Now, please look back at the simple risk plot of Figure 1. Figures 1 and 4 agree except that risk F, "failure of DC to AC inverters," has been transferred from Table IV to a table for risks from the consumers' point of view.

6.1.1. Comparison with the Approach of Haimes

We will now compare these results with the approach of Haimes. We will consider only risk A:

Row 3 of Table IV, simplified

Failure Event	Consequences	Frequency of Occurrence	Severity of Consequences
Solar panel output fluctuates by more than 60 MW in a 15-min interval	A1 Breakers could trip and leave customers without electric power A2 Voltage on the grid could drop A3 Grid frequency could change A4 TEP would have to initiate a controlled brownout with load shedding	94.6	200

The domain experts have stated that when "solar panel output fluctuates by more than 60 MW in a 15-min interval," there are four important consequences: (A1) Breakers trip leaving customers without electric power, (A2) grid voltage drops, (A3) grid frequency changes, and (A4) blackouts. To show how Haimes computes the severity of consequences, we have created the following heuristic data:

The severity of consequence A1 has a probability density function with an expected value of 100 units of damage, where units could be dollars, thousands of dollars, millions of dollars, etc. The likelihood of consequence A1 occurring given that "solar panel output has fluctuated by more than 60 MW in a 15-min interval," is one fourth. These numbers give a risk value (product) of 25.

The severity of consequence A2 has a probability density function with an expected value of 200 units of damage. The likelihood of consequence A2 occurring given that "Solar panel output has fluctuated by more than 60 MW in a 15-min interval," is one half. These numbers give a risk value of 100.

The severity of consequence A3 has a probability density function with an expected value of 300 units of damage. The likelihood of consequence A3 occurring given that "solar panel output has fluctuated by more than 60 MW in a 15-min interval," is one fourth. These numbers give a risk value of 75.

The severity of consequence A4 has a probability density function with an expected value of 100,000 units of damage. The likelihood of consequence A4 occurring given that "solar panel output has fluctuated by more

Table V. The Biggest Operating Performance Risks from Table IV (Condensed), with the Addition of Linear Technique Data in Columns H, I, and J

	A	B	C	D	E	F	G	H	I	J
Row	Potential Failure Event	Consequences	Frequency of Occurrence, (events per year)	Severity of Consequences, range of 1 to 10^6	Estimated Risk	Risk Rank Order	Identification Tag	Severity, range of 1 to 10	Estimated Risk	Risk Rank Order
4				Log-log technique				Linear technique		
5	Terrorist Attack	Blackouts, chaos	0.01	10^6	10^4	2		10	0.10	11
6	Volcanic Eruption	Ash blocks sunlight	0.01	10^5	10^3	3		9	0.09	12
7	Solar power drops 60 MW in 15 minutes	Power production plummets	94.6	200	18,920	1	A	6	568	2
8	Feeder circuit disconnects from substation	Voltage gets out of phase with grid	330	1	330	4	B	3	990	1
9	Short to ground	Equipment is damaged	24	10	240	6	C	5	120	3
10	Western Power Grid fails	Western United States is without electric power	0.03	10^4	300	5	D	8	0.2	10
11	Lightning strikes system	Equipment is damaged	0.39	100	39	7	E	5	2.0	7
12	Grid voltage exceeds limits	Service suffers. PV systems trip off-line.	24	1	24	8	G	3	72	4
13	Transient local outages	PV systems shutdown	24	1	24	9	H	3	72	5
14	Dust accumulation	Generated power drops	2	10	20	10	I	5	10	6
15	Junction box fails	Generated power drops	0.27	50	14	11	J	4	1.1	8
16	Data acquisition system fails	Data cannot be read from the solar farm	0.14	50	7	12	K	4	0.6	9

With the addition of columns 8, 9, and 10 which were derived with a linear technique that estimates severity of consequences on a scale of 1–10. Estimated risk is defined as the product of frequency and severity.

than 60 MW in a 15-min interval," is 10^{-6}. These numbers give a risk value of 0.1.

These four consequences could be treated separately, or they could be fit with a probability density function. The expected value of the integral of this probability density function from zero to infinity yields a severity of consequences value of 200, which, by coincidence, is the same as in row four of Table IV. Haimes' approach would also add a comment such as: "You should also be aware that there is an unlikely occurrence (A4) that could be catastrophic."

The above section shows the mechanics for implementing Haimes' process for computing the severity of consequences. It shows that Bahill's process and Haimes' process could be compatible if there were sufficient data.

6.1.2. Normalization of Frequency and Severity

In this section, each cell of a table will be identified with {Table, Row, Column}. For example, the cell in Table VI, row 5, column DD will be identified as {VI, 5, DD}.

The linear technique, {V, all, C, H, I & J}. Let us now go back to the principle of normalizing frequency and severity so that they have the same range. First, we put the biggest risks from Table IV into cells {V, 7 to 16, A to G}. Then we introduced a new linear technique for computing severity. The severities {V, all, H} were assigned using a linear scale of 1 to 10 [DoD, 2006; Bahill and Smith, 2009; Haskins, 2011, Figs. 5–10]. This will be called the *linear technique*. The severities {V, all, H} were then multiplied by the frequencies {V, all, C} to estimate the risks presented in {V, all, I}. These estimated risks were used to compute the risk rank order in {V, all, J}.

Table VI. Correlation Coefficients between Frequency, Severity, and Risk Data of Table V

	AA	BB	CC	DD	EE
Row	Technique	Data Set	Range, orders of magnitude	Correlation Coefficient, r, for estimated risk versus frequency	Correlation Coefficient, r, for estimated risk versus severity
3					
4	Linear	10 failure events	frequency= 4 severity = 1	0.964	-0.21
5		12 failure events	frequency = 4.5 severity = 1	0.965	-0.30
6					
7	Log-log	10 failure events	frequency= 4 severity = 4	0.17	-0.08
8		12 failure events	frequency = 4.5 severity = 6	0.10	0.39

Correlation coefficients, linear technique, 10 failure events, {VI, 4, DD & EE}. Next, we used Excel to calculate the correlation coefficients (*r*) between frequency, severity and estimated risk. The results of applying Excel to the new linear technique data are shown in Table VI. Cell {VI, 4, DD} shows that for this linear technique the correlation coefficient, *r*, of estimated risk {V, all, I} and frequency {V, all, C} is 0.964: this is a large value, which means that frequency is dominating the estimated risk calculations. In contrast, estimated risk {V, all, I} versus severity {V, all, H} has an *r* of only –0.21 as shown in {VI, 4, EE}, which means that severity is having little effect on the estimated risk. This difference in influence on risk values is caused by the mismatch between the ranges of the frequency data (four orders of magnitude) and the severity data (one order of magnitude). *Frequency* has the larger range and *totally dominates* the calculation of risk.

Correlation coefficients, linear technique, 12 failure events, {VI, 5, DD}. In order to change the frequency and severity ranges, the frequency of occurrence for Terrorist Attacks and Volcanic Eruptions were assigned non-zero values and were put into {V, 5 & 6, all}. Column {V, all, C} now has a range of 4.5 orders of magnitude, but the linear technique for severity {V, all, H}, still has a range of one. Cell {VI, 5, DD} shows that the correlation coefficient of the linear technique estimated risk {V, all, I} versus frequency {V, all, C} is now 0.965, which is a large value indicating that once again *frequency dominates* the calculation of risk, because the frequency range is larger than the severity range.

Correlation coefficients, log-log technique, 10 failure events, {VI, 7, DD & EE}. In contrast, for the log-log severity technique and the original set of ten potential failure events, both the frequency data {V, all, C} and the severity data {V, all, D} have a range of four. Data in {VI, 7, DD} show that the correlation coefficient of estimated risk {V, all, E} versus frequency {V, all, C} is only 0.17: this is a small value, which means that now frequency is not dominating the estimated risk calculations. Furthermore, estimated risk {V, all, E} versus the log-log technique severity {V, all, D} has an *r* of only –0.08 {VI, 7, EE}, which means that severity is not dominating the estimated risk. These low correlation values, indicate that the estimated risk is a combination of frequency and severity and *neither one dominates*.

Correlation coefficients, log-log technique, 12 failure events, {VI, 8, DD & EE}. When frequencies for Terrorist Attacks and Volcanic Eruptions were added into {V, 5 & 6, all}, the range of the frequency data {V, all, C} became 4.5 orders of magnitude and the range of the log-log technique severity data {V, all, D} became six. The correlation coefficient of estimated risk {V, all, E} and frequency {V, all, C} decreased from 0.17 to 0.10 {VI, 7 & 8, DD}. The correlation coefficient of estimated risk {V, all, E} and severity {V, all, D} increased from –0.08 to 0.39 {VI, 7 & 8, EE}. The range for the log-log technique severity data has become larger than

Table VII. Environmental Risk for Incorporating Solar PV Subsystems into a Commercial Electric Power Grid

Failure Event	Consequences	Frequency of Occurrence	Severity of Consequences	Estimated Risk
More stringent siting requirements by city, county, and state zoning jurisdictions	Plans would become obsolete. Costs would increase. Obstructionist activities and lawsuits would delay the project.	2	100	200
Destruction of natural habitats	Strong opposition and lawsuits from environmental groups	1	20	20
Modification of animal migration paths	Migrating species might be affected. Loss of public support, project may require additional environmental studies.	0.2	30	15
Unsuspected hazards	Fines, lawsuits, loss of public confidence	0.1	150	15
Higher than expected disposal or recycling cost	Budget overrun, loss of profit	0.1	100	10

Estimated risk is defined as the product of frequency of occurrence and severity of consequences.

Table VIII. Project Management Risk for Incorporating Solar PV Subsystems into a Commercial Electric Power Grid

Failure Event	Consequences	Frequency of Occurrence in the TEP control area (events per year)	Severity of Consequences	Estimated Risk
Drastic human mistakes	Human fatalities. With 1500 employees, TEP has had no fatalities in the last 25 years of operation.	0.02	1,000,000	0×∞
Accidents	Injury to humans requiring medical attention	12	10,000	120,000
Project costs becomes higher than projected	The project may have to be delayed or cancelled.	1	1,000	1,000
Maintenance costs become higher than expected	Budget overrun, reduction of profits	0.5	1,000	500

Estimated risk uses Eq. (3), the product of frequency of occurrence and severity of consequences.

Table IX. Economic and Government Risk for Incorporating Solar PV Subsystems into a Commercial Electric Power Grid

Failure Event	Consequences	Frequency of Occurrence	Severity of Consequences	Estimated Risk
Economic				
Interest rates changes	NPV calculations may become invalid, may affect interest payment on floating rate loans, etc.	12	10	120
Government				
Carbon emission regulations are different than expected	TEP would need to revise their projections and alter their renewable energy acquisition plans	0.5	50	25
Early elimination of rebates	This would increase the net cost of distributed generation (DG) systems to the consumer and may jeopardize TEP's ability to meet the DG requirements.	1.2	100	120

Estimated risk is defined as the product of frequency of occurrence and severity of consequences.

Table X. Operating Performance Risks for a 20-MW Backup Quick-Start Natural-Gas Motor-Generator Set

Failure Event	Consequences	Frequency of Occurrence in the TEP control area (events per year)	Severity of Consequences	Estimated Risk	Identification Tag
Backup power generation is unavailable in a timely manner	Natural-gas motor-generator backup sets are complicated machines. They are designed to start up in less than ten minutes, but it could take an hour or two, causing load shedding.	2	200	400	P
Unforeseen MG unit outages	Backup generating capacity is inhibited. Given TEP's seasonal capacity requirements, this is only critical during summer months	1	200	200	Q
Grid frequency changes abruptly by more than 0.5 Hz.	This would harm the MG set.	0.2	300	60	R
MG set introduces transients on grid.	Big electric generators can be negatively affected by transients.	4	8	32	S
Software failure	Software failures are ubiquitous, but hard to diagnose, particularly when they involve interacting systems. Redundancy and built in self-test help reduce the severity.	0.4	70	28	T
System connects MG set out of phase with the grid.	The MG set could be damaged.	2	9	27	U
System connects MG set out of frequency with the grid.	The MG set would be damaged.	0.5	50	25	V
Human override of the control system causes the MG set to connect 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.	0.2	50	10	W
Lack of fuel	TEP would lose backup capability.	0.4	40	16	X
MG backup set hardware failure	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 brownout and load-shedding program.	0.2	10	2	Y
TEP's short-range weather prediction system fails.	A gas-turbine MG set requires ten minutes for startup. Therefore, TEP must have a system that will predict cloud cover ten minutes in advance. Otherwise, voltage on the grid could decline and the frequency of coal-fired generators could drop.	0.8	10	8	Z
These values were estimated by Terry Bahill, February 2010, based on Tom Hansen's data.					

These data are also plotted in Figure 5. Estimated risk is defined as the product of frequency of occurrence and severity of consequences.

the range for the frequency data and *severity is now more important than frequency*.

Is a linear correlation coefficient appropriate? {VI, 4, DD}. Excel's CORREL and PEARSON functions are the same. They return a value for r that indicates the goodness of a linear fit between two data sets. But what does r mean if the data sets are *not linearly* related? To answer this question, we fit exponential, linear, logarithmic, second-order polynomial and power law trend lines to the data sets. Different functions fit different data sets better or worse. For example, {VI, 4, DD} shows $r = 0.964$. The functions CORREL, PEARSON, RSQ and the linear trend line from the scatter chart all have

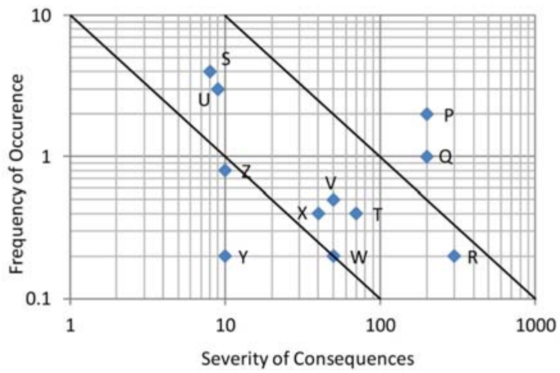

Figure 5. A log-log risk chart for the risks of Table X. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the exact same number (to fourteen decimal places). However, the power function trend line gave a better match with $r = 0.995$. Small differences like these were common. We used all five of the Excel functions to fit every combination of data sets that we were considering. Functions other than the linear function offered no improvements: investigating these other functions merely ensured that we were not trying to fit (for example) a sinusoid with a linear regression line.

Differences between the two techniques. Finally, the most important risks are different for the log-log and the linear techniques. The log-log severity technique {V, all, A to G} indicates that the most serious risks are (in order of importance): (1) Solar power drops 60 MW in 15 minutes, (2) Terrorist Attack, (3) Volcanic Eruption and (4) Feeder circuit disconnecting from the substation. Whereas, the linear severity technique {V, all, A to C & H to J} indicates that the most serious risks are (in order of importance): (1) Feeder circuit disconnecting from the substation, (2) Solar power drops 60 MW in 15 minutes, (3) Short to ground and (4) Grid voltage exceeds its ±5% limits. To quantify this mismatch we note that the correlation coefficient between the log-log estimated risk {V, all, E} and the linear estimated risk {V, all, I} is only 0.3: this is a small value. It seems that it is time to discuss these results with the customer.

Table XI. Safety Risks for a Backup Quick-Start Natural-Gas Motor-Generator Set

Failure Event	Consequences	Frequency of Occurrence in the TEP control area (events per year)	Severity of Consequences	Estimated Risk
Drastic mistakes	Human fatalities	0.0002	10^6	0×∞
Accidents	Injury to humans requiring medical attention	0.12	10^4	1200
Infrastructure damage from violent storms	TEP would be without backup for an extended period of time.	0.1	10	1

Estimated risk is defined as the product of frequency of occurrence and severity of consequences.

6.1.3. Other Risks

Table VII summarizes the environmental risks. These risks are related to the environment surrounding the system and affect various stakeholders (utility company, wildlife, humans, and the 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. In the complete study, Tables VII, VIII, and IX had dozens of rows.

Table VIII 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 IX summarizes economic and government risks. These risks are associated with 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.

To mitigate risk A of Table IV, unexpected demand peaks or decreases in power output; motor-generator (MG) sets are used as backup generators. The backup generators that are being considered for future PV projects produce 20 MW of power and have startup times of approximately 10 min. To further emphasize the hierarchical nature of risk analyses that was first presented in Section 3, we will now show the main results of a risk analysis performed on the motor-generator backup system. The risk analysis for a quick-start natural-gas motor-generator set, which is described in Tables X and XI, was conducted in the same manner as the risk analysis for the distribution grid with Solar PV systems; however, the severities for this table used the following scale:

Severity Description	Numeric values
Very High	1000
High	100
Medium	10
Low	1
Very Low	0.1
Minuscule	0.01

Because of the illustration in Table III, the range of magnitudes for Frequency of Occurrence and Severity of Consequences were made about the same. In Table X, the frequency of occurrence covers 2 orders of magnitude and the severity of consequences also covers 2 orders of magnitude.

Figure 5 shows that (1) risk A, "backup power generation is unavailable in a timely manner," is the riskiest failure event and mitigation efforts should be applied to it; (2) risk K, "grid frequency changes abruptly," is in the rare but severe corner, so we should keep an eye on it; and (3) risk H, "the system connects the MG set out of phase with the grid," is in the common but benign corner: It is not high risk, but inexpensive mitigation would improve the overall reliability of the system; a little money would go a long way.

Because a 20 MW natural-gas MG set would produce 1% of the total 2000 MW power generated, we multiplied the

Table XII. Risks That Have Already Been Addressed

Failure Event	Consequences	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	Homeowners could be electrocuted if they installed the systems themselves. 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 with their green incentives program
Electric companies refuse to buy electricity from homeowners	Homeowners would not benefit from net-metering on days when their power output is higher than their power consumption	Federal rules require electric companies to buy electricity from their consumers [IREC, 2009; Arizona Corporation Commission, 2008]	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

frequency of occurrence data of Table VIII by 1% for use in Table XI.

In addition to the previously described risks, some risks that we identified for the Solar PV system had already been mitigated. They are presented in Table XII. Discovering risks that have already been mitigated is very important because it validates the completeness of the search.

6.1.4. Identified Risks That Were Not Included

Failure of DC to AC inverters of the solar subsystems is the most common hardware failure. Data for failures of the DC to AC inverters were supplied by Mike Sheehan [personal communication]. In 2010 TEP had 3500 3-kW residential inverters connected to their grid. These inverters had typical product warranty periods of about 10 years. We assumed that manufacturers used percentile warranty $p_w = 50\%$ and that the underlying failure rate is an exponential distribution, $p_w = e^{-\lambda t}$. For $p_w = 0{:}5$ and a warranty period $t = 10$, $\lambda = 0.0693$. For 3500 inverters connected to the power grid, we can expect around 240 failures per year. When an inverter fails, the homeowner who owns it loses a part of his electric generating capacity and has to buy a new inverter. However, this failure produces only minor inconvenience to TEP. Table IV was constructed from the point of view of the utility company, not the homeowner. Therefore, risk F was removed from Table IV.

A recently discovered risk, that the installers install the solar panels wrong so that they are damaged or get appreciable shade, was also not included in Table IV. Acts of war such as cloud seeding and weather manipulation were considered but not included.

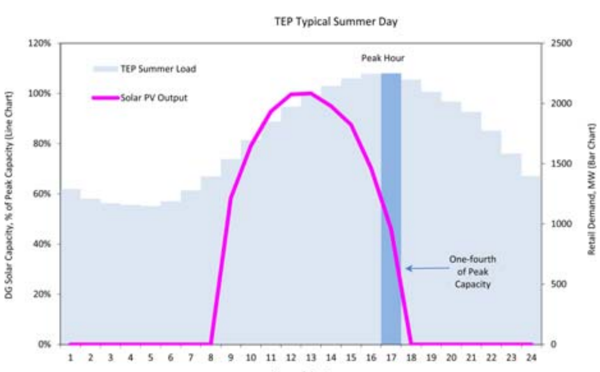

Figure 6. solar PV generating capacity and retail electric demand projected for a typical summer day in Tucson in 2025. The solar PV generating capacity peaks at 600 MW around noon and drops to 25% of its peak capacity by 5:30 PM (the dashed vertical line). These data are used in Tables XIII and XIV. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table XIII. TEP Power Projections for 2025

TEP Power Projections for 2025	Power, MW
Solar Nameplate Power Generating Capacity	600
Solar Power Generating Capacity at Noon	600
Solar Power Generating Capacity at 5 PM	150
Conventional Generating Capacity	2400
Peak Retail Load Obligations at Noon	2000
Peak Retail Load Obligations at 5 PM	2250
Planning Reserve	300

Table XIV. Planning Reserve and Cloud Cover

In 2025, will TEP be able to meet its load obligations under the worst conditions?						
Condition	Load obligation, MW	Planning reserve, MW	Necessary condition	Conventional generating capacity, MW	Solar generating capacity, MW	Equation satisfied?
5 PM, normal	2250	300	≤	2400	150	Yes
5 PM, total cloud coverage	2250	0	≤	2400	0	Yes
Noon, normal	2000	300	≤	2400	600	Yes
Noon, total cloud coverage	2000	0	≤	2400	0	Yes

Perhaps the greatest risk, uncontrollability of the electric grid, was not included. Each of the US electric power grids is a complex system that may be uncontrollable in itself. When many of these are networked together, the problems may become insurmountable. Farley [2004, p. 1] wrote that "mathematical modeling suggests that big blackouts are inevitable."

6.2. Sensitivity Analyses

Both approaches 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 approaches recommend mathematical sensitivity analyses [Hsu, Bahill, and Stark, 1976; Karnavas, Sanchez, and Bahill, 1993; Smith et al., 2008], as well as a qualitative analysis (a what-if analysis) by describing and exploring possible outcomes and consequences. The next section contains a what-if analysis for an electric power grid with Solar PV subsystems.

6.2.1. What-If Analysis

6.2.1.1. Early Elimination of Rebates. Early elimination of rebates would reduce customer incentives to install solar-powered electric generating systems.

6.2.1.2. Cloudy Days. Weather is the most uncontrollable factor for a PV subsystem. 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) when the system load peaked? There are two important factors to consider: First, TEP peak summer loads typically occur in the late afternoon, around 5 PM, and second, during these late afternoon hours, output from PV panels has fallen to one-fourth of their peak output, as shown in Figure 6.

In order to meet the Renewable Energy Standard, TEP predicts that by 2025 its system will have about 600 MW of utility-scale renewable-generating capacity. Assuming that this is all Solar PV subsystems, this would produce 600 MW at noon and 150 MW at 5 PM.

Tables XIII and XIV show that TEP can meet is load obligations under the worst weather conditions (zero solar power output) during peak summer loads. The first row of Table XIII is used to compute the needed conventional generating capacity. It states that the peak load in the summer at 5 PM plus the planning reserve must be less than or equal to the conventional generating capacity plus the solar generating capacity. The other rows show that the total load can be met at the other significant conditions.

6.2.1.3. Hardware Reliability. Another significant source of risk is failure of the electric generators. Electric generators (renewable or nonrenewable) 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 backup 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 and/or call on sharing reserves. In most cases, when generating units trip offline, TEP is able to call on backup capacity from the Southwest Reserve Sharing Group, which enables TEP to rely on regional utilities for backup capacity for 1 h or less. TEP then uses a combination of its own units (if available) and market resources to replace the needed capacity for the next dispatch hour.

6.2.1.4. Economic Factors. There are also economic factors that could affect the PV penetration on TEP's system. For example, if the cost of solar subsystems suddenly dropped, then more homeowners might buy solar photovoltaic panel systems. If a large number of households bought solar subsystems and put them on their houses, then, during the day, customers would reduce their dependence on electricity supplied by TEP. If this happened throughout the city of Tucson, it could affect TEP's bottom line. TEP would have underutilized capacity during the day, since they would not be selling as much electricity to residential customers, and thus their revenues would drop. TEP is obligated to provide generating capacity to meet demand during nighttime, during the afternoon (low PV output and high demand hours), and during cloudy days. Additionally, if all of these residential PV systems were grid-tied and customers were taking advantage of net-metering, then during sunny days, TEP will be required to buy all the excess electricity produced by residential customers. As a result, TEP could lose money from decreased revenues and increased net-metering costs. Consequently, TEP could substantially reduce net-metering payments, eliminating one of the incentives for residential customers to acquire PV systems in the first place. This is a negative feedback system with a long time delay (a potentially unstable system).

6.2.2. Analytic Sensitivity Analyses

You should perform a sensitivity analysis anytime you create a model, write a set of requirements, design a system, make a decision, plan a tradeoff study, search for cost drivers or engineer a risk analysis [Smith et al. 2008]. A sensitivity analysis of risk analyses is simple and it can be done in general terms. In this TEP risk analysis case study, our problem statement was, "In a risk analysis, what parameters can change the rank order of the most important risks?"

To be general, we will use the definition of risk given in Eq. (4) where the frequency and severity have weights of importance as exponents. Estimated risk (R) equals frequency of occurrence (F) raised to the power of weight of importance of frequency (w_F) times severity of consequences (S) raised to the power of weight of importance of severity (w_S), like this, $R = F^{w_F} \times S^{w_S}$. In economics, this functional form is called the Cobb-Douglas production function. The first step is to derive the partial derivatives.

$$\frac{\partial R}{\partial F} = S^{w_S} w_F F^{w_F - 1} = S^{w_S} F^{w_F} \frac{w_F}{F} = R \frac{w_F}{F}$$

$$\frac{\partial R}{\partial S} = w_S S^{w_S - 1} F^{w_F} = F^{w_F} S^{w_S} \frac{w_S}{S} = R \frac{w_S}{S}$$

$$\frac{\partial R}{\partial w_F} = S^{w_S} F^{w_F} \ln F = R \ln F$$

$$\frac{\partial R}{\partial w_S} = F^{w_F} S^{w_S} \ln S = R \ln S$$

Now the partial derivatives will be multiplied by the normal values of the parameters to get the semirelative sensitivity functions [Smith et al. 2008]. The $|_{NOP}$ symbol means evaluated at the Normal Operating Point.

$$\tilde{S}_F^R = \frac{\partial R}{\partial F} F_0 \big|_{\text{NOP}} = R_0 w_{F_0}$$

$$\tilde{S}_S^R = \frac{\partial R}{\partial S} S_0 \big|_{\text{NOP}} = R_0 w_{S_0}$$

$$\tilde{S}_{w_F}^R = \frac{\partial R}{\partial x} w_{F_0} \big|_{\text{NOP}} = R_0 w_{F_0} \ln F$$

$$\tilde{S}_{w_S}^R = \frac{\partial R}{\partial w_S} w_{S_0} \big|_{\text{NOP}} = R_0 w_{S_0} \ln S$$

Note that in the above equations $\tilde{S}_{w_S}^R$ is the semirelative sensitivity function of R with respect to w_S, whereas S (*without the tilde*) is the severity of the consequences. Let F, S, R, w_F and $w_S \geq 1$. Which data set (F or S) is most important? If $w_{F_0} > w_{S_0}$ then $\tilde{S}_F^R > \tilde{S}_S^R$. This is simply a restatement that the data set with the bigger weight (bigger data range) is more important.

Next, Which individual potential failure events give rise to the greatest risks? If the weights of importance are the same, then the potential failure events with the largest sensitivity values create the greatest risks, because the sensitivities are determined by the values of R_0, as shown in the above equations. This means that we should spend extra time and effort estimating the frequency and severity of the highest ranked risks, which seems eminently sensible. Of the potential failure events in Table IV for which data could be collected, the most important are "Solar power drops 60 MW in 15 minutes" and "Feeder circuit disconnects from substation." TEP already has good data for the former (several databases with a data set every 15 minutes for years). Therefore, they should spend more time and resources getting better data for the Feeder circuit failure event.

6.3. Risk Management

Risk analysis is not an isolated step that should be conducted in order to understand the risks associated with the system. Instead, risk analysis should be an integral iterative process that is accompanied by a risk management initiative. After most of the risks inherent in a system have been identified, several risk management or risk mitigation strategies may be implemented to improve the system. The following section describes some risk management strategies that have already been implemented for electric power grids with Solar PV subsystems and suggests additional alternatives.

6.3.1. Variations in Power Demand and Power Output

Electric power demand varies significantly. 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 backup quick-start combustion turbines as possible mitigation strategies [Sheehan 2009].

Additionally, electric power output also varies. TEP will create computer models to predict the output of wind and solar systems [GE Energy, 2010]. Forecasts will be needed annually, monthly, daily, and on a minute-by-minute basis. Annual and monthly forecasts will help with load planning, daily forecasts will help handle the mismatch between peak solar output at noon and peak customer demand at 5 PM, and the minute-by-minute forecasts will allow nonspinning offline natural-gas motor-generator sets the opportunity to start up in response to rapidly incoming storms.

To accommodate changes in power demand and output power, TEP will revise their backup capacity and operating reserve policies. The possibility of designing curtailment options 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 should reduce output variations and mitigate 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.

TEP will create demand-forecasting models, power output models, and real-time weather-forecasting models in order to identify risky dispatch scenarios that might require higher levels of backup generating capacity. 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 US Department of Energy [2010] is writing a Solar Energy Development Programmatic Environmental Impact Statement to analyze the environmental impact that solar projects might have and to develop and implement programs that would facilitate responsible solar energy development. All projects will 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). They are conducted to ensure that the project's environmental impact is below acceptable levels. Once the Department of Energy develops solar-specific environmental guidelines, the risks associated with developing solar farms in open land will be reduced, because there will be known requirements that must be met.

What is the carbon footprint for incorporating solar photovoltaic subsystems into a commercial electric power grid? No carbon emissions are produced during solar photovoltaic electric generation; however, the solar panel manufacturing process might not be a zero-emissions process. We were concerned that the whole manufacturing, installing, and operating process could have a net positive carbon footprint; however, this is not the case. A study conducted by the Solar Hydrogen Education Program [Mason, 2004] found that the Springerville Solar Generating Station reduced the carbon footprint by 36 tons of CO_2 per kW DC installed. Thus, this Station produces 91% less carbon than a comparable fossil fuel powered plant. Additionally, the total energy used to manufacture the hardware of the Springerville Solar Generating Station was 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 [Moore et al., 2010]. According to the United Kingdom's Parliamentary Office of Science and Technology [2006], the carbon footprint of solar panel manufacturing is expected to be reduced with the development of thin film technologies and the implementation of new, less energy intensive, semiconductor materials. Therefore, incorporating solar photovoltaic systems into a commercial electric power grid will contribute to *global cooling*.

Many technologies are available to simplify project planning and help 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, GIS may be used to identify solar-feasible greyfields[2] and convenient installation sites such as the roofs of buildings [Chaves and Bahill, 2010] 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 mitigation strategy includes constructing utility-scale projects on greyfields such as reclaimed landfills and previous mining sites.

6.3.3. Financial Risks

Solar energy is currently in 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, in order to use these funds to promote the use of renewable energy. Revenues generated by these tariffs are passed on to customers who incorporate renewable-energy solutions in 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, there is a cap on the rate that 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 1, 2013 (TEP 2009 Annual Report). Therefore, this is not a viable risk management alternative for mitigating the higher power costs from renewable energy sources.

When the Springerville Solar Generating Station was built, there were no federal incentives or rebates to help subsidize the project, and TEP does not now have federal incentives that can be used to lower the investment cost of a solar farm. Therefore, TEP uses another alternative for mitigating financial costs: It creates special purpose entities (SPEs) to develop and own the solar farms and develop lease agreements with them. An 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 that are not related to TEP and therefore may qualify for federal or state rebates that are not available to TEP. This may help reduce the investment cost and would reduce the electric generation cost for this facility.

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 in interest rate swaps, they swap floating debt for fixed rate debt (or vice versa) in order to either exploit their com-

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

petitive advantage in the fixed or floating rate market, or reduce their exposure to interest rate risk.

6.4. Unintended Consequences

Implementing new systems, strategies, laws, or controls often has unintended negative or positive consequences. Therefore, it is important that early in the system lifecycle the designers 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 [Bahill, 2012].

Connecting a Solar PV system to an electric power grid could cause problems for the grid. For example, presume that an illumination-controlled building is in the state of Selling AC Electricity, when clouds suddenly cover the sun. The voltage generated by the solar panels will drop as will the illumination in the building. Sensors will sense this drop in illumination and will command the lights to produce more illuminance. The lights will draw more power from the source. This will produce a bigger voltage drop across the source internal impedance, which will further drop the operating voltage. This is a *positive* feedback loop that could cause the grid to become unstable. A second problem with clouds blocking the sun is that the PV system would soon deplete its small local energy store and would switch to the Buying AC Electricity state. This would increase the operating voltage. This is a negative feedback loop, but it contains a significant time delay. Time delays make systems susceptible to instabilities. Therefore, utility companies should create 1-s scale simulations of the interactions between these systems in order to investigate potential instabilities [Bahill, 2010].

A third problem with clouds blocking the sun is that, if the voltage of the electric power grid falls out of its ±5% limits, then most of the local solar PV subsystems will isolate themselves from the grid. This will further decrease the grid voltage. This is a positive feedback loop. Positive feedback loops can make a system unstable.

Incorporating solar photovoltaic subsystems into a commercial electric power grid has another interesting possible unintended consequence. Solar panels do two things: They absorb solar energy and transform it into electricity, and they also reflect solar energy back into the atmosphere. Both of these actions reduce the solar energy that hits the ground and is absorbed by the Earth. Therefore, solar panels have unintended consequences of reducing the amount of energy absorbed by the Earth and therefore contribute to *global cooling*.

Solar panel systems are in positive feedback control loops and negative feedback control loops with large time delays. Both of these could cause instability on the grid. Bahill [2012] has listed other unintended consequences of installing solar panels into a commercial electric power grid.

7. SUMMARY

Both approaches use quantitative data: these data range from estimates by experts to statistical databases that are expensive to develop and maintain. Bahill's published examples lean toward the former: while Haimes' published examples lean toward the latter. In particular, Haimes' PMRM method requires a significant amount of data about the probability-damage relationship. Bahill's approach focuses on analyzing and understanding the risks, whereas Haimes' approach is oriented towards risk management. In addition, the approaches differ in the quantification of risk. Bahill uses the frequency of occurrence of the risky event times the severity of consequences, while Haimes computes the probability density function for the severity of consequences. According to Haimes, the probability of the severity of consequences can be assessed well, based on historical and technical records, and is more informative and representative. Both approaches will work on existing systems as well as on new systems being designed. However, Haimes' approach was optimized for existing systems, where abundant statistical data either exist or can be collected. In contrast, Bahill's approach was designed to be an integral part of the system design process, although, in this paper, it is being applied to an existing system. So what should a system developer do? If the developer is limited to only one approach and the developer has sufficient budget and data, then the preferred approach might be the Haimes approach.

This comparison of the two risk analysis approaches suggests two important points. The first is that the frequency and severity scales must be normalized in order to give equal weight to both factors [Bahill and Smith, 2009]. The second is to beware of the problems of extreme events and to avoid basing conclusions about them *exclusively* on the expected value of risk, because this would give equal weight to events with high frequency of occurrence and low severity and events with low frequency of occurrence and high severity [Haimes, 2009].

Regarding this whole Solar PV system risk analysis, the risk of clouds blocking the sun and introducing output variability is the biggest risk. Additionally, as Solar PV becomes a larger component of an electric company's energy portfolio, it is important to revise the backup capacity policies and consider alternative storage methods in order to reduce the risk of reduced power output during periods with high demand. For TEP to meet the Arizona Corporation Commission's requirements, rebates and federal tax incentives must remain.

After conducting a 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 power shortages. Based on how much Solar PV energy TEP has, it may be important to develop and implement state-of-the-art, 1-min-scale weather forecasting, which combined with their current demand forecasting methods, will help them identify risky scenarios and act appropriately. Utility companies should also create 1-s-scale simulations of the interactions between customer PV subsystems and the electric power grid in order to investigate potential instabilities.

The risk analysis approaches discussed in this paper have some common weaknesses. (1) Publishing the results of a risk analysis (both internally and externally) in a timely manner is a vital part of risk analysis. However, the publication cycle is slow, but policies and data change rapidly. For example, by the end of 2012 TEP phased out rebates for PV systems and the Department of the Interior gave fast-track approval for PV sites in six Western states (http://solareis.anl.gov/documents/index.cfm). These changes could not be included in this paper. (2) It is hard to get time. In the beginning of a risk analysis, the risk analyst (RA) needs time with the domain experts to identify and quantify the risks. Near the end, the RA needs time with the decision makers to explain the risk analysis. It is hard to schedule such time. RAs don't have the clout. (3) It is hard to get relevant data. An RA cannot just, for example, get on the Internet and ask for data concerning "Solar panel output fluctuates by more than 60 MW in a 15-min interval due to clouds, thunderstorms, etc." However, if the RA is willing to change his/her design to match what is available on the Internet, then a googolplex of data are available. (4) Data that the RA does get are usually fraught with uncertainty, mistakes, estimated probabilities, and human mental biases.

In a risk assessment, the RA could spend more and more time and money getting better and better data, but that would not make the risk recommendations more precise. Haimes and Chittester [2005, p. 6] drew an analogy to the Heisenberg Uncertainty Principle, which states that a person cannot simultaneously measure the position and the velocity of a particle with high precision. Then they a expanded this analogy with, "recall Einstein's statement: 'So far as the theorems of mathematics are about reality, they are not certain; so far as they are certain, they are not about reality.' Adapting Einstein's metaphor to risk assessment and management translates into: 'To the extent risk assessment is precise, it is not real; to the extent risk assessment is real, it is not precise.'"

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REFERENCES

A.B. Agrawal, K. Barker, and Y.Y. Haimes, Adaptive multiplayer approach for risk-based decision-making: 2006 Virginia gubernatorial inauguration, Syst Eng 14(4) (2011), 455–470.

A. Arnauld and P. Nicole, Logic, or, the art of thinking: Containing, besides common rules, several new observations appropriate for forming judgment (1st edition, 1662; 5th edition, 1683), translated from French by J.V. Buroker, Cambridge University Press, Cambridge, 1996.

Arizona Corporation Commission, Rulemaking regarding net metering, Phoenix 2008, http://images.edocket.azcc.gov/docketpdf/0000089952.pdf, accessed August 2, 2011.

E. Asbeck and Y.Y. Haimes, The Partitioned Multiobjective Risk Method (PMRM), Large Scale Syst Theory Appl 6(1) (1984), 13–38.

A.T. Bahill, Design and testing of an illuminance management system, ITEA J 31(1) (2010), 63–89.

A.T. Bahill, Diogenes, a process for finding unintended consequences, Syst Eng 15(3) (2012) 287–306.

A.T. Bahill and F.F. Dean, "Discovering system requirements," in A.P. Sage and W.B. Rouse (Editors), Handbook of Systems Engineering and Management, Wiley, 1st edition, 1999, pp. 175–220, 2nd edition, 2009, pp. 205–266.

A.T. Bahill and W.J. Karnavas, Risk analysis of a Pinewood Derby: A case study, Syst Eng 3(3) (2000), 143–155.

A.T. Bahill and E.D. Smith, An industry standard risk analysis technique, Eng Management J 21(4) (2009), 16–29.

A.T. Bahill, R. Botta, and J. Daniels, The Zachman framework populated with baseball models, J Enterprise Architecture 2(4) (2006), 50–68.

A.T. Bahill, F. Szidarovszky, R. Botta, and E.D. Smith, Valid models require defined levels, Int J Gen Syst 37(5) (2008), 533–571.

J. Ben-Asher, Development program risk assessment based on utility theory, Proc 16th Annu Int Symp INCOSE, Key Reserve #8, 2006.

R. Botta and A.T. Bahill, A prioritization process, Eng Management J 19(4) (2007), 20–27.

B.G. Buchanan and E.H. Shortliffe, Rule-based expert systems: The MYCIN experiments of the Stanford Heuristic Programming Project, Addison-Wesley, Reading, MA, 1984.

T.A. Carbone and D.D. Tippett, Project risk management using the project risk FMEA, Eng Management J 16(4) (2004), 28–35.

A. Chaves and A.T. Bahill, Locating Sites for Solar photovoltaic Panels, ArcUser (2010), 25-27, http://www.esri.com/news/arcuser/1010/files/solarsiting.pdf, accessed August 2, 2011.

CMMi, Risk Management (RSKM), Software-Quality-Assurance, San Francisco, 2012. http://www.software-quality-assurance.org/cmmi-risk-management.html#sp1.2.

J.A. Cooper, Soft mathematical aggregation in safety assessment and decision analysis, Proc 17th Int Syst Safety Conf, Orlando, FL, August 16–21, 1999.

J. Daniels, P.W. Werner, and A.T. Bahill, Quantitative methods for tradeoff analyses, Syst Eng 4(3) (2001), 190–212 [correction 8(1) (2005), 93].

DoD, Risk management guide for DoD acquisition, 6th edition, US Department of Defense, Washington, DC, 2006, https://acc.dau.mil/CommunityBrowser.aspx?id=17757.

DSMC, DSMC risk management guide for DoD acquisition, 4th edition, Fort Belvoir, VA, 2001, http://www.mitre.org/work/sepo/toolkits/risk/references/files/DSMC_RiskMgmt_Guide.pdf.

P. Farley, The unruly power grid, IEEE Spectrum 41(8) (2004), 22–27, http://spectrum.ieee.org/energy/the-smarter-grid/the-unruly-power-grid/0.

FDA, Guidance for Industry, Q9 Quality Risk Management, US Department of Health and Human Services, Food and Drug Administration, 2006, www.fda.gov/downloads/Drugs/GuidanceComplianceRegulatoryInformation/Guidances/ucm073511.pdf.

GE Energy, Western wind and solar integration study (2010), National Renewable Energy Laboratory, Golden, CO, May 29, 2010, http://www.nrel.gov/wind/systemsintegration/pdfs/2010/wwsis_final_report.pdf.

G. Gigerenzer, Reckoning the risk, Penguin Books, New York, 2002.

Y.Y. Haimes, Hierarchical holographic modeling, IEEE Trans Syst Man Cybernet 11(9) (1981), 606–617.

Y.Y. Haimes, Risk modeling, assessment, and management, 3rd edition, Wiley, Hoboken, NJ, 2009.

Y.Y. Haimes, Modeling complex systems of systems with phantom system models, Syst Eng 15(3) (2012), 333–346.

Y.Y. Haimes and C.G. Chittester, A roadmap for quantifying the efficacy of risk management of information security and interdependent SCADA systems, J Homeland Security Emergency Management 2(2) (2005), Article 12.

Y.Y. Haimes, S. Kaplan, and J.H. Lambert, Risk filtering, ranking, management framework, Risk Anal 22(2) (2002), 383–297.

M.H. Henry and Y.Y. Haimes, A comprehensive network security risk model for process, Risk Anal 29(2) (2009), 223–248.

F.K. Hsu, A.T. Bahill, and L. Stark, Parametric sensitivity of a homeomorphic model for saccadic and vergence eye movements, Comput Prog Biomed 6 (1976), 108–116.

INCOSE, Systems engineering handbook, v. 3.2.2, Seattle, WA, 2011.

IREC net metering model rules, Latham, NY, 2009, http://irecusa.org/category/newsletters/connecting-to-the-grid-newsletter/.

IRM, A risk management standard, Institute of Risk Management, London, UK, 2002, http://www.theirm.org/publications/PUstandard.html.

S. Kaplan, Y.Y. Haimes, and B.J. Garrick, Fitting hierarchical holographic modeling (HHM) into the theory of scenario structuring and a refinement to the quantitative definition of risk, Risk Anal 21(5) (2001), 807–819.

W.J. Karnavas, P. Sanchez, and A.T. Bahill, Sensitivity analyses of continuous and discrete systems in the time and frequency domains, IEEE Trans Syst Man Cybernet SMC-23(2) (1993), 488–501.

H. Kerzner, Project management: A systems approach to planning, scheduling and controlling, eighth edition, Wiley, Hoboken, NJ, 2002.

J. Mason, Life cycle analysis of a field grid-connected, multi-crystalline PV plant: A case study of Tucson Electric Power's Springerville PV Plant, Solar Hydrogen Education Project, Farmingdale, NY, November 5, 2004.

L. Moore, H. Post, T. Hansen, and T. Mysak, Photovoltaic power plan experience at Tucson Electric Power, February 16, 2010, Available at http://www.greenwatts.com/Docs/TEPSolar.pdf, accessed August 22, 2010.

J. Reyes Santos and Y.Y. Haimes, Applying the partitioned multiobjective risk method, Risk Anal 24(3) (2002), 697–713.

Parliamentary Office of Science and Technology, Carbon footprint of electricity generation: 1-4, Postnote, London, October 2006.

D. Richerson-Smith, Energy efficiency and renewable programs, Tucson Electric Power, Tucson, AZ, March 23, 2010, http://www.tep.com/Company/News/Richerson-SmithEE&Renewables-Workshop2.pdf, accessed August 22, 2010.

M. Sheehan, Renewable resources, Tucson Electric Power, Tucson, AZ, October 22, 2009.

E.D. Smith, W.T. Siefert, and D. Drain, Risk matrix input data biases, Syst Eng 12(4) (2009), 344–360.

E.D. Smith, F. Szidarovszky, W.J. Karnavas, and A.T. Bahill, Sensitivity analysis, a powerful system validation technique, Open Cybernet Systemics J 2 (2008), 39–56, http://www.bentham.org/open/tocsj/openaccess2.htm, accessed August 2, 2011.

US Department of Energy, Solar Energy Development Programmatic Environmental Impact Statement, Washington, DC, http://solareis.anl.gov/about/index.cfm, accessed August 22, 2010.

H.H. Willis, A.R. Morral, T.K. Kelly, and J.M. Jamison. Estimating terrorism risk, Rand, Santa Monica, CA, 2005, http://www.rand.org/pubs/monographs/MG388.html.

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