RISK SPEND EFFICIENCY ASSESSMENT

DELIVERABLE 2.1: IOU BASELINE ASSESSMENT

Version History

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Approvals

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2. Introduction.

2.1. Project Background.

The California Public Utilities Commission (CPUC) regulates services and Investor-Owned Utilities (IOUs), protects consumers, safeguards the environment, and assures Californians' access to safe and reliable utility infrastructure and services. Within the CPUC, the Safety Policy Division (SPD) works with the Safety & Enforcement Division (SED) and other divisions to analyze, develop, recommend, and implement safety policy.

The purpose of this contract is to evaluate California electric and natural gas IOU Risk Spend Efficiency (RSE) modeling and assumptions to assess whether they maximize the effectiveness of safety investments while minimizing ratepayer impacts. Level 4 is tasked to determine the effectiveness of the use of RSE in the IOUs' safety mitigation proposals related to their General Rate Case (GRC) applications, Risk Assessment Mitigation Phase (RAMP) applications, and annual Wildfire Mitigation Plans (WMPs).

One may think of the RSE framework as a consolidated financial statement for risk, or a consolidated risk statement. The cost of risk mitigation can be thought of as investment and the amount of risk reduction as Return On that Investment (ROI). However, where a consolidated financial statement only requires standard accounting, a consolidated risk statement requires three forms of accounting:

1. Accounting for the costs of mitigation using arithmetic.
2. Accounting for the uncertainty of both risk events and consequences using the arithmetic of uncertainty.
3. Accounting for stakeholder preferences and risk attitudes using decision analysis.

We believe that by drawing on best practices in other industries, each of these areas of accounting can be improved and simplified within the current RSE framework.

In the Settlement Agreement [S-MAP 2018, 2020], the CPUC, California's four investor-owned utilities, and several intervenor organizations agreed to an RDF for assessing and managing risks and investments to mitigate those risks. This Safety Model Assessment Proceeding (S-MAP) framework specifies the use of a Multi-Attribute Value Function (MAVF) as a method to combine multiple objectives (attributes) into a single metric to quantify the Consequences of a Risk Event (CoRE).

Key elements of the MAVF [S-MAP, 2020] are:

- An **attribute hierarchy**, with primary attributes that may each be composed of sub-attributes.
- The bottom level attributes must be **observable** with a range **in natural units** (or a measurable proxy attribute).
- **Weights** for each attribute, based on their range from best to worst, to combine them into a single consequence score for each outcome of a risk event.
- **A scaling function** for each attribute, which may be linear or nonlinear, that converts from its natural units to scaled units from 0 to 100 (Appendix A, pages A-5).

Appendix C on the Arithmetic of Uncertainty describes five concepts that must be added to standard arithmetic to validly model risk. These are not fully addressed by the Settlement Agreement. As a result, in comparing the risk models of the Investor IOUs, it must be noted that even strict adherence to the Agreement can lead to logical absurdities.

For instance, for proper aggregation of risk, the interrelationships between risks and mitigations must be captured as described in Appendix C. Also, the aggregation of risk scores with nonlinear scaling may be invalid as described in Appendix D, where we show a numerical example in which a 100% chance of ten fatalities has the same MAVF score as a 10% chance of ten fatalities. The good news is that because the IOUs are already using Monte Carlo simulation, it may be possible to apply their output to techniques such as Scenario Optimization[1], which has been employed in the insurance and finance industries to solve similar problems. In fact, these techniques, pioneered four decades ago, have more recently been applied to portfolios of projects ranging from Pharmaceuticals to Petroleum Exploration [Sharpe, 1998; and Savage, 2006]. These would be ideal tools in finding optimal portfolios of mitigation in the sense of Risk/Spend Efficiency.

The remaining chapters of this report will dive deeper into this area, beginning with an overview of the current approaches to RSE used by the IOUs.

[1] Dembo R. Scenario Optimization. Annals of Operations Research 1991 30: 63-80.

3. IOU Approaches to Risk Spend Efficiency.

We will begin with a general description of how each of the IOUs approaches RSE, with the intention of defining the current, baseline situation. This chapter applies to all risk areas, including wildfires and climate change. Subsequent chapters will then expand on this discussion in the areas of MAVF, wildfires, climate change, and Public Safety Power Shutoffs (PSPS).

3.1. General IOU Approach to Risk Spend Efficiency.

In this section we will address the following aspects of the IOU RSE approach:

- Ramp structure.
- Risk selection.
- Risk models.

3.1.1. Ramp structure.

The IOUs all have similar RAMP structures as outlined in Table 1, based on the IOUs' RAMP briefings. Because San Diego Gas & Electric (SDG&E) and SoCalGas are both part of the Sempra family, many of their procedures are the same. In this section we include the risks selected by each of the IOUs for inclusion in their RAMP. We will address the remaining areas in the Risk Model section.

Table 1: IOU ramp structures.

	SDG&E/SoCalGas	PG&E[2]	SCE[3]
Risk Selection	Risks are stored in Enterprise Risk Register (ERR). They are ranked and compared to the previous year.	Risks are stored in ERR. They are ranked and compared to the previous year.	Top-down evaluation of major safety impacts, then bottom-up ranking of the ERR.
MAVF Attributes	Safety, reliability, financial, and shareholder satisfaction.	Safety, electric reliability, gas reliability, and financial.	Serious injuries, fatalities, reliability, and financial.
MAVF Scaling	Linear for all attributes.	Convex for safety and cost, linear for reliability attributes.	Concave for all attributes.

[2] Pacific Gas & Electric.

[3] Southern California Edison.

	SDG&E/SoCalGas	PG&E[2]	SCE[3]
Risk Spend Efficiency	(Risk Reduction x Discounted Time)/Total Cost.	Measured per year, summed across tranches. Incorporates severe outcomes.	(Baseline MARS[4]-Post MARS)/Expenditure.
Horizontal Factors	Mitigation factors impacting multiple ramp risks.	Risk factors that drive multiple RAMP risks.	Mitigations with combined Impact.

3.1.2. Risk selection.

The risks selected for the RAMP are addressed in separate chapters of the RAMP filing, as summarized in Table 2, Table 3, Table 4. And Table 5. As per the Settlement Agreement, there is a year-over-year comparison of the lists to highlight changes in risk priorities.

Table 2: SoCalGas RAMP risk chapters.

Chapter	Title
SCG-Risk-1.	Incident Related to the High-Pressure System (Excluding Dig-in).
SCG-Risk-2.	Excavation Damage (Dig-in) on the Gas System.
SCG-Risk-3.	Incident Related to the Medium Pressure System (Excluding Dig-in).
SCG-Risk-4.	Incident Related to the Storage System (Excluding Dig-in).
SCG-Risk-5.	Incident Involving an Employee.
SCG-Risk-6.	Cybersecurity.
SCG-Risk-7.	Incident Involving a Contractor.

Table 3: SDG&E RAMP risk chapters.

Chapter	Title
SDG&E-Risk-1.	Wildfire Involving SDG&E Equipment.
SDG&E-Risk-2.	Electric Infrastructure Integrity.
SDG&E-Risk-3.	Incident Related to the High-Pressure System (Excluding Dig-in).
SDG&E-Risk-4.	Incident Involving a Contractor.
SDG&E-Risk-5.	Customer and Public Safety – Contact with Electric Equipment.
SDG&E-Risk-6/SCG-Risk-6.	Cybersecurity.
SDG&E-Risk-7.	Excavation Damage (Dig-In) on the Gas System.
SDG&E-Risk-8.	Incident Involving an Employee.
SDG&E-Risk-9.	Incident Related to the Medium Pressure System (Excluding Dig-in).

Table 4: PG&E RAMP risk chapters.

Chapter	Title
Chapter 7.	Risk Assessment and Mitigation Phase Risk Mitigation Plan: Loss of Containment In Gas Transmission Pipeline.
Chapter 8.	Risk Assessment and Mitigation Phase Risk Mitigation Plan: Loss of Containment on Gas Distribution Main or Service.
Chapter 9.	Risk Mitigation Plan: Large Overpressure Event Downstream of Gas Measurement and Control Facility.

[4] Mitigation Action Risk Spend.

Chapter	Title
Chapter 10.	Risk Mitigation Plan: Wildfire.
Chapter 11.	Risk Mitigation Plan: Failure of Electric Distribution Overhead Assets.
Chapter 12.	Risk Mitigation Plan: Failure of Electric Distribution Network Assets.
Chapter 13.	Risk Mitigation Plan: Large Uncontrolled Water Release.
Chapter 14.	Risk Mitigation Plan: Real Estate and Facilities Failure.
Chapter 15.	Risk Mitigation Plan: Third-Party Safety Incident.
Chapter 16.	Risk Mitigation Plan: Employee Safety Incident.
Chapter 17.	Risk Mitigation Plan: Contractor Safety Incident.
Chapter 18.	Risk Mitigation Plan: Motor Vehicle Safety Incident.

Table 5: SCE RAMP risk chapters.

Chapter	Title
Chapter 3.	Safety Culture & Compensation Policies tied to Safety.
Chapter 4.	Building Safety.
Chapter 5.	Contact with Energized Equipment.
Chapter 6.	Cyberattack.
Chapter 7.	Employee, Contractor & Public Safety.
Chapter 8.	Hydro Asset Safety.
Chapter 9.	Physical Security.
Chapter 10.	Wildfire.
Chapter 11.	Underground Equipment Failure.
Chapter 12.	Climate Change.

Because the different IOUs are responsible for different types of assets operating in different environments, it is not surprising that they do not have identical Risk Chapters in their RAMP filings. However, when IOUs are referring to the same system of assets, it would be preferable to give them the same names. For example, SDG&E's risks associated with their gas system (excluding dig ins) are:

- SDG&E-Risk-3 Incident Related to the High-Pressure System (Excluding Dig-in).
- SDG&E-Risk-9 Incident Related to the Medium Pressure System (Excluding Dig-in).

where we assume high pressure refers to their transmission pipe, and medium pressure to their distribution pipe.

PG&E lists three risks related to their gas system (Table 6):

Table 6: PG&E gas system risks.

Chapter 7	RISK ASSESSMENT AND MITIGATION PHASE RISK MITIGATION PLAN: LOSS OF CONTAINMENT ON GAS TRANSMISSION PIPELINE

Chapter 8	RISK ASSESSMENT AND MITIGATION PHASE RISK MITIGATION PLAN: LOSS OF CONTAINMENT ON GAS DISTRIBUTION MAIN OR SERVICE
Chapter 9	RISK MITIGATION PLAN: LARGE OVERPRESSURE EVENT DOWNSTREAM OF GAS MEASUREMENT AND CONTROL FACILITY

It appears that the first two of PG&E's risks correspond to SDG&E's but the third does not. This lack of standardization makes the comparison of Risk Spend Efficiency between the two IOUs more difficult. Risks must be defined more uniformly across IOUs. Sources such as the Gas Technology Institute and the Canadian Energy Regulator apparently have good information on this for gas. For electric we understand that the Electric Power Research Institute (EPRI) has similar standardized risks. We recommend that the CPUC create a standard taxonomy of risks, in coordination with the IOUs and other stakeholders, and with input from industry recognized sources such as these.

3.1.3. Risk models.

In this section we will provide descriptions of the IOU approach to risk modeling across the dimensions of:

- Assumptions.
- Bow Tie.
- MAVF.
- Monte Carlo simulation.
- Risk spend efficiency.
- Horizontal factors.
- Aggregation across tranches.
- Time dynamics.

3.1.3.1. Assumptions.

All IOUs rely on a combination of historical data and subject matter experts to drive their risk models. All IOUs appear to be competent in this area based on the documents reviewed. Where possible, we would recommend either public or pooled sources of risk statistics, for example, the Pipeline and Hazardous Materials Safety Administration (*PHMSA)* for gas or *EPRI* for electricity. It is not clear to what extent the IOUs are allowed or encouraged to share risk statistics, but given the similar environments, this might further standardize the results.

3.1.3.2. Bow Tie.

The Bow Tie is a standard diagram in risk management that displays the relationship of the triggers of a risk event to the event itself, followed by the connection of the event to the consequences. All IOUs use this established approach. The Bow Tie can provide the architecture for a Monte Carlo simulation of the full distribution of triggers and consequences. Examples from each IOU are displayed below (Figure 1, Figure 2, and Figure 3).

Figure 1: A Bow Tie from SDG&E/SoCalGas.

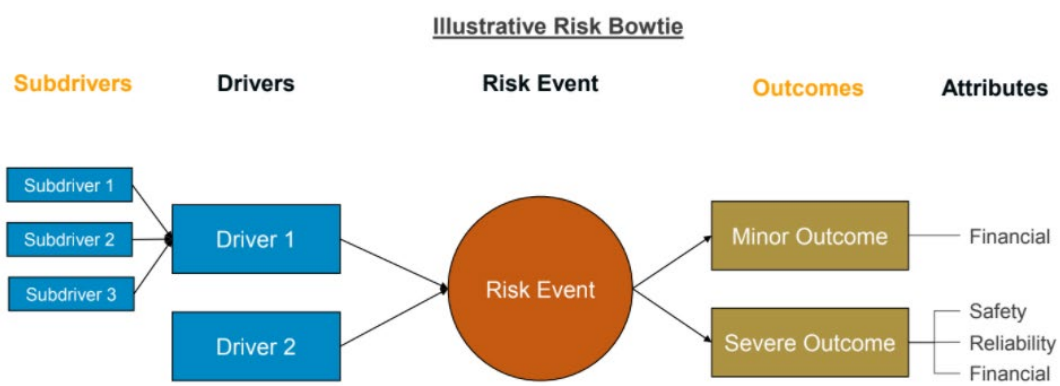

Figure 2: A Bow Tie from PG&E.

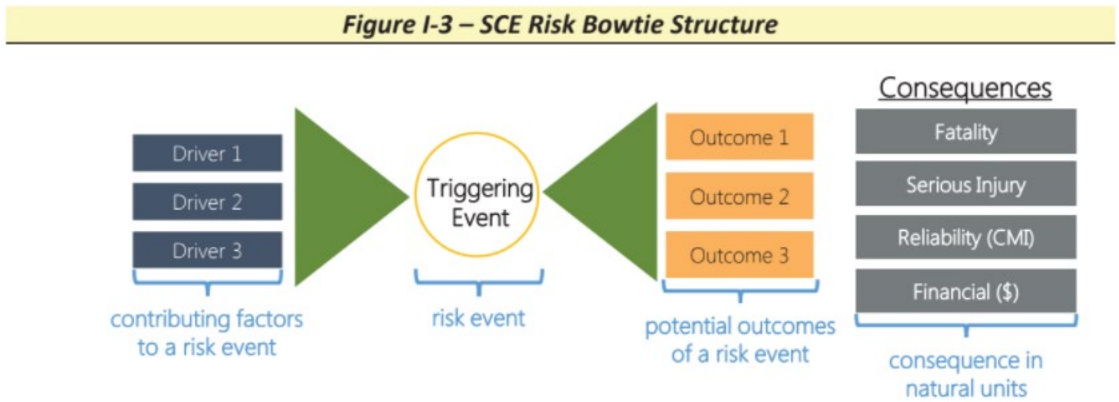

Figure 3: A Bow Tie from SCE.

All IOUs appear to be competent in this aspect of risk modeling. The Bow Tie driven by coherent simulations (stochastic libraries) of cross cutting risk factors could help solve the problem of modeling interrelated risks. Stochastic libraries are libraries of precalculated simulation inputs following probability distributions appropriate to either individual risk events or cross cutting factors such as climate change. These libraries provide multiple benefits: They are auditable; they allow results to be aggregated; and they allow the modeling of multiple factors with interdependencies. Standardizing the Bow Ties and input libraries across the IOUs provides the ability to compare results across IOUs, and to audit IOU risk modeling. Having common cross cutting libraries ensures coherent simulations. That is, if two separate risk events have sea level rise as an input into their Bow Tie, and event 1 has a sea level rise of two feet on simulation trial 1,000 then event 2 will have a sea level rise of two feet on its own simulation trial 1,000. Further expanding this concept, one could in theory roll up all sea level rise related risks across all the IOUs, to calculate state wide risks due to climate change to help guide policy at the state level.

3.1.3.3. MAVF.

The MAVF is focused on the third level of risk accounting, stakeholder preferences and risk attitude. The MAVF is composed of relative weights between risk attributes to guide acceptable tradeoffs between, for example, safety and reliability, and the scaling of natural units of risk consequence to reflect tail risk and risk attitude. In Appendix C and D, we discuss the potential problems with the application of MAVF in the aggregation of risk across Tranches. The high-level point in terms of describing the IOU's approach to MAVF are:

- The IOUs use qualitatively different scaling:
    - SoCalGas/SDG&E uses a Linear or Risk Neutral scaling.
    - PG&E uses a Convex or Risk Averse scaling.
    - SCE uses Concave or Risk Tolerant scaling.

The IOUs seem to follow the terms of the Settlement Agreement, but:

a. The Settlement Agreement may not be internally consistent as discussed in Appendix D.

b. The IOUs use qualitatively different weighting and scaling as discussed in the chapter discussing the MAVF in more detail.

The current approach as specified by the Settlement Agreement is unsatisfactory. The weighting and scaling of MAVF must be applied after the risks are rolled up probabilistically across tranches as discussed in Appendix D. See the following chapter for details on weights and scaling.

3.1.3.4. Monte Carlo simulation.

All IOUs make use of Monte Carlo simulation. For example, page 22 of PG&E's RAMP briefing shows clearly how this technique is used in a CoRE calculation (Figure 4).

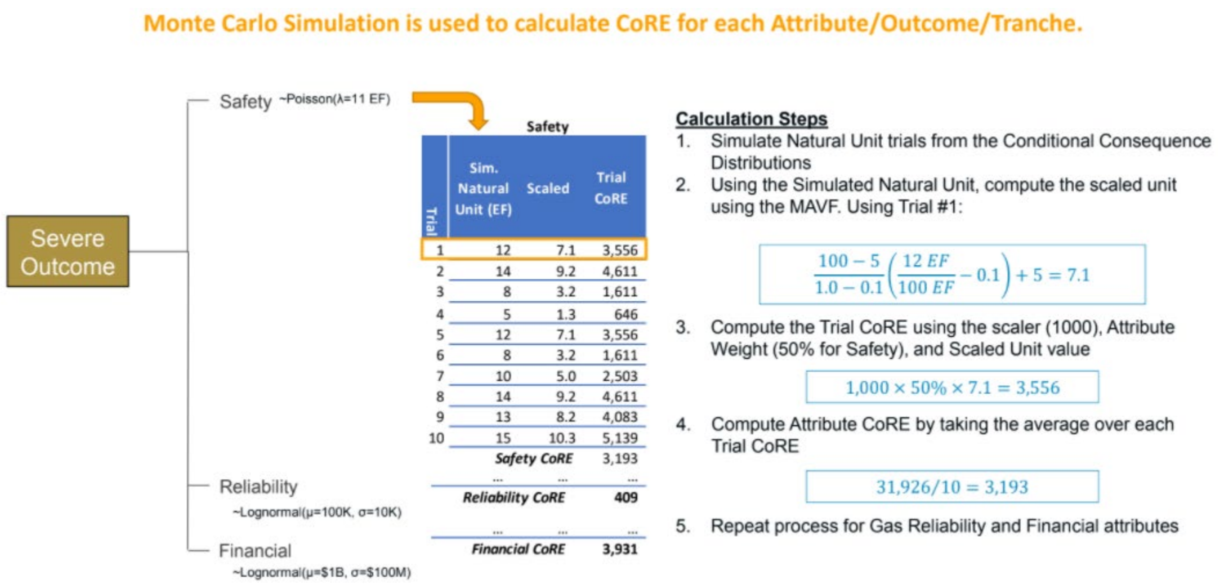

Figure 4: The use of Monte Carlo simulation to calculate a CoRE value.

PG&E and SCE specifically reference the use of lognormal distributions of consequence, which is commonly used in risk management. The current use of Monte Carlo could be enhanced using stochastic libraries. First, this would solve the problem of aggregation across tranches. Second, libraries of cross cutting factors such as climate change could drive multiple Bow Tie models to ensure proper interrelationships between risks driven by common inputs. Third, they could drive time dynamic models of mitigations for deteriorating assets.

3.1.3.5. Risk spend efficiency.

Here the IOUs have slightly different approaches. SoCalGas/SDG&E uses a discount factor over the time during which risk is reduced. As we interpret this, in their approach risk reduced in the future is not worth as much as risk reduced today. PG&E specifically factors in reduction for severe outcomes. SCE uses scaled risk reduction divided by expenditure. Because of inconsistencies in both the selected risks and MAVF weights and scoring, plus invalid aggregation across tranches, we do not feel that the IOU RSE calculations are valid, let alone comparable across IOUs. We do not feel that the IOU RSE calculations are comparable across IOUs for three reasons. First, the selected risk categories are not identical. It should be fairly easy to standardize on these. Second, the MAVF parameters are not consistent across IOUs, and we feel that they should be consistent and specified by the CPUC. Third, the aggregation of MAVF scores across tranches may not be valid in some cases.

All IOUs recognize that risk management involves an investment in a portfolio of mitigations. As such it cannot be done strictly at the tranche level but must be viewed more holistically. We feel the best way to judge the RSE of a specific tranche level mitigation project is to compare the RSE of the entire portfolio of interrelated mitigations, both with and without the project of interest. By interrelated we mean projects, which either reinforce or diminish each other. An example of the former would be the case where project 1 and project 2 each require moving a team to a site, and both projects provide additional risk reduction when applied together. An example of the latter is like undergrounding a tranche of electric transmission lines or covering conductors on the same tranche. Portfolio effects do not impact risks and mitigations that are statistically independent. In the independent case the projects may simply be sorted by decreasing RSE and added in that order. But portfolio effects do need to be incorporated in the RSE optimization for interrelated mitigations.

3.1.3.6. Horizontal factors.

All three IOUs explicitly recognize that they are managing portfolios of mitigations. Both external factors such as climate change, and mitigations can impact multiple risks and are a source of complication and potential over or under counting in estimating RSE. SDG&E/SoCalGas describe actions that impact multiple risks as *cross-functional factors* (Table 7). PG&E describes external *cross-cutting factors* that may impact multiple assets (Table 8). SCE describes the potential of understating risk reduction by missing the combined impact of mitigations across risks (Table 9). Proper modeling of horizontal factors is important, for example in accounting for climate change, but does not seem to be fully developed at any of the IOUs.

Table 7: SDG&E/SoCalGas cross-functional factors.

SoCalGas Cross-Functional Factor Volume	
Chapter	**Subject**
SCG-CFF-1	Asset and Records Management
SCG-CFF-2	Energy Resilience
SCG-CFF-3	Emergency Preparedness and Response and Pandemic
SCG-CFF-4	Foundational Technology Systems
SCG-CFF-5	Physical Security
SCG-CFF-6	Safety Management System
SCG-CFF-7	Workforce Planning / Qualified Workforce

Table 8: PG&E cross-cutting factors.

No.	Cross-Cutting Factor	Impacts the Likelihood of a Risk Event	Impacts the Consequence of a Risk Event
1	Climate Change	x	x
2	Cyber Attack	x	x
3	Emergency Preparedness and Response (EP&R)		x
4	Information Technology (IT) Asset Failure	x	x
5	Physical Attack	x	
6	Records and Information Management (RIM)	x	x
7	Seismic	x	x
8	Skilled and Qualified Workforce (SQWF)	x	

Table 9: SCE mitigations with combined impacts across risks.

Mitigations in Multiple Chapters	Mitigations that benefit multiple risks were accounted for separately in each chapter, while full costs included in each chapter • This approach potentially understates the risk reduction and RSE of these mitigations by not showing the combined impact across risks

Capturing horizontal factors is critical for optimizing the portfolio of mitigations. That is, factors such as climate change must be run coherently through all the Bow Ties that they impact to correctly model correlation within the portfolio.

3.1.3.7. Aggregation across tranches.

In accordance with the Settlement Agreement, all IOUs aggregate the risk scores across tranches to total risk event scores. In general, when dealing with uncertain quantities such as risk consequences, this is not a valid approach, as demonstrated in Appendix C and D. By storing the results of current Monte Carlo models in stochastic libraries, risks may be validly aggregated across Tranches. This approach is explained further in Appendix F.

3.1.3.8. Time dynamics.

Many risks are time dependent, for example, corrosion on gas transmission pipes or deterioration of electric poles. All IOUs appear to recognize this issue in their analysis. Dynamic models driven by stochastic libraries could better mitigate the risks of deteriorating assets, and that approach will provide consistency with respect to time dynamics for similar initiatives across the IOUs.

3.2. Modeling Recommendations: Granularity and the RSE of Testing

3.2.1. Aggregation vs. Granularity

A key question when applying the Risk Decision Framework (RDF) is what level of aggregation or granularity to use for defining tranches – by program, project, or even by asset. The Settlement Agreement [2018, pA-11] Element 14 "Definition of Risk Events and Tranches" says:

> "For each Risk Event, the utility will subdivide the group of assets associated with the risk into Tranches. Risk reductions from the mitigations and RSE will be determined at the Tranche level, which gives a more granular view of how mitigations will reduce risk. The determination of Tranches will … strive to achieve as deep a level of granularity as reasonably possible."

This is easier said than done.

First, risks may not be validly aggregated without addressing nonlinearities and statistical dependence, as discussed in Appendix C and D. The first problem occurs when using nonlinear scaling of risk scores, and the second involves interdependent risks, such as where high demand affects transformer failure frequencies. The solution to the second problem is to address how a project impacts the RSE of the portfolio as a whole, as this will properly capture the interdependencies. As an intuitive example, imagine you owned nothing but had $1 million in cash to spend. You are then offered things to purchase one at a time and can accept or reject them sequentially. If the first thing you were offered was a fire insurance policy you would reject it, because you would not have a house to protect, and the RSE of insurance on its own is negative. On the other hand, once you own a house, adding insurance to the portfolio is a very attractive investment, with a large RSE value. By measuring how a project changes the

RSE of the portfolio, and being mindful of nonlinearities, one can properly go to any level of granularity.

Secondly, the question is what level is “reasonably possible”? The RAMP submissions mostly report RSE at the *program* level, such as enhanced vegetation management by California High-Cost Fund-A (HCFA) tier, not at the *project* level – say vegetation management by specific line segment or circuit. That may be appropriate in RAMP or GRC submissions if the CPUC wants to evaluate mitigation options at the program level. But, for the utilities, it may be more useful to calculate RSE at the project level, if that’s the level at which they make decisions on what to do.

There are often large variations in risk level and mitigation cost between different lines of the same type even within an HCFA area and sometimes even within different sections of the same line – due to differences in population density, vegetation, terrain (flat lands, forested slopes, or rocky mountainous areas), size of fire risk area, and so on. In such cases, an aggregate RSE computed over a program, or even for a particular project, may mislead by disguising these variations. The Pareto rule may apply: E.g., 20% of the lines or assets may account for 80% of the risks. In such cases, it would be helpful to compute RSE at a more granular level to help guide the utility in designing and selecting the most cost-effective mitigation projects, and portfolios of projects.

Recommendation: To follow Element 14 of the Settlement Agreement and apply RDF and calculate RSE at “as deep a level of granularity as reasonably possible,” The Utilities should start with potential portfolios of projects, then measure the change in Portfolio RSE as individual projects are added or removed. This approach is further discussed in Appendix G.

3.2.2. The RSE of Testing

This somewhat subtle but vital concept seems to be missing from the current discussion. This refers to the actual monetary benefit of performing a particular test if one includes the appropriate mitigation in the case of a negative outcome. By definition if you could learn nothing from a test that would trigger a maintenance decision the value of that test is zero. The Value of Testing (VOT) is based on the theory of the economic value of information. Many mitigations involve testing, for example In-Line Inspections (ILI) or pressure testing of Gas Transmission Pipe. The testing, which may be costly itself has no RSE unless you account for the option to repair the asset in the event that the test identifies a problem such as a corroded or cracked pipe. A numerical example is useful.

There is a 2% chance Likelihood of Risk Event (LoRE) that an asset has a defect, in which case the consequence (CoRE) is a $10 million loss. Given that this is the only risk attribute, and a linear scaling function, then this risk represents an expected $200k loss.

This may be viewed as the fault tree below (Figure 5).

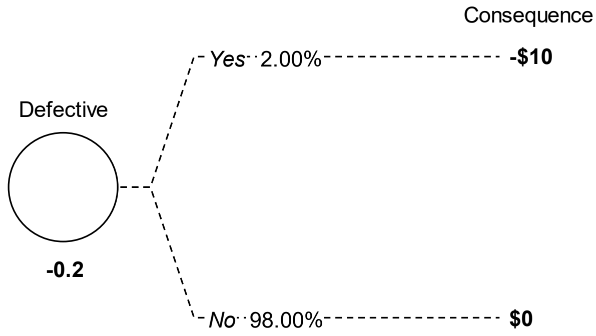

Figure 5: RSE fault tree.

If it costs $500k to replace the pipe, this mitigation will have an RSE of negative $300k and will not be worth it.

Now suppose we can perform a test, which will detect 60% of all defects, and yield false positives on 1% of non-defective assets. This information is reflected in Table 10 below.

Table 10: RSE sample test matrix.

LoRE	Risk CoRE	Risk
2%	-$10	-$0.20

	Pos Test	Neg Test
Defective	60%	40%
OK	1%	99%

What is the RSE of such a test?

This involves a standard form of Bayesian analysis known as a Value of Information calculation. Suppose we replace the asset for $500k only if we get positive test. We can determine the probabilities of a defect given both a positive and negative test as shown in another fault tree below. Note that now the expected risk has been reduced to -$0.0909. The value of the test is then the difference between the risk without doing the test and risk with the test where we replace the asset if there is a positive test. That is, nearly $110,000 or

-$0.0909 minus -$0.20 = $0.1091.

So, the RSE of the test is this value minus the actual cost of the test (Figure 6).

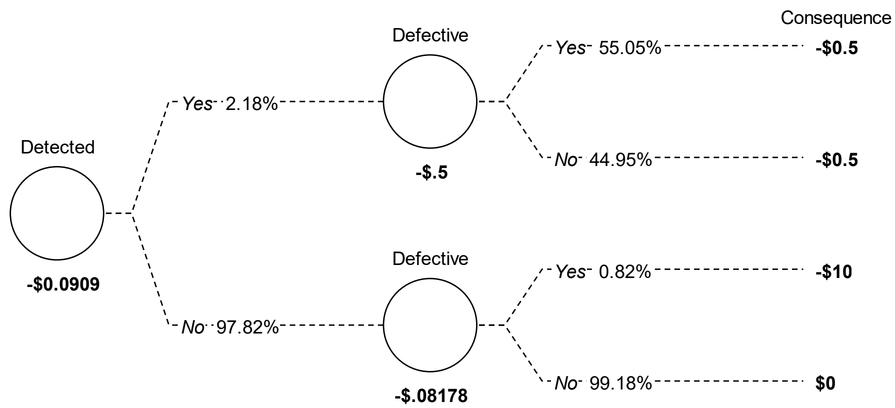

Figure 6: Test valuation diagram.

There is an analogous situation with respect to pilot and Research and Development (R&D) projects, however in those situations the relevant question is, how will future actions change based on the results from these pilot or R&D projects, and what is the potential value of those changed actions?

3.3. Transparent Calculation and Communication of the Process and Results.

Risk management is a complex process, which can never eliminate risk all together. For the system to be trusted by the public, regulators, and the IOUs it must be as transparent as possible.

The RAMP submissions and accompanying briefings are admirably transparent in the way they provide worked examples to explain how they calculate RSE. But they vary widely in how they present results. In some but not all cases, they present MRR, and mitigation cost, along with RSE for selected mitigation programs. They often omit key input assumptions and how the risk events contribute to the underlying attribute values, safety, cost, and reliability. Most mitigations analyzed are at the program level, rather than individual projects. While PG&E explains that they treat interactive effects between mitigations, it is not clear how or whether the other utilities do so. The reporting form and level of detail varies over mitigation results even within the same RAMP submission, and often in the underlying spreadsheets. These inconsistencies make it challenging for reviewers to understand many of the underlying calculations.

We believe that transparency can be improved at three levels.

1. The very representation of uncertainty can be made repeatable and auditable by adopting the scenario approach pioneered in finance and insurance. This not only enables the arithmetic of uncertainty, but allows averages, percentiles, chance of exceedance or graphs to be generated from the results as needed.
2. Standard templates should be established to present input assumptions, intermediate results, and final values for RSE.

3. The Bow Tie, a special case of the broader concept of the Influence Diagram, has already been adopted as a standard for representing the causes and consequences of risk events. Extending Bow Ties to full Influence Diagrams will further increase the domain of transparent representation of risk.

How should uncertainty and probabilities be calculated and communicated as part of IOU filings?

The IOUs are already using Monte Carlo simulation whose output may be easily stored in stochastic libraries of coherent scenarios, which obey both the laws of arithmetic and the laws of probability. This approach is applied in insurance and finance where risk aggregation is paramount. Here is how the approach has been applied to portfolios of projects in other fields and could be applied to aggregate the two tranches of risk shown in Figure 7, which are based on the figure on slide 22 of the PG&E RAMP Briefing.

Tranche 1		Tranche 2	
Trial	Sim. Natural Unit (EF)	Trial	Sim. Natural Unit (EF)
1	12	1	10
2	14	2	12
3	8	3	7
4	5	4	6
5	12	5	8
6	8	6	6
7	10	7	12
8	14	8	12
9	13	9	10
10	15	10	5

Figure 7: Monte Carlo trials of consequence.

First these results could be run separately and stored as stochastic libraries of data.

I7 =C7+F7

	Tranche 1		Tranche 2		Aggregated Risk	
	Trial	Sim. Natural Unit (EF)	Trial	Sim. Natural Unit (EF)	Trial	Sim. Natural Unit (EF)
	1	12	1	10	1	22
	2	14	2	12	2	26
	3	8	3	7	3	15
	4	5	4	6	4	11
	5	12	5	8	5	20
	6	8	6	6	6	14
	7	10	7	12	7	22
	8	14	8	12	8	26
	9	13	9	10	9	23
	10	15	10	5	10	20
Average		11.1		8.8		19.9

Figure 8: The aggregation of risk consequence.

These libraries could later be retrieved and aggregated trial by trial as shown in Figure 8. The key is that the arithmetic of uncertainty is reduced to multiple instances of standard arithmetic, applied to each of the trials of the two tranches. In computer science, this is a technique known as vectorization, and it can be performed in Excel, R, Python, or virtually any computer environment. Thereafter MAVF may be correctly applied to the total column. This approach is also transparent and is already being used to communicate uncertainty by PG&E as shown in Figure 9.

TABLE 3-9
SAMPLE BOW TIE: SIMULATED SEVERE OUTCOMES VALUES IN NATURAL UNITS AND ATTRIBUTE CORE CALCULATIONS[(a)]

Trial	Safety				Reliability				Financial			
	Sim Natural Unit (EF)	Normalized	Scaled	Total CoRE	Sim Natural Unit (1k Cust)	Normalized	Scaled	Total CoRE	Sim Natural Unit ($M)	Normalized	Scaled	Total CoRE
1	5	0.05	1.3	646	84	0.11	6.3	315	871	0.17	12.8	3,207
2	8	0,08	3.2	1,611	86	0.12	6,6	330	871	0.17	12.8	3,209
3	8	0.08	3.2	1,611	91	0.12	7.2	362	982	0.20	15.2	3,791
4	10	0.10	5.0	2,503	96	0.13	8.0	400	987	0.20	15.3	3,819
5	12	0.12	7.1	3,556	97	0.13	8.0	401	1,006	0.20	15.7	3,923
6	12	0.12	7.1	3,556	104	0.13	8.1	406	1,028	0.21	16.2	4,039
7	13	0.13	8.2	4,083	104	0.14	9.1	453	1,031	0.21	16.2	4,053
8	14	0.14	9.2	4,611	108	0.14	9.1	456	1,051	0.21	16.6	4,158
9	14	0.14	9.2	4,611	108	0.14	9.6	481	1,119	0.22	18.1	4,517
10	15	0.15	10.3	5,139	109	0.14	9.7	486	1,134	0.23	18.4	4,594
11	**Safety CoRE 3,193**				**Reliability CoRE 409**				**Financial CoRE 3,931**			
Sum of Attribute Values: 7,533												

(a) The Attribute CoRE is the average of the CoRE per trial for that Attribute.

Figure 9: Trials from a PG&E Monte Carlo simulation.

How should input assumptions and results be presented as part of IOU filings?

Standard templates would be helpful for presenting input assumptions and results estimating RSE for a set of mitigations, with the flexibility to be practical for all utilities. Indeed, there has already been considerable discussion of ways to improve transparency in presentation of RDF results. In March 2021, in a session of the Technical Working Group (TWG) convened under Phase 1, Track 1 of R.20-07-013, The Utility Reform Network (TURN) offered a presentation on “Transparency of Estimates and Assumptions” with guidelines proposed for transparency and uncertainty as a “Streamlined Format for Reporting Estimates and Assumptions”. Based on a pilot experiment with this format, PG&E recommended that Standard Workpaper Templates be developed as relational data tables, consisting of tables for Risk Results, Risk Sensitivity Analysis, and a Model Listing. ["PG&E Transparency and Uncertainty-Highlighted.pdf" in CPUC-Risk Study\CPUC Risk Files\CPUC R.20-07-013 ALJ/CF1/sgu]. As relational tables, they can easily be pivoted to create summary tables for a wide variety of purposes. The proposal includes criteria to describe the quality of each estimate, whether based on quantitative data or judgments of subject matter experts. These proposals to develop standard templates to present RDF assumptions and results continue to be discussed and refined in the CPUC's RDF proceeding.

How should risk models be presented as part of IOU filings?

Bow Tie diagrams are used by all submissions to follow the SMAP Guidelines as a clear visual method to identify threats, drivers, and consequences for each risk or type of risk. It would be helpful to extend the Bow Ties to the more general concept of the influence diagram to show causal factors or cascading threats on the left, to incorporate mitigation decisions and the sequence of calculations used to compute the range of effects, attributes, the multi-attribute value function, and calculation of RSE. Influence diagrams are a useful representation commonly used by decision analysts, well suited for this kind of application [Howard & Matheson 1981; Charleworth 2017]. The influence arrows depict deterministic or probabilistic relationships. Influence diagrams extend the chance variables used in Bow tie diagrams with decision variable, computed variables, and objectives (see Figure 10).

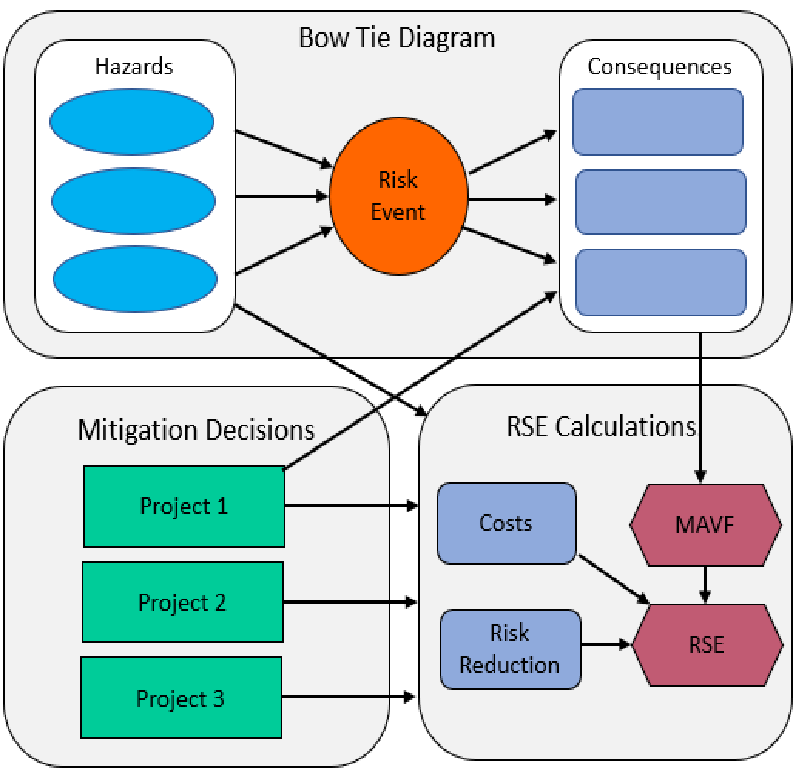

Figure 10:Bow Tie diagram extended to show influence.

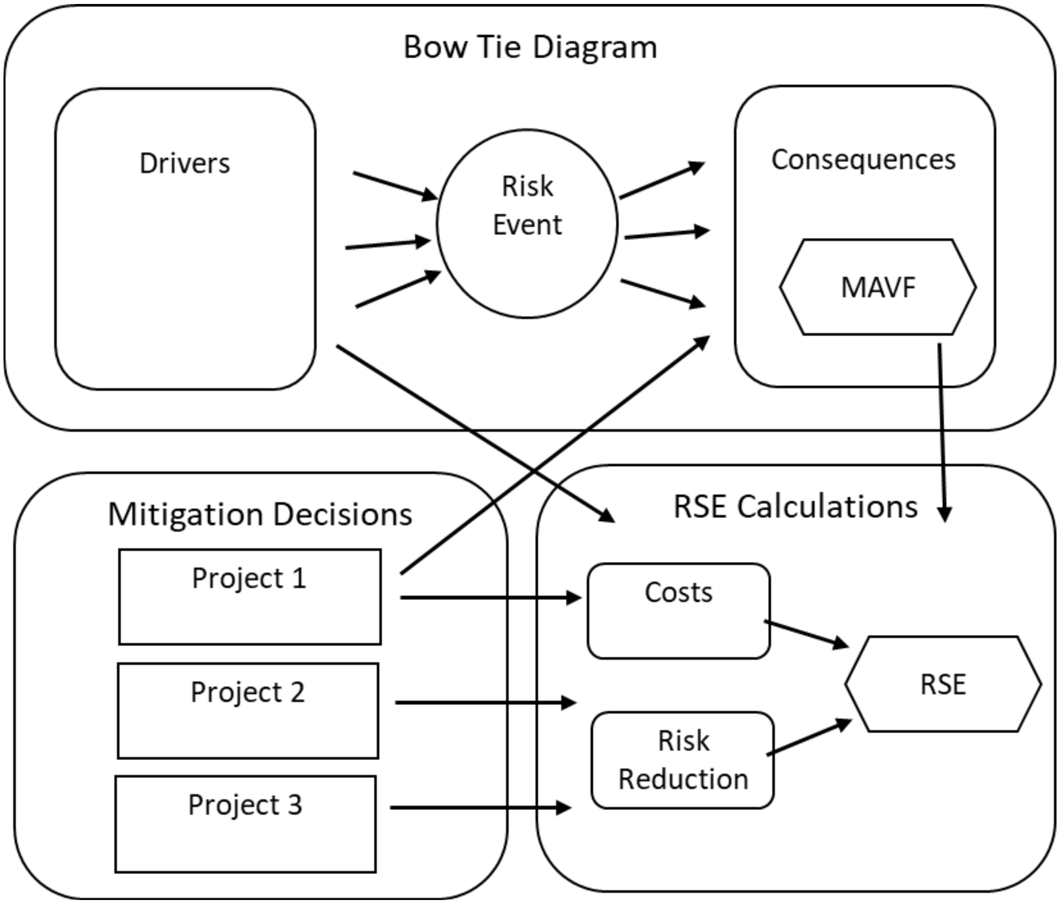

Figure 11: Influence diagram general structure.

Figure 11 is an example influence diagram that expands the **Bow tie diagram** with **Mitigation Decisions**, and **RSE calculations** including a **MAVF (Multi-Attribute Value Function**) feeding into the **RSE**.

Influence diagrams, like Bow Tie diagrams, provide an intuitive visual depiction of the key factors or variables with causal or probabilistic relations shown as arrows (influences). But they extend the notation to include the decisions (mitigations), parameters, intermediate calculations, and objectives (e.g., RSE) that comprise the full risk decision framework. They communicate the key variables and influences in a qualitative graphical form that is complementary to and much easier to grasp than the underlying mathematical formulas.

3.4. Risk Spend Optimization.

Ultimately the purpose of Risk/Spend Efficiency should not be to merely compare mitigation projects for relative efficiency, but to guide the overall portfolio of projects. This was the original purpose of scenario optimization when applied to financial assets, and instead of Risk/Spend Efficiency it was applied to Risk/Return Efficiency, but the methodology is the same. In finance an efficient portfolio is one that has maximum return for its level or risk, or equivalently minimum risk for its level of return. Replace maximum return with minimum cost, and the same concept applies in this context as shown in Figure 12.

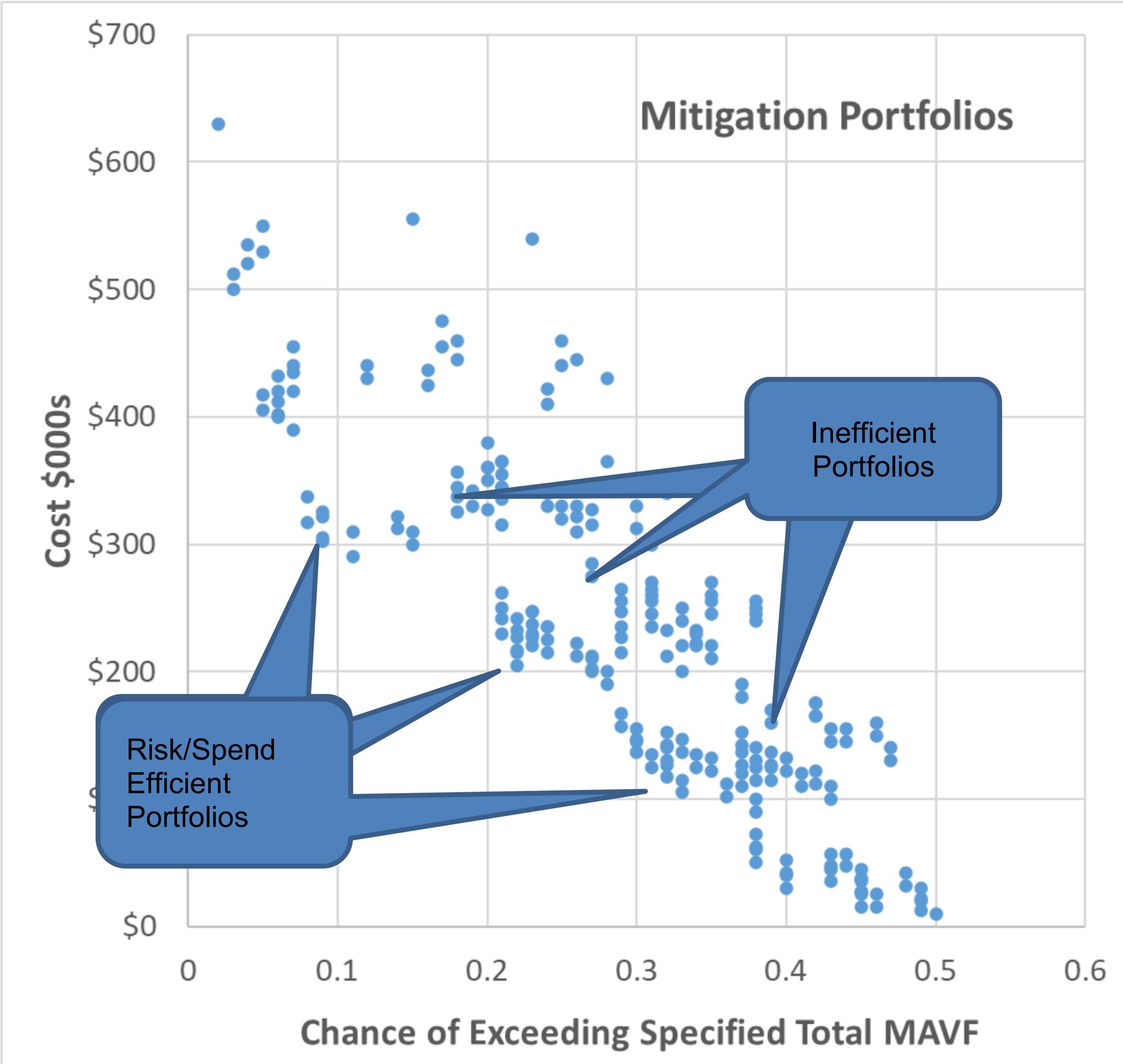

Figure 12: Efficient frontier of mitigation portfolios.

3.4.1. References

- Howard & Matheson 1981: Howard, R.A., and J.E. Matheson, "Influence diagrams" (1981), in *Readings on the Principles and Applications of Decision Analysis*, eds. R.A. Howard and J.E. Matheson, Vol. II (1984), Menlo Park CA: Strategic Decisions Group.

- Charlesworth 2017: David Charlesworth, *Decision Analysis for Managers,* Second Edition, Business Expert Press; 2nd edition (April 11, 2017), ISBN-13 : 978-1631576041

3.5. Recommendations

Our recommendations related to overall risk modeling and transparency are shown in Table 11.

Table 11: General risk modeling and transparency recommendations.

1. Define RAMP risks uniformly across the IOUs. This standard taxonomy of risks should incorporate prior work by industry recognized sources such as the Gas Technology Institute, the Canadian Energy Regulator, and the Electric Power Research Institute.
2. Define a consistent measure of electric reliability across all IOUs.
3. Use a common time horizon (across all IOUs) for costs and benefits, based on the lifetime of the mitigation and its assets – which may range from one or two years for vegetation management to perhaps 50 years for covered conductors or undergrounding.
4. Establish a standard method for utilities to discount costs and benefits (risk reduction) over mitigation lifetime using the same discount rate for both, perhaps using the average combined cost of capital for each utility.
5. Maximize the use of public or pooled sources of risk statistics, for example, *PHMSA* Pipeline and Hazardous Materials Safety Administration, or *EPRI* for electricity. Where such sources are not available, standardize on risk statistics across the California IOUs where possible.
6. Interrelationships between risks must be modeled to correctly aggregate risk across tranches as specified in the Settlement Agreement. See Appendix C and Appendix D.
7. RDF analysis should identify interactions where mitigations have synergistic or antagonistic effects on each other. Where there are significant interactions, results should be presented for a group or portfolios of mitigations. The contributions of individual mitigations may be reported in terms of the marginal effect to MRR and RSE of adding each mitigation to (or subtracting it from) a portfolio.
8. Risks should be aggregated at a level of granularity such that the risk characteristics of each risk tranche are consistent.
9. Analysis of all risk mitigations should include a systematic sensitivity analysis to identify which uncertain assumptions could have large effects on RSE and to clarify the robustness of its use to prioritize mitigation projects.
10. To follow Element 14 of the Settlement Agreement and apply RDF and calculate RSE at "as deep a level of granularity as reasonably possible," when there are interdependencies between projects, the utilities should start with potential portfolios of projects, then measure the change in Portfolio RSE as individual projects are added or removed. This approach is further discussed in Appendix G.

11. The representation of uncertainty should be made repeatable and auditable by adopting the scenario approach pioneered in finance and insurance. This not only enables the arithmetic of uncertainty, but allows averages, percentiles, chance of exceedance or graphs to be generated from the results as needed.
12. Stochastic Libraries of uncertainties should be standardized and used within the context of Monte Carlo simulation for risk modeling by all of the IOUs. This would allow the proper aggregation of risk while increasing transparency and trust in the results.
13. To guide future decisions on where to choose enhanced powerline safety settings (EPSS), covered conductors (CC), undergrounding (UG) or something else, it would be helpful to ask the utilities to address these questions more directly using the RDF framework for selected circuits in various situations – e.g., by tier 3 vs tier 2 fire safety regions, vegetation, and terrain type – and to do so with a framework that allows direct comparison of their results to identify the sources of the differences.
14. Adopt a consistent readability factor for all utilities, e.g., 1000. For RSE, we recommend dividing MRR*1000 by the mitigation cost in millions of dollars so that most RSEs are greater than one.
15. Standard templates should be established to present input assumptions, intermediate results, including MAVF attribute values, risk reduction, mitigation costs, and final values for RSE.
16. The Bow Tie, a special case of the broader concept of the Influence Diagram, has already been adopted as a standard for representing the causes and consequences of risk events. Extending Bow Ties to full Influence Diagrams will further increase the domain of transparent representation of risk.
17. Canonical, standardized Bow Ties and influence diagrams should be developed where possible for risk events and mitigations both for ease of use and better comparisons between IOUs.

4. IOU Use of MAVF

4.1. Background

In the Settlement Agreement [S-MAP 2018, 2020], the CPUC, California's four investor-owned utilities, and several intervenor organizations agreed to an RDF for assessing and managing risks and investments to mitigate those risks. This S-MAP framework specifies the use of a MAVF as a method to combine multiple objectives (attributes) into a single metric to quantify the CoRE. Recall from Chapter 3 that the key elements of the MAVF [S-MAP, 2020] are:

- An **attribute hierarchy**, with primary attributes that may each be composed of sub-attributes.
- The bottom level attributes must be **observable** with a range **in natural units** (or a measurable proxy attribute).
- **Weights** for each attribute, based on their range from best to worst, to combine them into a single consequence score for each outcome of a risk event.
- **A scaling function** for each attribute, which may be linear or nonlinear, that converts from its natural units to scaled units from 0 to 100 (Appendix A of the Settlement Agreement, pages A-5),

In this chapter, we compare how the utilities have created their own MAVFs, describe their strengths and weaknesses, describe best practices for using MAVFs, and provide some recommendations for improving use of MAVFs.

4.2. Approaches of the four IOUs.

The four California investor-owned utilities have followed the framework from the S-MAP agreement in their RAMP submissions. In this section, we summarize their similarities and differences.

Table 12 summarizes the MAVF used by each utility company, including the primary attributes, sub-attributes, ranges, weights, and type of scaling function. All four utilities have the primary attributes specified by S-MAP: *Safety* (*Fatalities* and *Injuries*), *Financial cost*, and *Reliability*. SoCalGas and SDG&E add *Acres burned* as a sub-attribute of *Safety*, and *Stakeholder satisfaction* (with only a 2% weight).

Table 12: MAVF summary.

Utility	Primary attributes	Sub attributes	Upper bound	Units	Primary weights	Sub attr factors	Scaling function Risk attitude
PG&E	**Safety**		100	Equivalent fatalities	50%		Averse
		Fatalities		Number		1	
		Serious injuries		Number		0.25	
	Electric reliability		4 billion	Customer minutes interrupted (CMI)	20%		Averse
	Gas reliability		750,000	Customers affected	5%		Averse
	Financial		$5 billion	USD ($)	25%		Averse
S. California Edison	**Fatalities**		100	Number	25%		Tolerant
	Serious injuries		500	Number	25%		Tolerant
	Reliability (CMI)		2 billion	Customer minutes interrupted (CMI)	25%		Neutral
	Financial		$5 billion	USD ($)	25%		Neutral
SoCalGas and SDG&E	**Safety**		20	Equivalent fatalities	60%		Neutral
		Fatalities		Number		1	
		Serious injuries		Number		0.25	
		Acres burned		acres		0.00005	
	Dollars		$500 million	USD ($)	15%		Neutral
	Stakeholder satisfaction		100	Index	2%		Neutral
	Reliability		1		23%		Neutral
SoCalGas		Gas Meters	100,000	Number of Gas Meters Experiencing Outage		50%	
		Gas Curtailment	666 MMcf	Volume of curtailments exceeding 250 MMcf/day		50%	
SDG&E		Gas Meters	50,000	Number of Gas Meters Experiencing Outage		25%	
		Gas Curtailment	250 MMcf	Volume of curtailments exceeding 250 MMcf/day		25%	
		Electric SAIDI	100 minutes	System Average Interruption Duration Index (SAIDI)		25%	
		Electric SAIFI	1 outage	System Average Interruption Frequency Index (SAIFI)		25%	

The utilities use very different scaling functions and risk attitude: PG&E uses a convex scaling function expressing high risk aversion for all attributes. SCE uses a concave scaling function expressing high risk tolerance of *Fatalities* and *Injuries.* SoCalGas and SDG&E use a linear scaling function expressing risk neutrality.

4.2.1. Attribute hierarchies.

At first sight, the attribute hierarchies used by each utility in Table 10 look a bit different. But closer inspection shows that they are substantially equivalent in some respects. All utilities have *financial cost* as a primary attribute. SCE has *Fatalities* and *Serious injuries* as primary attributes, where PG&E and SoCalGas/SDG&E treat *Fatalities* and *Serious injuries* as sub-attributes of *Safety*.

PG&E treats *Electric reliability* and *Gas reliability* as primary attributes, where SDG&E has *reliability* as primary attribute, with E*lectric* and *Gas reliability* as sub-attributes. SCE has electric reliability only, naturally, since it offers electricity only. Similarly, SoCalGas uses only *Gas reliability,* being a gas-only utility. PG&E and SCE both use Customer-Minutes Interrupted (CMI) as their observable metric for electric reliability. SDG&E uses System Average Interruption Duration Index (SAIDI), and System Average Interruption Frequency Index (SAIFI), with equal weights. SAIDI is CMI averaged over customers, and SAIFI is the average number of interruptions per customer. The details of the PG&E calculations with respect to PSPS and extreme events are not currently clear to us. PG&E uses the number of customers affected as the only metric for *Gas reliability*, SoCalGas and SDG&E use two metrics, the Number of Gas Meters Experiencing Outage, and Volume of Curtailments of Natural Gas exceeding 250 million cubic feet/day.

SoCalGas/SDG&E uniquely adds *Acres burned* as a sub-attribute of *Safety* with a weight of 0.000,05 fatalities equivalent per acre*.* This is likely a simulation modelling exercise for which they have an estimate of area burned over a standard 8-hour time period for a given weather scenario (wind speed, wind direction, and fuel moisture content). The data likely do not exist as maps of actual acres burned. They are also alone in including *Stakeholder satisfaction* as an attribute, although they give it a weight of only 2%. All three IOUs appear to be moving toward incorporating fire size in their consequence modeling, but details were not available in any of the documents we reviewed or at the OEIS workshops.

4.2.2. Attribute weights and ranges.

In standard methods for MAVF used by decision analysts, attribute weights represent not the relative importance of each attribute in the abstract, but specifically the relative value of changing the attribute from its worst to best value. The S-MAP agreement reflects this perspective where it specifies Step 7 in building a MAVF:

> "Each Attribute should be assigned a weight reflecting its relative importance to other Attributes. Weights are assigned based on the relative value of moving each attribute from its least desirable to most desirable level, considering the entire range of the Attribute." [S-MAP 2018, p A6]

Thus, to compare the importance of attributes in MAVFs of different utilities, we cannot consider the weights alone. We must consider the weights in combination with ranges.

We must also look at them in relation to the other attributes. For example, PG&E and SCE appear to treat *financial cost* identically. They both assign this attribute a weight of 25% with a range up to $5 billion. However, PG&E and SCE assigns a range of 100 fatalities a weight of 50% and 25% respectively. Thus, SCE would score a disaster with 100 fatalities the same as a $5 billion cost, where PG&E would score the same disaster to be twice as bad as a $5 billion cost. Their nonlinear scaling functions make it more complex to compare events with less than 100 fatalities or $5 billion in costs, as we shall discuss below.

PG&E and SoCalGas/SDG&E all count a serious injury (requiring hospitalization or resulting in permanent disability) as 0.25 of a fatality. SCE assigns 500 serious injuries the same score as 100 fatalities, implying a ratio of 0.20, which is close. PG&E cites Federal Aviation Administration (FAA) [2016] as supporting the 0.25 weight.

4.2.3. Scaling functions.

S-MAP allows utilities to use ***non-linear scaling functions*** for each attribute. Such scaling functions enable a utility to express an attitude or preference that the value of a unit increment in an attribute is worse (or less bad) when added to a small value than to a large value. For example, an extra fatality may be considered worse (increasing scaled score by more) when added to an outcome with 1 fatality than an outcome with 99 fatalities. SoCalGas and SDG&E chose to use only linear scaling functions, where the incremental value of a unit in attribute is independent of the base value.

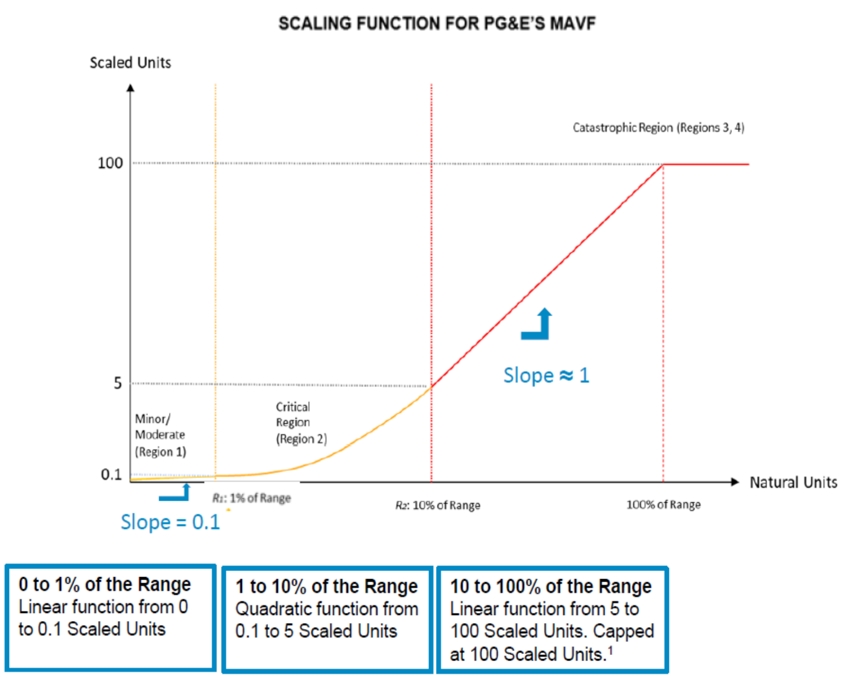

Figure 13: PG&E MAVF scaling function used for fatalities and serious injuries.

PG&E applies the same nonlinear scaling function to each attribute, shown in Figure 13. They justify this function by saying "it enables us to focus on tail events" and to capture aversion to extreme outcomes." [PG&E RAMP, 2020, p1-4]. Between 0 and 1% of the range (up to one fatality), it is *linear* with a small slope (0.1); between 1 to 10% the slope increases quadratically. Above 10% (from 10 to 100 fatalities), it is linear again with a higher slope (near 1.0). Thus, it treats each fatality from the 10th to 100th as being about ten times the value (or rather loss) of the first fatality.

Figure 14 compares the scaling functions for each utility by showing the scaled risk from 0 to 100 as a function of the number of fatalities. The scaling function for SoCalGas-SDG&E is linear up to 20 fatalities, the upper bound of its range. PG&E's scaling function is *convex* or *risk averse*.[5]

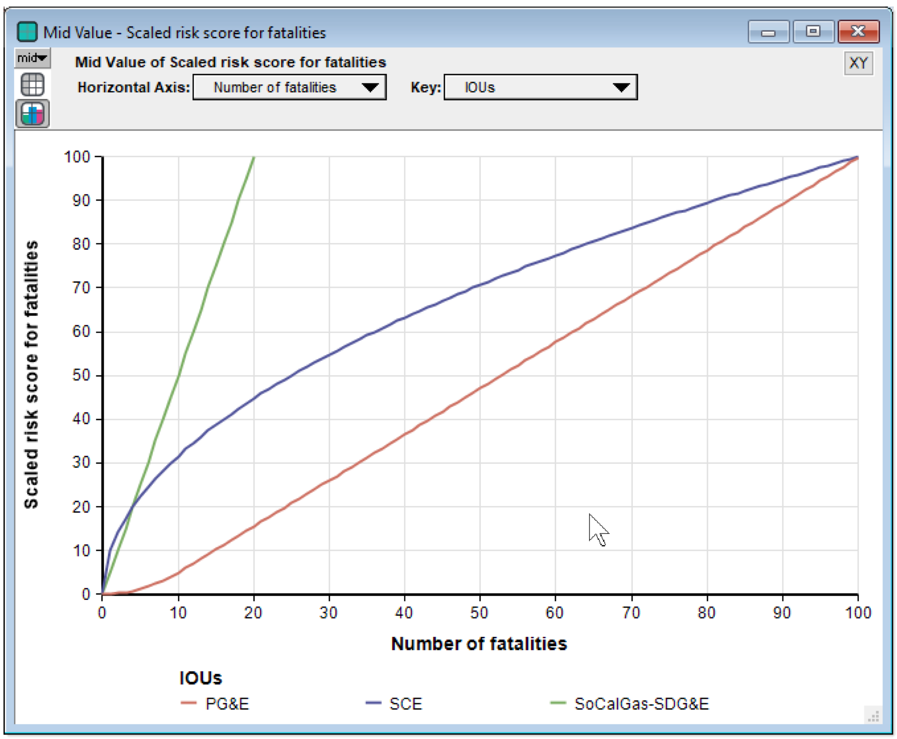

Figure 14: Scaled risk score as a function of the number of fatalities.

In contrast, SCE's scaling function for fatalities and injuries are *concave* – i.e., the incremental value decreases as the base value increases – based on a square root function. SCE explains:

> "Steep initial curves reflect low tolerance for serious injuries or fatalities." [SCE RAMP, 2018].

To be precise, it reflects low tolerance for a few serious injuries or fatalities, but an increasing tolerance (per injury or death) for events with larger impacts. They also say

[5] PG&E's scaling function looks a bit different because the horizontal axis is nonlinear.

the “Scales amplify the impact of safety versus the other two attributes (financial and reliability)”. These scales give greater weight to consequences with small numbers of injuries and fatalities — and therefore less weight to incremental consequences with large numbers of injuries and fatalities. Decision analysts characterize such a function as *risk tolerant* or even *risk seeking*.

4.3. Observed Strengths and weaknesses.

4.3.1. Attributes.

All the utilities follow the S-MAP guidelines to include the primary three attributes: *Safety*, *Reliability*, and *financial cost*. They all include *Fatalities* and *Injuries* either as primary attributes (SCE) or as sub-attributes of *Safety* (the others).

S-MAP [CPUC, 2018 pA-2] defines a MAVF as “A tool for combining *all* potential consequences of the occurrence of a risk event” (emphasis added). This begs the question of whether the existing MAVFs do include *all* potential attributes.

Environmental impact is an important candidate attribute that appears to be missing or incompletely addressed by all utilities. All the utilities considered environmental effects in some form, but they found them challenging to address explicitly. SoCalGas and SDG&E say:

> “. . .the companies were unable to determine how to express an environmental attribute that would enable meaningful comparison of utility risks while meeting the standard of the Settlement Decision.” [SoCalGas RAMP, 2020, p C-9].

PG&E says:

> “Environmental attributes are accounted for financially (i.e., within the financial Attribute) because there are no commonly accepted measures of non-monetary environmental consequences.” [PG&E RAMP 2020, p1-11]

There would be advantages in clarity and completeness to include *Environmental impacts* as a primary attribute rather than including it in *financial costs*. Sub-attributes might include *Ecosystem damage*, *Air quality impacts*, and *greenhouse gas emissions*, for example from wildfires and natural gas leaks. A notable example of the latter was the 2015/2016 leak from the Aliso Canyon storage facility of over 100,000 tons of natural gas with an estimated global warming potential of over 9 million tons of carbon dioxide.

SoCalGas and SDG&E include *Stakeholder satisfaction* as an attribute, to “represent effects on stakeholder groups that are not captured in the other attributes.”

Undoubtedly, there are some important effects that are not adequately captured by the other attributes, and it is impressive that they have attempted to do so. However, they report difficulty in developing a clear definition of this “everything else” attribute so that it can be measured other than by estimates from Subject Matter Experts (SMEs). [SoCalGas/SDG&E RAMP, pC-21]. The inclusion of *Stakeholder satisfaction* raises the question of whose objectives the other attributes are intended to represent. Do they represent the preferences only of the utility, or of their ratepayers and other California residents?

4.3.2. Scaling functions.

All the utilities used scaling functions consistent with S-MAP requirements. It is not clear why the three used such different scaling functions, ranging from very risk averse to risk neutral to very risk tolerant. Some guidance from CPUC or a future S-MAP process could lead to greater consistency. And as with attributes, a valid question might be, “whose attitude toward risk”? Should the scaling functions be defined based on the risk tolerance of the IOUs, the shareholders, or the ratepayers and other California residents?

4.3.3. Comparing tradeoff values for attributes.

S-MAP and the utilities do not appear to have discussed the explicit monetary trade-off values between attributes in the form of, say, the financial value of improving reliability in $/SMI, or value of a statistical life saved. However, it is possible to compute these implied values from each MAVF. One can then compare the implied values against values from the literature on the value of reliability or values used by government agencies such as the Value of a Statistical Life (VSL) as a test of consistency among utilities and check on their reasonableness. In this section, we perform such comparisons.

4.3.3.1. The value of reliability.

A simple example is the tradeoff between *financial cost* and *Electric reliability*. PG&E assigns a weight of 20% to *Electric reliability* ranging up to 4 billion CMI and 25% weight to *financial cost* ranging to $5 billion, implying an approximate[6] equivalence of $1 per CMI. SCE assigns 25% weight for 2 billion CMI – and the same 25% for a cost of $5 billion, implying an equivalence of $2.50 per CMI. There are certainly reasons why some kinds of customer might be more sensitive to outages than others. But we might wonder if the customers of SCE are 2.5 times more sensitive to outages than PG&E’s.

It is hard to compare the value of electric reliability of PG&E and SCE against SDG&E, which uses different measures of reliability, SAIDI and SAIFI. For similar reasons, it is hard to compare the value of gas reliability between PG&E and SoCalGas. It would be simpler if S-MAP agreed on a consistent set of measures for these attributes.

[6] The equivalence is approximate because the scaling functions are nonlinear.

4.3.3.2. The value of a statistical life or value of mortality reduction.

Federal government agencies, such as the US EPA and Department of Transportation, generally use the VSL to compare monetary expenditures and human fatalities when performing cost-benefit analysis of proposed regulations. This phrase includes "statistical" to indicate that it does not quantify the value of the life of specific identified people, but rather probabilistic fatalities from a large population at risk. Typically, society at large is willing to make much larger investments to avoid the death of a particular person than the expected (average) number of deaths for unspecified people.

In recent years, US EPA prefers the phrase *Value of Mortality risk Reduction* (VMR). This term may also be appropriate for the CPUC's RSE and risk decision framework given the focus on risk mitigation. In 2000, US EPA [EPA 2021] recommended using a central value for VMR of $4.8 million in 1990 dollars — approximately $9.5 million in 2020 dollars.

S-MAP and the RAMP submissions do not mention VSL or VMR explicitly.[7] But it is possible to infer equivalent VMRs from the MAVFs. For SoCalGas and SDG&E with their linear scaling functions, the calculation is straightforward (details in Appendix C). Their implied VMR is $100 million per fatality avoided.

The nonlinearities in the scaling functions for PG&E and SCE make the calculations more complicated because the VMR varies according to the total number of fatalities.

Figure 15 shows the average VMR per fatality up to 100 fatalities. The VMR for SoCalGas-SDG&E is $100M for any number of fatalities (as just mentioned). For PG&E, it has a minimum of $64 million for the second fatality and is $100 million per fatality above 10. The odd-looking curve below 10 fatalities is due to the interaction between the nonlinear scaling functions for mortality and costs.[8] For SCE, average VMR starts at $500 million for the first fatality, drops rapidly, and reaches $50 million for the 100th fatality. This is a result of the square root scaling function for fatalities that gives a much larger incremental value per fatality for small numbers of fatalities than for large numbers coupled with the linear scaling function for financial costs.

[7] PG&E RAMP 2020 mentions VSL when quoting and responding to a comment from TURN. See below.

[8] For PG&E, the VMR above 50 fatalities is extrapolated where the implied cost goes above the maximum range of $5 billion.

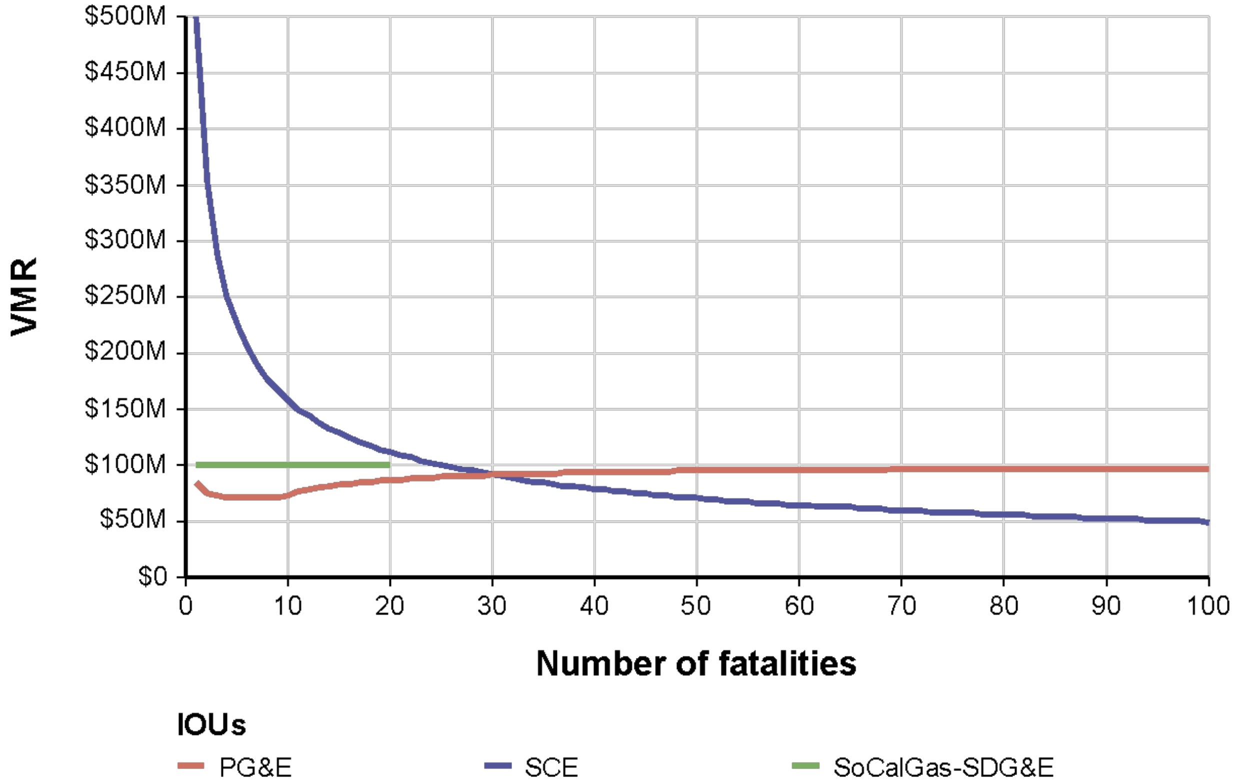

Figure 15: Value of mortality reduction.

TURN, an intervenor organization, pointed out that:

> ". . .the implied Value of Statistical Life (VSL) given by PG&E's weights and the attribute ranges for safety and financial impacts is $100 million, which is ten times higher than statistical values used by the U.S. Environmental Protection Agency to evaluate health risk and the U.S. Dept. of Transportation to evaluate vehicle safety features. TURN is concerned that PG&E's use of this higher value may result in skewing the ranking of different risks and misallocating risk management dollars." [TURN, 2020, p3, Item 1c, cited in PG&E RAMP, 2020]

4.4. Best practices.

MAVFs are a special case of multi-attribute *utility* functions (MAUFs). MAVFs and MAUFS are widely used to help organizations in government and industry to quantify their preferences among competing objectives and attitudes to risk so that they can compare complex uncertain options and make better decisions [e.g., von Winterfeldt and Edwards, 1986; Keeney & Raiffa,1993; Abbas, 2010; Henrion, Bernstein and Swamy 2015].

4.4.1. Risk attitude

The key difference between MAVFs and MAUFs is that a MAUF has a single *utility function* (often nonlinear) applied to the combined weighted attribute value to express overall attitude to uncertainty – risk aversion, neutrality, or tolerance. In contrast, the MAVF scheme as specified by S-MAP lacks a top-level scaling function applied to the overall risk value. Instead, it applies separate nonlinear scaling functions to some or all attributes to express risk attitude separately for each attribute.

With a MAUF, there is usually only reason to apply a nonlinear scaling function for each individual attribute where the value to stakeholders is nonlinear in the standard metric – such as where a two-day outage is more than twice as bad as a one-day outage due to spoilage of refrigerated food. This nonlinear scaling function need not represent risk attitude separately for each attribute since this is represented by the single overall utility function. This MAUF approach is simpler since it usually requires only a single nonlinear scaling function. It sidesteps the complicated question of whether there are interactions in risk attitude between attributes – e.g., between disasters with fatalities and high financial costs.

Recognizing that the term *utility function* invites confusion when applied to gas and electric utility companies, one might use the term *risk attitude function* instead. For convenience one could retain the term "multi-attribute *value* function" MAVF even if the parties adopt an overall risk attitude function.

As explained in the section on representing uncertainty, it is essential to represent and propagate the uncertainty in each attribute through the MAVF when there are nonlinear scaling functions, whether separately for each attribute as now, or if S-MAP adopted a more conventional scheme with a single overall risk attitude function.

4.4.2. Use tradeoff values from the literature or US federal agencies.

Best practice in performing multi-attribute and cost-benefit analysis is to base them on standard estimates of key tradeoff values, such as VSL or VMR adopted by Federal government agencies or estimates of the value of reliability from scientific surveys. An organization may modify these estimates where it considers it appropriate but should provide a justification.

The utilities are not explicit about such trade-off values in their MAVFs in their RAMP filings. But, as we have seen, a value of reliability and VSL or VMR are implicit in the MAVFs. PG&E and SoCalGas/SDG&E's schemes imply a VMR at or near $100 million per fatality. SCE's function implies a VMR that varies from $500 million for a single fatality down to $50 million per fatality for 100 fatalities. There is also substantial variation in the implied value of electric reliability. PG&E implies a value of about $1 per CMI. SCE implies $2.50 per CMI. SoCalGas/SDG&E uses different metrics for reliability, which are hard to compare with CMI.

It is unclear if there are sound reasons why these tradeoff values should vary so widely among the utilities or their customers. It would be possible to develop more consistent trade-offs or implied values by basing them on values recommended by the US EPA or other Federal or State agencies for use in cost-benefit and risk analyses. There has been considerable research to estimate the value of electric reliability at least for short-term outages [e.g., Sullivan et al. 2015, LaCommare et al. 2018, Baik et al, 2020]. It might make sense for all utilities to use similar implied values for their MAVFs based on a summary of the results of such studies. There is less literature on the value of gas reliability, but again it would make sense to base MAVFs on common implied values where available.

If S-MAP or individual utilities choose to add *Environmental effects* as an attribute, environmental trade-off values could be based on those recommended or used by US Federal agencies – for example, using values for the "social cost of carbon" to value the cost of greenhouse gas emissions associated with natural gas leaks and wildfires.

4.4.3. Constraints on attribute importance.

S-MAP specifies that the weight for safety should be at least 40% to ensure that safety is treated as adequately "important". But this constraint may not have the desired effect due to the interaction between ranges and weights. Consider for simplicity a MAVF with only two attributes, each with equal 50% weight: *Fatalities* with range to 100 and *financial cost* with range to $5 billion. That implies that 100 fatalities are equivalent to $5 billion costs, and a VMR of $500 million. Suppose that, while preparing a revised RAMP, the utility discovers a risk event that could cost up to $10 billion (and no fatalities), so it adjusts the maximum *financial cost* accordingly. If it wishes to retain the equivalence of 100 fatalities and $5 billion, it should then change their weights to 33.3% for *Fatalities* and 66.7% for *financial cost*.

The resulting 33.3% weight for *Fatalities* would be inconsistent with the S-MAP guidance that the weight for safety should be at least 40%, even though the utility has not actually changed the trade-off between safety and cost in terms of implied VMR. The lower bound of 40% may reflect a misunderstanding that the weights reflect the "general importance" of attributes, ignoring the fact that they depend on the attribute ranges. Indeed, PG&E [PG&E RAMP 2020] implies that this limit plays a role in the high $100 million implied VSL about which TURN complained. [TURN 2018]. Note that these concerns are present whether or not the utility explicitly determines or acknowledges a VSL number.

4.4.4. Sensitivity analysis.

A best practice in developing MAVFs is to perform extensive sensitivity analysis to examine the effect of uncertainties about weights, risk attitude and other parameters. It is a challenge to estimate attribute weights that imply the value of reliability to customers, the costs of environmental impacts, let alone tradeoffs between lives and dollars, even if using estimates or recommended values from Federal agencies. How much difference do these weights make? If MAVFs are used to calculate RSEs for mitigation project, the practical question is whether plausible variations in the weights could change the relative RSEs of mitigation projects – and hence change priorities for which projects to perform given a limited budget for risk management.

In some cases, even large changes in weights may have only slight changes in relative RSEs, and so we can be comfortable with our priorities even when there are significant differences of opinion about these trade-offs. In other cases, variations in weights may have large effects on project recommendations. In sensitivity analyses, you change key attribute weights (and other parameters of an MAVF) over plausible ranges to see the effects on RSEs and other results. If the effects are small, we can be confident in recommendations on mitigation priorities. If the effects turn out to be substantial, it suggests that further work would be worthwhile to refine the most sensitive parameters.

4.4.5. Whose MAVF?

A key best practice among practitioners using MAVF and MAUF methods is to clearly identify whose preferences they represent. A MAVF can express the preferences, tradeoffs, and risk attitude of an individual, a group of stakeholders, an organization, or a society, such as the people of California. The S-MAP process is not explicit about whose preferences the MAVFs should represent -- although by assigning MAVF construction to the utilities, it might be taken to imply that each MAVF should represent the preferences of the utility that developed it.

S-MAP is explicit about one limitation: The *Financial costs* attribute should not represent the interests of the shareholders. The RAMP submissions do not discuss interviews or surveys of stakeholder groups to identify their preferences. Even the *Stakeholder Satisfaction* attribute used by SoCalGas, and SDG&E was assessed by subject matter experts, not in direct consultation with stakeholders. In any case, they assigned that attribute a weight of only 2%.

Each utility has clearly expended a very substantial effort to develop its own MAVF within the S-MAP guidelines. Each decision comes with a variety of challenges, include the choice of attributes and sub-attributes, the definition and measurement of attributes, attribute weights, scaling functions, and the treatment of uncertainty. Utilities have updated their MAVFs as they have gained sophistication and evolved in response to changes in the S-MAP guidelines reflecting comments from CPUC and intervenors. While it is interesting to see the variation among the choices made by each utility, some may see the duplication of efforts as a waste of resources.

If the MAVFs are intended to represent the preferences of each utility, it is reasonable that they might differ modestly from each other. Although it is questionable whether they should differ as much from each other as they now do in terms of risk attitude and implied value of mortality reduction. If they are intended to represent the collective preferences of their customers or of California as a whole, there may be less reasons to expect wide variation. It would be helpful for a successor S-MAP to provide more explicit guidelines on this point.

Alternatively, the CPUC might consider whether they should manage the development of a single unified MAVF to best represent the consensus values of utility ratepayers or California residents rather than require each utility to develop their own MAVF. Such a process should of course consult the utilities, the intervenors, and other stakeholders. Tradeoffs to be made between costs, reliability, and safety, and attitudes to risk are matters of great public importance.

There would be several advantages in developing a single consistent MAVF for use by all California utilities, rather than having each utility develop their own. A single MAVF would reduce duplicate efforts among utilities. It would make it much easier to compare risks and RSE across utilities. The specific circumstances of each utility will remain unique to each utility, but these are inputs to the MAVF function, rather than attributes of the MAVF function itself.

4.5. Climate related changes (trends and forecasts) affecting MAVF.

The MAVF scheme could more clearly reflect climate-related issues by including *environmental effects* as a primary attribute rather than subsuming it inside other attributes such as *safety* and *financial cost.* Key sub-attributes of environmental effects could include greenhouse gas emissions (including from natural gas leaks and wildfires), criteria pollutants, including particulates, and ecosystem damage from wildfires. Arguably, the human health effects of fine particulates and other criteria pollutants should be included in the *Safety* attribute.

For the most part, it appears that the upper bounds for key attributes including fatalities, injuries, and financial costs were set to be a bit larger than the largest historical disasters. Unfortunately, given climate-change trends towards increasing drought and tree die-offs in California, catastrophic wildfires seem likely to continue to increase in frequency and size. A trend to extreme storm events (and more capable cyber-attacks) may also increase the frequency and scope of outages. It is important that the upper bounds of attributes be high enough to encompass conceivable future catastrophes that may be even larger than in the past.

4.6. Researchable question

Should the Commission identify any guiding principles, best practices, aspirational characteristics, and/or minimum requirements for developing an RDF Multi-attribute Value Function, or another approach to combining different types of risks?

4.6.1. A statement of the issue/problem.

A key challenge of the risk decision framework is to quantify complex risks that have uncertain consequences for multiple objectives. In comparing risks and mitigation projects, it is desirable to have a single quantity to characterize each risk as well as probability distributions to characterize the uncertainty associated with this quantity. It is important that the method for quantifying the risks be clear, transparent, reasoned, and easy to apply.

4.6.2. A review of relevant background material.

MAVFs are a special case of MAUFs. These methods have a compelling theoretical basis and are practical and widely used to quantify preferences among options with multiple objectives and uncertain outcomes including attitude to risk. As such, they are well suited for quantifying the uncertain consequences of risk events as used in the risk decision framework.

There is extensive literature that shows how various forms of MAUF may be derived from decision theory based on well-defined assumptions about the kind of independence among the attributes [e.g., von Winterfeldt and Edwards, 1986; Keeney & Raiffa,1993; Abbas, 2010]. There is also extensive literature showing how decision theory, including probabilistic treatment of uncertainty and utility functions to express attitudes to risk, may be logically derived from simple compelling qualitative axioms about rational decision making [Savage, 1954; deFinetti, 1974]. There are many practical applications of MAVF and MAUF methods [e.g., Henrion, Bernstein and Swamy 2015; Abbas 2018] as well as cost-benefit analyses that illustrate the use of tradeoffs between monetary costs and lives [e.g., Howard 1984; EPA 2021]

4.7. Recommendations

Our MAVF related recommendations are shown in Table 13 (numbering for recommendations in this report carry forward so that each recommendation will have a unique number for discussion purposes.)

Table 13: MAVF related recommendations.

18. The MAVF should represent the interests of the citizens of California. A single consistent MAVF, including scaling functions, ranges, and weights, should be created to represent those interests, instead of a separate MAVF for each IOU.
19. Develop a **simplified MAVF scheme** that transforms each attribute (except cost) directly to a cost equivalent by multiplying the attribute by a trade-off value, such as Value of Mortality Reduction (VMR) for Safety, VOLL (Value of Loss of Load) for Reliability, and Social Cost of Carbon (SCC) for the greenhouse gas component of the proposed Environmental attribute. The trade-off value for each attribute replaces the current weight, range, and scaling function for each attribute in the current scheme. This simplified scheme avoids the need to estimate the maximum possible range for each attribute, and the conceptual challenge of representing the relative importance of attributes by two (or more) numbers -- weight and range. It also simplifies the current framework by replacing the separate nonlinear scaling functions for each attribute by a single nonlinear risk-attitude function which adjusts the summed costs over the attributes to account for

risk aversion or other attitude to uncertainty (as described in a separate recommendation.) The benefit (or risk reduction) of a mitigation is the reduction in overall risk-adjusted cost due to applying the mitigation. RSE remains the ratio of the risk reduction (benefit) to the mitigation cost, as now.
20. Use a single risk-attitude function (utility function) for the MAVF to represent attitude to uncertainty (risk aversion, neutrality, or tolerance) for the citizens of California, applied to the weighted sum of the (nonlinear) scaled attribute values, instead of applying nonlinear scaling functions separately to some or all attributes before combining them.
21. Use trade-off values from scientific surveys or recommended values from US Federal agencies as a reference or basis for estimating attribute weights within the MAVF. For example, estimate the value of reliability from scientific surveys of dollars per customer minute interrupted (CMI), estimate value of mortality reduction (VMR) using the standard set by the US EPA, and use the EPA recommended social cost of risk event related carbon emissions of $51/tCO2e.
22. Add Environmental effects as an attribute, including GHG emissions from gas leaks, smoke, and ecosystem damage from wildfires.
23. Define a consistent metric for each of the electric reliability attribute and the gas reliability attribute across the IOUs.
24. Use a simplified MAVF that does not use bounded attribute ranges.
25. Use Monte Carlo simulation to estimate the uncertainty in the MAVF results and RSE, and a probabilistic sensitivity method such as importance analysis (rank-order correlation) to provide improved estimates of the contribution of uncertainty to results of each uncertain assumption.

5. IOU Approaches to Wildfire RSE

The field of wildfire risk assessment and management recognizes two broad types of wildfire risk assessment–"*in situ*" and "transmitted". An *in situ* assessment of wildfire risk characterizes the risk of wildfire to assets (buildings and infrastructure) and natural resources (timber, drinking water, wildlife habitat, etc.) where they exist on the landscape, regardless of the sources[9] of the wildfires that result in the risk. Assets and resources are the "receivers" of wildfire risk (Table 14). Wildfires can damage the generation, transmission, and distribution equipment (assets) of an electric utility, which threatens reliability because the equipment could take considerable time to replace. In this case the IOUs are receivers of wildfire risk. The California Energy Commission (CEC) is currently funding an ongoing project under the Electric Program Investment Charge (EPIC) program to develop open-source wildfire risk models to assess wildfire threats to the electric power systems in California. This is an example of an electric utility as a receiver of wildfire risk.

In contrast, transmitted risk refers to the potential for wildfires arising from a particular source (or a particular location or land ownership) to cause customer-side economic impacts as well as secondary and tertiary harm to persons or damage to assets and natural resources some distance from the wildfire origin. Because utility-related wildfires tend to originate under extreme fire weather conditions, they often spread quickly and therefore become large—a significant threat to public safety.

Table 14: Example wildfire risk mitigation actions for different risk types and time horizons.

	Near-term (hours to days)	**Long-term (years to decades)**
Source of wildfire risk (safety)	• Operational restrictions and situational awareness. • Equipment settings (reclosing). • Staging field observers and firefighting resources. • PSPS.	• Install covered conductors or bury conductors underground in high-risk locations. • Sectionalize overhead distribution to minimize required PSPS footprint. • Replace equipment prone to failure.

[9] Sources can refer to a location, such as a land ownership, to a particular cause or cause class, or to a party responsible for the ignition. For land management planning, the USFS sometimes assesses wildfire risk associated with ignitions that originate on its land, regardless of the cause of the ignition. For utility-wildfire risk assessment, sources refer to wildfires that originate from electric power generation, transmission, and distribution equipment.

		• Increase inspection frequency in high-risk locations.
Receiver of wildfire risk (reliability)	• Situational awareness. • Pretreat wooden poles as fire approaches to minimize fire damage. • Stage equipment to quickly replace fire-damaged equipment.	• Using fire-resistant equipment (poles) in locations with high likelihood of wildfire. • Mitigate fuel immediately surrounding critical but sensitive equipment (e.g., substations).

5.1. Near-term versus long-term wildfire risk.

Utility-related wildfire risk is assessed (and mitigated) over two distinct time horizons. Near-term risk is the wildfire risk over the next few hours to few days. In response to a forecast of elevated near-term wildfire risk, a utility can implement any number of actions designed to either reduce the likelihood of a wildfire occurring or reduce the consequence of a wildfire on utility equipment (Table 11). Near-term wildfire risk assessment follows near-term weather forecasts and the fire growth potential associated with the forecast weather.

In locations subject to long-term wildfire risk (due to fuel, climate, topography, and equipment factors), a utility has a wide array of mitigation actions available. The grid system can be “hardened” to mitigate electric equipment as a source of wildfire risk. Hardening can entail replacing failure-prone equipment, including replacing bare conductors with covered conductors or even undergrounding distribution lines. To enable more precise PSPS events, the overhead distribution system can be optimally sectionalized to deenergize power only to the highest risk segments of a circuit. Long-term wildfire risk assessment can potentially inform optimal sectionalization. These opportunities for long-term mitigation must be identified and prioritized based not on near-term weather but on long-term climate—the relative frequency of weather types.

5.2. Utility-wildfire risk modeling approaches—best practices.

Utility-wildfire risk assessment is a relatively young field. The California IOUs, together with their vendors and the CPUC itself, have been at the forefront of the field for roughly a decade. The past, present, and future utility-wildfire risk assessment practices developed in California are likely to become a model not only for smaller utilities in California, but for the entire western United States and beyond.

Three broad wildfire risk likelihood and consequence modeling approaches are available to an electric utility: an “average-worst” assessment, “complete enumeration” of potential consequences, and “stochastic simulation” of wildfire occurrence, growth, and impact.

Average-worst—an average-worst approach quantifies the tail of the distribution of wildfire likelihood and/or consequence. Taken literally, an average-worst assessment calculates the mean of the worst (greatest) potential outcomes. For example, an average-worst assessment was employed on a project of the California Public Utilities Commission to map environmental influences on utility wildfire threat. That project first identified the top 2% of fire-weather records, then calculated the mean Ignition Potential Index of those "worst" records.

Relying exclusively on an average-worst approach could overstate wildfire risk when comparing that risk to others, including PSPS risk, which could overstate the risk-reduction capacity of PSPS under more benign conditions.

Complete enumeration—whereas the average-worst analysis focuses on the tail of the distribution, a complete-enumeration approach attempts to characterize the full range of ignition potential and fire sizes (and consequences) for the full range of possible weather scenarios. This approach classifies the influence of weather into many classes based on wind speed, wind direction, and fuel moisture content (up to several hundred unique classes). Fire-growth potential and consequence to persons, assets, and resources are simulated for each unique weather scenario. Spatially and temporally detailed climatology data is available within California to identify the relative frequency of each weather type at a 2-km resolution. However, care must be taken when aggregating the results of the individual weather scenarios to account for the increased likelihood of an ignition occurring during the extreme weather scenarios. Aggregating based only the relative frequency of the weather types will underestimate the true utility-wildfire potential. Although the climate data is available at 2-km resolution, wind models and Digital Elevation Model (terrain) data enables downscaling of wind speed, wind direction, temperature, and relative humidity to a resolution on the order of 30 to 200 m.

The Complete Enumeration approach typically simulates fire growth potential from all possible ignition locations for a relative short burning period—8-15 hours. A potential shortcoming of this approach is the current inability to simulate fires that grow large over weeks to months. The destructive potential of most utility-related wildfires arises from their tendency to occur during high-wind events, some such wildfires can become large due to long duration. The 2021 Dixie Fire is an example.

Stochastic simulation—it is possible to build a comprehensive stochastic utility-wildfire modeling system that simulates the full range of wildfire risk: ignition, escape, growth, and consequence of utility-related wildfires. Reax Engineering has used stochastic simulation for SCE, but it is not clear whether the simulations combine ignition probability with the growth simulation. Stochastic simulation permits proper aggregation of risk across tranches but does not remove the limitation of short burning periods.

Comprehensive stochastic simulation could have advantages for aggregating wildfire risk with other climate-related risks facing an electric utility, such as drought and sea-level rise. To properly aggregate all climate-related risks, the stochastic simulations for all risks would need to use the same basic trials because climate risks are not independent—periods of drought also produce more and larger fires. For example, stochastic simulation of wildfire impacts, heat impacts, and drought impacts based on the same stochastic weather event set would reveal how often those separate risks coincide temporally.

5.3. Potential use of power-law distributions.

Many fire scientists have noted that wildfire-size distributions tend to follow a power-law distribution, and that the distributions for utility-related wildfires have a shallower slope than the distribution for fires of all types [CPUC, 2021]. Parameterizing any statistical fire-size distribution requires many data points. To ensure enough data points, fire occurrence data are typically gathered over a very large area—even the state of California as a whole. A statistical fire-size distribution produced with data from a large fire-occurrence area inherently generalizes any spatial variability in growth potential that may be present within the fire-occurrence area, making this approach far less granular than other approaches. For example, fires originating on Angel Island, located in the San Francisco Bay, can reach a maximum of 740 acres[10]—the size of the island—whereas fires originating within much of the northern part of the state are relatively unconstrained by barriers to fire spread and could reach more than 1MM acres.

Power-law and other statistical distributions may have relevance to utility-wildfire risk assessment and management only at the enterprise level. However, at the enterprise level it will be necessary to aggregate wildfire risk with other risks facing electric utilities, including other climate-related risks like sea-level rise and drought. Aggregating those risks cannot be done properly without temporal coordination of the risks. For example, the probability of exceeding a certain wildfire size or consequence during a given time is not independent of the probability of also having drought-related impacts during that time, because climate affects both.

As currently employed by the IOUs, wildfire simulations are limited to relatively short fire simulations of up to 8-15 hours. Such simulations are unlikely to properly simulate very large wildfires, such as the 2021 Dixie Fire. PG&E has explored the use of power law distribution recommended by the Mussey Grade Road Alliance (MGRA) and has found it provides a suitable fit to observed wildfire consequences. (Reference: PG&E TY2023 GRC Exhibit 2, WP 1-13) However, power-law distributions provide suitable fits to observed wildfire consequences only at very large scales (e.g., an entire service territory). They can be used for enterprise-level risk, but they do not provide the highly granular information needed for identifying and prioritizing mitigation activities.

A hybrid approach may be needed to capture the advantages of both approaches—highly granular short-duration wildfire simulations and broad-scale power-law distributions for longer duration fires currently missed.

[10] An October 2008 wildfire burned 380 acres of Angel Island.

5.4. CPUC High Fire Threat Districts.

All three IOUs rely to some extent on the CPUC's High Fire Threat Districts (HFTDs), which identify locations of elevated (Tier 2) and extreme (Tier 3) risk of utility-related wildfire. To support development of the HFTDs, the CPUC formed an Independent Expert Team (IET) to produce a map of the environmental influences (climate and fuel) on the potential for utility-related wildfires across the state of California. The main result of that project was a spatial dataset called Utility Threat Index (UTI), a relative index of the likelihood of a utility-related wildfire ignition that escapes initial attack. The analysis in that report reviewed climate data over ten-year period (2004-2013) and had no specific accommodation for changing climate.

During the subsequent Fire Map 2 process, the CPUC formed an Independent Review Team (IRT) to review proposed wildfire threat tier assignments made by the utilities. To support their reviews, the IRT extended the UTI by adding spatial information on the consequences of wildfires originating across the state. The consequence data was informed by wildfire simulations performed using the FSim large fire simulator (Finney and others 2011). Those simulations were calibrated to a reference period of 1992-2015, also with no specific accommodation for changing climate. This impact raster was combined with the original UTI to produce a dataset called *Integrated* UTI (iUTI). The iUTI was available to the IRT as one factor for reviewing threat tier polygons proposed by the utilities.

It is now widely accepted that fire seasons are becoming longer—there are more days of the year during which fire spread is possible. That leads not only to a greater chance of ignition given a utility-related failure, but also to longer-duration fires that therefore become larger and potentially expose more persons, homes, infrastructure, and ecosystem services to harm or damage. The changing climate brings increasing likelihood and consequence of wildfire. Because the data and modeling underlying UTI and iUTI did not explicitly account for changing climate, it likely underestimates the current and future extent of elevated- and extreme-risk land in California.

Improvements to the HFTDs are necessary to increase granularity of the threat districts, account for the influence of changing climate on wildfire risk and increase consistency in mapping method across utilities.

5.5. IOU Wildfire risk modeling approaches

In this section we summarize the wildfire risk modeling approach used by the four IOUs in their RAMP, WMP, and GRC filings.

SoCalGas supplies natural gas to customers in southern California. Its equipment is largely underground and is not known to have caused a wildfire, though the potential certainly exists due to a catastrophic failure event. Routine gas operations and maintenance—cutting, grinding, welding, etc.—can result in a wildfire. Some wildfire damage to the aboveground portions of the SoCalGas equipment is possible but was not described as a significant threat to gas operations. For these reasons, and because the gas operations and equipment of PG&E and SDG&E is not covered in this section, no further discussion of wildfire risk modeling from SoCalGas is required.

5.5.1. SCE wildfire risk modeling

As expected in the current fire environment, SCE's wildfire risk modeling focuses primarily on its equipment as a potential source of risk rather than a receiver of risk. SCE is now using several of Technosylva's utility-wildfire risk modeling tools: Wildfire Risk Reduction Model (WRRM), FireCast, and FireSim.

For long-term modeling of its equipment as a source of wildfire risk, SCE is transitioning to using Technosylva's WRRM framework, which treats wildfire risk as the product of Probability of Ignition (POI) and the consequence of a wildfire if one were to occur at a given location on the landscape. SCE's POI component uses machine learning to estimate failure rates for certain distribution assets as well as transmission and sub-transmission equipment. The POI modeling covers the entire service territory. The WRRM framework is about identifying locations of higher versus lower risk within a service territory given the current climate to inform current decisions about mitigating wildfire risk. Cal-adapt scenarios are about trends in fire probability over time across the state.

The consequence component is modeled by simulating fire growth and its impact to structures and population. SCE is now using Technosylva for producing updated wildland fuel data layers and for fire growth modeling using 400+ weather scenarios. This appears to be an "average-worst" approach (as described above). It is not clear from the documents reviewed how conditional consequence for a given asset location is accomplished. The consequence modeling covers the HFRA plus a 20-mile buffer.

For near-term modeling of its equipment as a source of wildfire risk, SCE is now using Technosylva's FireCast, which assesses near-future fire growth potential (and associated potential consequences) based on SCE's gridded weather forecasts. This approach is sufficiently detailed to allow assessment of circuits, circuit segments, and even individual assets. FireCast is limited to 8 hours of fire growth, so it underestimates the potential for consequences associated with long-duration wildfires.

For near-term modeling of wildfire risk to its equipment (and for situational awareness to support electrical operations), SCE uses Technosylva's FireSim, which predicts the near-term growth potential of active fires.

No information was found regarding SCE's long-term assessment of wildfire risk to its equipment. SCE does account for long-term transmitted risk.

SCE is using Technosylva to produce up-to-date fuel maps for fire modeling. The fuel maps are updated semi-annually to reflect recent fuel changes due to wildfires and other disturbances. The fuel data are not available for review, and the methods used are not published.

5.5.2. SDG&E wildfire risk modeling

SDG&E's wildfire risk modeling also focuses on its equipment as a potential source of risk rather than a receiver of risk. For long-term modeling of its equipment as a source of wildfire risk, SDG&E developed a WRRM beginning in 2013, with updates in 2017 and 2021. The WRRM was intended to guide prioritization of system hardening. The Wildfire Next Generation System (WiNGS) model modifies and extends the WRRM and allows assessment of circuits and circuit segments. The WiNGS system guides grid hardening investments at the circuit-segment level. SDG&E used Technosylva for fuel mapping and wildfire growth and consequence modeling within the WRRM, likely with a "complete enumeration" approach as described above.

For near-term modeling of its equipment as a source of wildfire risk, SDG&E developed WRRM-Ops in 2014 and then WiNGS-Ops in 2020. SDG&E's Circuit Risk Index models the likelihood of a fire ignition as the product of failure probability and ignition probability given a failure. Failure probability is highly sensitive to gust wind speed (X^3), but also on asset factors like conductor type, as well as wind direction and elevation range. Ignition probability is a function of weather type, fuel sources, and conductor type, which means the index produces span-level ignition probabilities. The WiNGS-Ops system combines conductor risk and maximum consequence from WRRM to estimate wildfire risk for a circuit segment, which permits comparison to PSPS risk.

For near-term modeling of wildfire risk to its equipment (and for situational awareness to support electrical operations), SDG&E uses what is now Technosylva's FireSim, which predicts the near-term growth potential of active fires.

No information was found regarding SDG&E's long-term assessment of wildfire risk to its equipment. SDG&E does account for long-term transmitted risk.

SDG&E is using Technosylva to produce up-to-date fuel maps for fire modeling. The fuel maps are updated semi-annually to reflect recent fuel changes due to wildfires and other disturbances. The fuel data are not available for review, and the methods used are not published.

SDG&E converts Technosylva consequence results into their MAVF framework.

5.5.3. PG&E wildfire risk modeling

Like the other IOUs, PG&E's wildfire risk modeling focuses on its equipment as a potential source of risk rather than a receiver of risk. For long-term modeling of its equipment as a source of wildfire risk, PG&E has developed the Wildfire Distribution Risk Model (WDRM). Their risk model follows the standard approach of measuring wildfire risk as the product of ignition probability and ignition consequence. Ignition probability includes a Vegetation Ignition Model and an Equipment Ignition Model. The WDRM informs system hardening, enhanced vegetation management, and inspection cadence. The probability of ignition models employs a Maximum Entropy (MaxEnt) approach that identifies locations with conditions like past ignition points. PG&E is evaluating Technosylva's WRRM to support long-term wildfire risk modeling. That modeling is currently limited to the first 8 hours of fire growth.

For near-term modeling of its equipment as a source of wildfire risk, PG&E is now using Technosylva's FireCast application, which assesses near-future fire growth potential (and associated potential consequences) based on PG&E's gridded weather forecasts. Previously, PG&E used Reax Engineering for wildfire growth and impact modeling.

PG&E is using Technosylva to produce up-to-date fuel maps for fire modeling. The fuel maps are updated semi-annually to reflect recent fuel changes due to wildfires and other disturbances. The fuel data are not available for review, and the methods used are not published.

PG&E is also building out-year fuelscapes (the estimated fuelscape for 2030, for example) to support long-term assessment of their equipment as a source of risk. Using an out-year fuelscape for long-term planning is important for correctly identifying locations where post-disturbance vegetation growth is expected to increase wildfire risk during the planning horizon.

The consequence modeling provided by Technosylva includes impacts to population, buildings, acres burned, and a proxy for fire intensity (rate of spread and flame length). It is not clear how these separate measures are combined. PG&E converts these consequence results into their MAVF framework. The consequence model does not currently account for damage to resources like timber, drinking water, wildlife habitat, carbon emissions, etc.

5.5.4. Summary

All three IOUs are using high-quality, highly granular climatology and weather forecast data to inform fire growth simulations in support of near-term and long-term assessment of electric equipment as a potential source of risk, and near-term assessment of wildfire risk to its equipment and operations.

All three IOUs are currently using or evaluating Technosylva's WRRM, FireCast, and FireSim software (or some variation of it). The fire growth modeling in those applications is highly granular, but potentially underestimates the fire growth potential of fires that become large and damaging over many weeks and months rather than hours.

All three IOUs are using Technosylva for current-condition fuel mapping. At least one IOU is also using Technosylva to produce an out-year fuelscape for long-term risk mitigation planning. The fuel data are not available for review, and the methods used are not published.

No information was found from any IOU about assessing long-term wildfire risk to its equipment. This type of wildfire risk assessment is less important than assessing its equipment as a potential source of risk.

All three IOUs are now using Technosylva for modeling wildfire consequence. Technosylva appears to be using impact to population, acres-burned, buildings, and fire intensity in their impact model, but it is not clear whether all three IOUs use the same impacts. The wildfire simulations that form the basis of the consequence are limited to the first eight hours of fire growth following ignition. Further, the IOUs may be assessing long-term consequence by reviewing the worst-case fire weather days—the IOUs are each reviewing a different number of worst-case days.

5.6. Recommendations

Our wildfire related recommendations are shown in Table 15.

Table 15: Wildfire related recommendations.

26. Require the IOUs to extend their wildfire risk assessments to include the consequences of long-duration utility-caused wildfires in addition to their current assessment of short-duration fires (up to eight hours).
27. Adopt a wildfire risk type classification. This will enable consistent descriptions of wildfire risk assessment approaches for near-term decisions like PSPS, versus long-term decisions like equipment replacement, undergrounding, etc. It will also highlight the different approaches for assessing IOU equipment as a source of the risk versus the risk to their infrastructure and equipment of wildfire of any cause.
28. Update the High Fire Threat District (HFTD) map to 1) increase its granularity, 2) account for fuel changes that have taken place since the map was created, and 3) account for the effects of climate change on wildfire size and consequence. An updated HFTD map should be generated using a single analytical approach across the entire state.
29. To guide future decisions on when and where to choose enhanced powerline safety settings (EPSS), covered conductors, or underground, it would be helpful to ask the utilities to address these questions more directly using the RDF framework for selected circuits in various situations – e.g., by tier 3 vs tier 2 fire safety regions, vegetation, and terrain type – and to do so with a framework that allows direct comparison of their results to identify the sources of the differences.
30. Update the consequence model to account for damage to resources like timber, drinking water, wildlife habitat, particulate emissions, carbon emissions, etc.
31. Develop or standardize on a statewide out-year fuelscape supporting a long-term assessment of risk priorities.

32. Adopt a wildfire risk type classification like that presented in Table 11. This will enable clearer descriptions of their wildfire risk assessment approaches for near-term decisions like PSPS versus long-term decisions like equipment replacement, undergrounding, etc. It will also highlight the different approaches for assessing their equipment as a source of the risk versus the risk of wildfire of any cause to their equipment.

6. IOU Approaches to Climate Change

In this chapter we compare select elements of each IOU's approach to climate change adaption. It is not our goal to use selected climate change adaption metrics to rank the approach of each IOU against one another, but instead to present elements that we deem applicable to climate change adaption; per the CPUC definition of adaption and compare what each IOU is presently doing (actions, plans, research, objectives) with regards to each approach element.

The CPUC definition of climate adaption per preceding 19-10-054 is, "*adjustment in natural and human systems to a new or changing environment. Adaptation to climate change for energy utilities regulated by the Commission refers to adjustment in utility systems using strategic and data-driven consideration of actual or expected climatic impacts and stimuli or their effects on utility planning, facilities maintenance and construction, and communications, to maintain safe, reliable, affordable and resilient operations.*"

The Level 4 team used the above definition to arrive at number of elements that drive an IOU's climate adaption approach and compared for commonalities, differences, and what we believe are long term goals of each IOU regarding climate change adaption.

Specifically, the Level 4 team aims to demonstrate how the IOUs compare in:

1. Approach and time-horizon stated or implied, for climate change mitigation and impact management endeavors.
2. Proposed and/or implemented risk mitigations.
3. Mitigation inclusivity: do IOUs account for less-visible but present third-parties who may be greatly impacted from climate change threats and not usually well represented in mitigation strategies?
4. Utilization of external data to strengthen climate change impact assessment and mitigations?
5. Asset hardening and Sea-Level Rise preparedness?
6. Utilization of external impact indices.

Utilities are expecting to be very broadly impacted by climate change [Zamuda, C et al., 2020]; three critical drivers of this impact are sea-level rise, the expected increased demand for power due to climate change, and current unpredictable weather patterns that cause and/or strengthen seasonal wildfires [Zamuda, 2020]. This is not a comprehensive list of climate change approach drivers, but IOUs acknowledge these considerations are critical in the development and management of their comprehensive climate change impact strategy.

The Level 4 team reviewed a selection of climate change mitigation materials from the IOUs as well as outside primary and secondary sources to arrive at the elements identified in to compare current baseline IOU approach to climate change adaption, from the four IOUs. Please see Table 16 for elements and definitions, and potential impact.

Table 16: Climate change approach elements and definitions.

CC[11] Risk Management Element	Definition	Potential Impact
Time-Horizon	Length of time over which climate change strategies are reviewed	Demonstrates a near-term and/or forward-looking approach in climate change readiness; near-term management vs long-term stability
Adaption or resilience	Is the overall approach to addressing climate change one of adaption or one of resilience	Following either/or can have significant impact in how IOUs operate and invest now to operate under more critical CC conditions
Asset Planning and Load Forecasting	Climate change impact on IOU planning for deployment of energy assets and demand forecasts	Long term impact in transmission and distribution of energy, as well as maintenance
Weather and hazard Monitoring	Technologies applied to monitoring weather and hazard patterns; specifically, as they apply to addressing climate change impact	Near-term, potentially long-term, impact through IOU policies and procedures for operating under peak or critical demand periods
Mitigations; internal and external costs	Inclusion of cc mitigation strategies for IOU assets and externalities; costs by borne by a third party	Ensures internal and external risks posed by CC are included in CC mitigation strategies
Application of External Risk Models	Utilization of external risk models to guide how IOU will apply its adaption and/or resilience endeavors	Internalizes the benefits from the inclusion of CC mitigation models developed by experts outside of the IOU
Sources of Data	Data sources used to address climate change risks; input for internal models used	Internalizes the benefits from the inclusion of CC mitigation models developed by experts outside of the IOU
Asset Hardening and SLR preparedness	Modification of generation, transmission, and distribution assets due to expect impact from CC	Critical determinant of a successful application of an adaption or/resilience planning
External Impact Indices	Tools or standards developed by external authorities to define, measure, and/or identify impact of climate change in specific instances	Demonstrates the application of a consistent approach in impact identification and mitigation

Publications from the utilities were reviewed against the elements; information that falls into the categories of each element was reviewed and summarized. We are not specifying any approach is the standard to follow, but instead we are providing a

[11] Climate Change.

summary of objective information that demonstrates how the IOUs are utilizing a time-horizon in their approach to climate change mitigations, how they compare in data sources used in the development of their adaption strategy etc.

Please see below for comparisons of the IOUs climate change approach

6.1. SDGE and SoCalGas Climate Change Approach. [SDG&E, 2021]

SDGE and SoCalGas, both owned and operated by Sempra, present a climate change adaption approach with increased energy storage projects, decentralization of grids through microgrids, implementation of technologies that soften impact from PSPS events, and the foundational interest in providing vulnerable populations with improved energy access. Critical elements of the SDGE/ SoCalGas climate change approach are:

- Current and on-going energy storage projects capable of hardening grid regions with greater exposure to climate change-related disruptions, these include (1) regional all-day renewable energy availability; *intermittency*, (2) decreased grid disturbances during peak-need events, and (3) buffering necessary to mitigate grid strains.
- Additionally, energy storage developments will play a critical role in the integration of planned microgrid projects; micro grids will be deployed in areas that typically have a concentration of users that are especially vulnerable to peak-need and seasonal disruptions such as fires.
- Together, energy storage and microgrid projects, are set to provide vulnerable users and utilities benefits that bolster energy stability with and without the risk of climate change; these include decreased risk of fires spreading through utility equipment, softened impact from PSPS events, and increased stability of energy access for rural hospitals, Access and Functional Needs (AFN) communities, infrastructure, and customer base.
- Utilization of the WRRM by SDGE; this model leverages 30 years of weather data to create probability-driven risk maps.
    - Technology-generated probable emergency scenarios and hardware failure rates to determine resource allocation decisions.
    - The model was subsequently automated to inform daily operations using weather drivers such as fuel moisture and other ignitors.
- SDGE and SoCalGas both use the California Department of Forestry and Fire Protection (CAL FIRE) historical data and “Redbooks” data for safety risk assessments; data is externally generated.
- Application of Access and Functional Needs (AFN), Generator Grant Program (GGP), and Medical Baseline (MBL) support models to identify historically

marginalized residents and/or residents with higher vulnerability to climate change related impact; programs include mitigations of potential PSPS events and energy access needs that are independent of climate change impact.

6.2. SCE Climate Change Approach. [SCE, 2021]

SCE follows a climate change adaption approach inclusive of mitigations that intend to stabilize energy amid ongoing threats from wildfires and imminent threats like sea-level rise. SCE demonstrates a more advanced position relative to the other IOUs in climate modeling and weather data generation; this is due to the utilization of IBM's higher frequency weather forecasting suite, and the maintenance of multiple climate change forecasts with various time horizons, each with varying input stimuli and resulting outputs to inform appropriate mitigations and timing. Highlights from SCE's climate change approach include:

- Decentralized distribution, specifically for areas that are in high-risk for fires and thus mitigation tactics such as PSPS; this includes the implementation of microgrids and energy storage facilities.
- Maintenance of three different climate change impact forecasts; a short-term (2018 – 2023), medium term (2030), and long-term impact forecast (2050) and mitigation plan, a near term and long-term forecast covered in detail in the RAMP filing, and a report, last printed in 2016, that details expected climate change impact and mitigations over the next 100 years.
- Climate change risk analysis with demonstrated impact from 10 abnormal weather triggering events; these include major storms, and consequences such as increased energy procurement costs due to adverse events, and other compounding factors.
- Application of four impact classifications; extreme, gradual, cascading, and compounding; to categorize climate change impact.

Regarding disadvantaged communities, SCE uses the externally defined vulnerability indexes CalEnviroScreen and the California Healthy Places Index to support their process of identifying and addressing expected increased impact of climate change on already vulnerable communities.

Foundational weather forecasting that serves as an input to all climate change risk modeling is based on a weather data-set that spans from 1976 to 2017; 1976 being a year when climate experts generally agree as being the beginning of a shift towards the current trends of hotter regular temperatures and leading up today's more visible abnormal weather patterns. [Trenbert, K et al,2007]

Implementation of IBM's Forecast on Demand System for weather forecasting, significantly increasing previous resolution and update frequency.

Deployment of new Fire Potential Index modeling hardware that serves as a primary tool for resource allocation and optimization decisions during weather emergency situations. [SCE, 2021]

6.3. PG&E Climate Change Approach. [PG&E, 2020]

The PG&E approach to climate change adaption is highly concentrated on data integration with extensive on-going research on how to include different risk stimuli as parameters in the decision-making framework. Most risks deemed applicable to the PG&E climate change response currently do not have data integrated into risk models due to on-going research to find a statistically significant link between the risk and long-term climate change forecasts, see Table 17.

Most other elements of the PG&E climate change approach are identical to that of other IOUs; similarities include how climate change risks are identified and integrated into the risk modeling. Like other large entities PG&E is following an approach of grid decentralization to serve areas with a current and expected higher-impact from climate change-related risks. Elements of the decentralization plans include microgrids, energy storage, and other grid resiliency endeavors that improve continuity for high-impact customers, especially during peak-need and adverse events.

Regarding the threat of sea level rise, PG&E climate change vulnerability assessments demonstrate on-going collaboration with external experts (academia, governing agencies) regarding threats to PG&E assets from a projected 24 inches of sea level rise by 2050 [PG&E, 2016]. The research is on-going, with no immediate plans for the impact of the long-term scenarios.

Table 17:PG&E climate change risk factor quantification and model integration status.

Risk [PG&E, 2020]	**Status of Climate Data Integration**	**Explanation of Climate Change Quantification Status**
Wildfire	Integrated into Model.	
Failure of Electric Distribution Overhead Assets	Integrated into Model.	
Failure of Electric Distribution Network Assets	Applicable but not integrated, pending further research.	Available data shows limited historical natural hazard impact. Developing statistical relationship between climate-driven natural hazards and equipment failure.
Loss of Containment on Gas Transmission Pipeline	Applicable but not integrated, pending further research.	Available data shows limited historical natural hazard impact. Developing statistical relationship between climate-driven natural hazards and equipment failure.
Loss of Containment on Gas Distribution Main or Service	Applicable but not integrated, pending further research.	Available data shows limited historical natural hazard impact. Developing statistical relationship between climate-driven natural hazards and equipment failure.
Large Overpressure Event Downstream of a Gas	Not applicable.	Asset failure insensitive to natural hazards based on available data.

Measurement and Control Facility		
Employee Safety Incident	Applicable but not integrated, pending further research.	Available data shows limited historical natural hazard impact. Developing statistical relationship between climate-driven natural hazards and employee safety.
Contractor Safety Incident	Not Applicable.	Difficult to build relationships between long-reaching climate change issues and risk events.
Third Party Safety Incident	Not Applicable.	Difficult to build relationships between long-reaching climate change issues and risk events.
Motor Vehicle Safety Incident	Applicable but not integrated, pending further research.	Difficult to build relationships between long-reaching climate change issues and risk events.
Real Estate and Facilities Failure	Applicable but not integrated, pending further research.	Available data shows limited historical natural hazard impact. Need for site-specific flood analysis.
Large Uncontrolled Water Release	Applicable; De facto integrated via existing FERC risk methodology.	Required Federal Energy Regulatory Commission (FERC) dam risk assessment is conservative by design and incorporates consideration of past observed and likely future events when considering the magnitude of extreme floods.
Wildfire	Integrated into Model.	
Failure of Electric Distribution Overhead Assets	Integrated into Model.	
Failure of Electric Distribution Network Assets	Applicable but not integrated, pending further research.	Available data shows limited historical natural hazard impact. Developing statistical relationship between climate-driven natural hazards and equipment failure.
Loss of Containment on Gas Transmission Pipeline	Applicable but not integrated, pending further research.	Available data shows limited historical natural hazard impact. Developing statistical relationship between climate-driven natural hazards and equipment failure.

6.4. Summary Comparison Across IOUs.

Table 18: Climate Change summary across IOUs.

Climate Change Approach	SDGE /SoCalGas [SDG&E, 2021 and SoCalGas, 2021]	PG&E [PG&E, 2016 and 2020]	SCE [SCE, 2018]
Time-Horizon	Three-time horizons.	Near-term and long-term climate change vulnerability assessment.	Three-time horizons; with a focus on near term (2018-2023) and long term (2018-2050) impact; additionally maintains a 100-year climate change impact study.
Decentralization	microgrids, energy-storage, support of vulnerable users.	microgrids, energy-storage, support of vulnerable users.	microgrids, energy-storage, support of vulnerable users.
Asset Planning and Load Forecasting	Optimization between difference sources per need forecasts.	Climate-change driven utility planning, maintenance, and construction.	Climate-change driven relation of assets.
Weather and hazard Monitoring	WRRM, WRRM-Ops models, Technosylva forecasting services, Fire Potential Index (FPI); PSPS.	Development of a foundational approach to weather monitoring; Technosylva forecasting services; PSPS.	Climate model 10 weather-related triggering events; development of weather modeling tool with IBM; Fire Potential Index model; Technosylva forecasting services; PSPS.
Plan for externalities and impact to disadvantaged communities	Solutions in CC impact inequity; Microgrids and energy storage projects; anticipation of energy affordability challenges.	Microgrids and energy storage projects.	Mitigations include funds to manage current risks and provides community grants in response to CC risks; microgrids.
External Risk Model Utilization	No mention of specific external climate change models followed; collaboration with external experts in the development of WRRM.	Limited application; acknowledged, but not used to drive assessment of CC risk decisions.	No mention of specific external climate change models followed.
Sources of Data for Climate Change mitigations	Calfire Data / Redbooks; San Diego Supercomputer Center (SDSC) collaboration; Wings model.	Calfire Data / Redbooks, weather forecasts from various sources; multiple CC sources currently in development.	Cal fire Data / Redbooks; academic research, internal and external climatologists/ meteorologists; used weather data from 1976 to 2017 as input; IBM weather data.
Asset Hardening and SLR preparedness	Distribution Overhead System Hardening program.	Multiple on-going studies reviewing short- and long-term impact to assets from SLR.	Change in specifications to address increased heat; increased system redundancy.
External Impact Indices	CalEnvironScreen and California Healthy Places Index.	CalEnvironScreen and California Healthy Places Index.	CalEnvironScreen and California Healthy Places Index.

6.5. Recommendations

Our climate change related recommendations are shown in Table 19

Table 19: Climate change related recommendations.

33. Climate change related risk Bow Tie inputs should be adjusted to reflect climate change related characteristics. In particular, climate change driven trendlines may be non-linear, and climate change impacted probability distributions may be skewed toward more extreme events, rather than distributed in accordance with a normal distribution curve.
34. Correlations between climate change related risk Bow Tie inputs (e.g., temperature, wind, drought) should be defined, modeled, and incorporated in the risk models.
35. Estimates of MRR and hence RSE from mitigations with long-term effects, such as covered conductors or undergrounding, should consider likely increases in the frequency and sizes of wildfires, and hence more frequent use of PSPS, in the absence of such mitigations, based on the best available estimates and ranges of the effects of climate change.
36. Risk Bow Tie outputs should be adjusted to incorporate greenhouse gas emissions, associated with risk events, using an accepted cost per added emission ton, such as the EPA recommended social cost of risk event related carbon emissions of $51/tCO2e.
37. IOUs should provide an inventory of assets that will be threatened by rising sea-levels and increased storm surges due to forecast climate change related impacts at ten-year increments over a fifty-year period, along with a plan for mitigating those threats.

7. IOU Approaches to PSPS and other high-stakes mitigations

While it will not be news to the CPUC, California utilities, and intervenors, it is important to acknowledge that few corporate decisions are of greater public concern or have higher stakes for a company's customers, employees, and shareholders than the public safety power shutoff (PSPS) decisions made by California electric utilities. The Camp Fire in November 2018, ignited by a faulty PG&E transmission line that had not been de-energized, burned 153,335 acres, destroyed over 18,000 structures including the town of Paradise, resulting in 85 fatalities, with a total cost estimated at over $16.6 billion. The consequences for PG&E included filing for bankruptcy, a settlement offer of $13.5 billion for wildfire victims, and conviction on 84 counts of involuntary manslaughter. The primary goal of PSPS is, of course, safety—to reduce the chance of such outcomes for the public and the company, but it is also the case that the inconvenience and cost of PSPS outages have led to widespread public discontent among customers. Some have accused the utilities of excessive caution in preemptively shutting off power without adequate recognition of the outage costs to customers [Lesser & Feinstein, 2020].

California utilities have been working to refine PSPS protocols and to mitigate the effects of shutoffs, including earlier and more effective warnings, segmenting circuits, and providing batteries, generators, and microgrids to some of the most electricity-dependent customers. At the same time, they are expanding programs to reduce the danger of igniting wildfires, including vegetation management, and line hardening. The RDF and RSE are designed to assist utilities and the CPUC to identify which mitigations will be most cost-effective to reduce the frequency and impacts of PSPS outages as well as the risk that electric equipment will ignite wildfires.

7.1. Approaches of the four IOUs.

In this section we summarize key issues in applying the RDF and RSE to help evaluate mitigations directed at reducing the frequency and effects of wildfires and at reducing the impacts on customers of PSPS events. We discuss whether or how each utility addresses each issue, and strengths and weaknesses of the approach. Although the focus is on how PSPS and mitigations relate to wildfires, some of these issues generalize to most or all mitigations to which the RDF is applied.

Table 20 summarizes selected issues of how each utility applied the RDF and RSE framework to PSPS mitigations, based on the most recent RAMP submission from each utility.

Table 20: Summary of PSPS approaches.

Issues	Utility		
	SCE	**PG&E**	**SDG&E**
Year of RAMP Report	2018	2020	2021
Plan dates	2018-2023	2020-22 & 2023-26	2022-24
Time horizon	To 2023	Life of the asset	Life of the asset
Discount rate for mitigation costs	No (explored discounts in Appendix 1)	7.1% (ATWACC)	Inflation rate (constant
Discount rate for risk reduction			3%
Readability factor (scaler) for risks	1 (no factor)	1000	100,000
Include outage impacts in PSPS analysis	No	Yes	Yes
Interactions between mitigations	No?	Yes	Yes?
Cost and benefits of PSPS	No	No	No
Covered conductors vs. undergrounding	Yes	Yes	Yes
Sensitivity analysis	Yes for time horizon and discount rate	No	No

This draft review discusses the treatment of PSPS and related types of mitigation in each utility's most recent RAMP submission, SCE in 2018, PG&E in 2020, and SDG&E Sempra in 2021. The utilities have continued to refine and expand their analyses of these mitigations over time, with feedback from CPUC and intervenors -- for example, as part of the S-MAP Phase 2 process, and as evidenced in SCE's 2021, Wildfire Mitigation Plan Update in February 2021 [SCE 2021]. So, some apparent weaknesses may have already been remedied.

7.1.1. Time horizon.

Many mitigations, such as covered conductors or undergrounding conductors, have significant capital and installation costs and a long lifetime impact. PG&E and SDG&E appear to use the asset lifetime as the time horizon for fair accounting to estimate risk reduction and costs. SCE presents its primary results on risk reduction, costs, and RSE using a 6-year planning horizon [SCE RAMP 2018, p1-25]. SCE also conducted a pilot experiment to explore the effects of a 50-year horizon for the Wildfire Covered Conductor Program, which they report increased the RSE by a factor of 18 [SCE RAMP 2019, IX. Appendix 1].

7.1.2. Net present value and discount factors.

S-MAP requires that a benefit in a future year is of less value than the same benefit in the present year. SCE did not apply a discount for benefits or costs in the main RAMP report. In an appendix, they explore a pilot methodology which applied various discount rates (and a long-time horizon), which they found materially changed RSE results [SCE RAMP 2018, Appendix 1].

PG&E and SDG&E addressed this by discounting benefits in future years. PG&E calculated NPV using the same discount factor for benefits (risk reduction score) and investment costs, in accord with a recommendation from TURN [PG&E RAMP 2020, p1-15, 3-25]. They advocate using the same discount for benefits and cost for a fair year by year comparison. They use PG&E's After-Tax Weighted Average Cost of Capital (ATWACC) of 7.1% per year for both benefits and costs.

SDG&E used different discount rates for benefits and costs. For benefits, they use 3% based on Federal recommendations from CDC [SDG&E, 2021, C-32]. They present mitigation costs in constant dollars to be consistent with requirements for GRC framework [SDG&E, 2021, C-33], which seems to imply a discount that reflects inflation but not their cost of capital.

7.1.3. Readability factor for risks.

The Mitigation Risk Reduction (MRR) scores (difference between risk before and after mitigation) are often small numbers much less than 1. PG&E, SDG&E, and SCE therefore multiply them by a readability factor or "scaler" to make them easier to read: 1,000, 100,000, and 1 billion, respectively. Similarly, some present mitigation costs in thousands or millions of dollars, which make them easier to read. But they seem to use different factors when computing RSE = MRR/Cost. These differences make it challenging for reviewers to compare results.

7.1.4. Include outage impacts in PSPS analysis.

When evaluating PSPS as a mitigation for the risk that electric equipment might ignite wildfires, it is important to include the impact of outages on customers in the reliability attribute, as well as the reduction of wildfire risk, primarily in safety and financial cost attribute. SCE explicitly excluded the impact of outages in estimating RSE of PSPS its 2018 RAMP report, where PG&E and SDG&E included them in their RAMP Reports in 2020 and 2021.

7.1.5. Interactions between mitigations and portfolio evaluation.

A key challenge in estimating MRR and RSE is that a mitigation may increase or reduce the MRR of another mitigation. For example, consider PSPS impact reduction projects, such as sectionalizing or segmenting lines to allow finer grained PSPS that affects fewer customers, and subsidizing batteries, generators, and microgrids to reduce the effect of outages on high-risk customers. These mitigations reduce the impact of outages from PSPS events, and hence *increase* the MRR and RSE of PSPS. On the other hand, mitigations that reduce the chance of energized circuits causing a wildfire, such as vegetation management, covered conductors, or undergrounding, reduce the need for and frequency of PSPS and so *reduce* its MRR and RSE.

The point is that you cannot evaluate an individual mitigation without knowing what other mitigations may also be selected. Hence, you cannot simply add the MRRs for a set of mitigations to estimate their combined MRR and RSE. When mitigations interact in their effects, you must evaluate and compare alternative *portfolios* of mitigations rather than consider them individually.

PG&E gives a helpful explanation of this issue using the example of how undergrounding a line avoids the need for and cost of vegetation management [PG&E RAMP Briefing 2020, slides 30 and 31]. They propose a way to estimate the marginal value (MRR) of a mitigation when included in a bundle of mitigations that apply to the same lines or areas by reducing the value of each mitigation in proportion to how much the collective MRR of all the mitigations in the bundle is less than the sum of their individual MRRs. One can use a similar method for mitigations that are *synergistic* – i.e., who's joint MRR is larger than the sum of their individual MRRs.

A recognition of these interactions is presumably why PG&E presents most results for mitigation projects relating to wildfires and PSPS in terms as evaluations of portfolios of mitigations, for example combining PSPS and PSPS Impact Reduction Initiatives (M5) and other projects [PG&E RAMP 2020, p10-73 to 10-77]. Similarly, SDG&E analyzes PSPS Events and Mitigation of PSPS Impacts together [SDG&E RAMP 2021, p 1-115], although not in combination with PSPS Sectionalizing, or Enhanced Vegetation Management [p 1-111, 1-114]. SCE appears not to treat these interactions explicitly [SCE RAMP 2018].

7.1.6. Covered conductors versus undergrounding overhead lines.

The need for PSPS can be reduced or eliminated by reducing the chance that energized lines might ignite a wildfire. A critical decision facing each utility is whether and where to convert lines to covered conductors or to bury lines underground in HFRAs. Replacing overhead bare wires with covered conductors greatly reduces the chance of ignition from contact with vegetation, between lines, or downed lines, with a conversion cost in the region of $300,000 to $450,000 per mile. Underground conductors are commonly used in dense urban environments.

Undergrounding wires is highly effective in reducing the ignition of wildfires and saves most costs of vegetation management but has a steep cost of up to $4 million per mile. Table 21 presents a summary of selected system hardening mitigations for the three utilities from their RAMP submissions. *Pages* identifies the page numbers in the RAMP submissions. *Miles of conductor* indicates the number of miles of Bare wire, CC

(Covered Conductor), and UG (undergrounding). For SDG&E MRR is specified as a percentage of original risk. Units of RSE vary according to readability factor.

Table 21: Summary of system hardening mitigations.

System Hardening Mitigations			Miles of conductor					Total cost	
	Pages	Years	Bare	CC	UG	Total	MRR	$millions	RSE
SDG&E SEMPRA RAMP 2021									
Proposed	1-119	2023-4	0	200	275	475	32.80%		100.35
Alternative #1	1-119	2023-4	0	0	475	475	34.10%		85.11
Alternative #2	1-119	2023-4	0	475	0	475	21.10%		93.36
Proposed	1-119	2023-30	0	865	584	1449	62.70%		69.35
Alternative #1	1-119	2023-30	0	0	1449	1449	70.90%		58.04
Alternative #2	1-119	2023-30	0	1449	0	1449	46.00%		66.58
SCE RAMP 2018									
C1 + M1 Proposed	10-54	2018-23	189	2491	0	2680	2.39	$ 1,263	0.00189
C1a + M1a Alternative #1	10-54	2018-23	1199	1481	0	2680	1.9	$ 1,044	0.00182
C1 + M1b Alternative #2	10-54	2018-23	189	1010	1481	2680	2.99	$ 5,501	0.00037
PG&E RAMP 2020									
M2 System Hardening	10-47,57,62	2020-22		1060		1060		$1,631	4.12
M2 System Hardening	10-59,61,62	2023-27		2118		2118	17,893	$3,400	7.3

All three RAMP submissions propose mitigations that include some covered conductors or undergrounding, but they vary substantially about which options they prefer. SDG&E examined plans for 475 miles in HFRA for 2023 to 2024. They prefer the hybrid plan with 200 miles of CC and 275 UG miles with the highest RSE, to option 1 with all UG, and option 2 with only CC [SDG&E RAMP 2021, 1-119]. For 2023 to 2030, SDG&E offers three plans for an additional 1449 miles. They again prefer the hybrid plan, which has a higher RSE than the alternatives with all CC or all UG.

On the other hand, SCE prefer a plan for 2680 miles of line with CC for most of the line with no UG over to Alternative #2 with some CC and most UG, for which they estimate a lower RSE [SCE RAMP 2018]. SCE reported the cost of undergrounding at $3 million per-mile, compared to covered conductors at $430,000 per mile. An SCE Fact Sheet argues in favor of CC over UG based on the cost and the difficulty of installing, troubleshooting, and maintaining underground lines [SCE 2018].

In their 2020 RAMP submission, PG&E proposed to underground only very limited portions of overhead circuits, such as in locations along main egress routes where a rebuilt overhead circuit could still potentially fall and block evacuation routes and access [PG&E RAMP 2020]. For Mitigation M2-System Hardening, they proposed adding 1060 miles of CC in HFTD areas in 2020 to 2022. For 2023 to 2026, they proposed converting a further 2118 miles to CC.

But, on 21 July 2021 Patti Poppe, CEO of PG&E, announced new plans to underground an unprecedented 10,000 miles of overhead wires in high-risk fire areas at an estimated cost of $15 to $20 billion. These numbers imply an average cost of $1.5 to $2 million per mile. They assume significant cost reductions, in part from new trenching methods. Mark Toney, Executive Director at TURN, suggested that $40 billion is a more realistic estimate and warned “We’d be living in a world where only the wealthy could afford electricity.” [New York Times 2021] A PG&E spokesperson responded that “system-hardening costs combined with vegetation management costs, per mile, are on par with the cost of undergrounding, but the wildfire risk reduction is more significant with undergrounding” [Canary Media 2021].

Given the high stakes, it is important to clarify the tradeoffs between covered conductors and undergrounding. Given the varying terrain and situations faced by each utility, it is understandable that they may prefer different options. Nevertheless, the apparent differences are striking. In principle, one might expect the RSE analysis to clarify the reasons for these differences. However, it is hard to extract a complete set of numbers for all of them. Even if we could, it would be hard to compare the results because of the variations among the utilities’ methodology, MAVF, weights, discount rates, and so on. However,, it should be possible to develop an expanded framework in cooperation with the utilities that would enable a more direct comparison. That should clarify whether the differences simply reflect varying terrains and assets and how far they are due to specific differences in risk models, costs, and risk attitudes implied by their MAVFs.

7.1.7. Sensitivity analysis.

Inevitably estimates of RSE are based on uncertain data and assumptions, using subject matter experts to help extrapolate from experience into an uncertain future. When using RSE to guide decisions on which mitigations to select, it is helpful to know how these uncertainties might affect the relative RSEs of competing projects. A simple way to address this is range sensitivity analysis (“Tornado charts”). You vary key input assumptions from a plausible low to high value while keeping all other assumptions at their base level and examine the effect on results such as RSE. Only SCE reports doing a sensitivity analysis. They focused on the effect of time horizon for analysis and discount rate on CC projects [SCE RAMP 2018, Appendix I]. They found that variations in these two quantities substantially change the RSE.

Lesser and Feinstein [2020] in their cost-benefit analysis of PSPS conducted an extensive sensitivity analysis to explore the robustness of their conclusions to variations in the increase in fire risk from electric equipment in high winds, the impact of wildfires, and the value of lost load (customers’ willingness to pay to avoid outages). They provide an excellent illustration of ways to perform deterministic sensitivity analysis.

Sensitivity analysis should be coordinated with the probabilistic treatment of uncertainty (see section on **Treatment of uncertainty**). When uncertain variables are probabilistic, you may use, say, the 10^{th} and 90^{th} percentiles of their probability distributions, as low and high values for range sensitivity analysis. If Monte Carlo simulation is extended from estimating the uncertainty in attribute values through to the MRR and RSE, it would be practical to perform "importance analysis" based on the rank-order correlation of the output of interest with each uncertain input. This probabilistic type of sensitivity analysis has advantages over deterministic methods by estimating the effect of each input averaged over the distributions for other inputs instead of assuming all other inputs are fixed at their base value.

7.2. Climate related changes and trends, and PSPS.

Wildfires have become more frequent and more catastrophic in California in recent years. This trend seems likely to continue based on the forecast effects of climate change causing higher temperatures, reduced rainfall, dryer vegetation, and dying trees. Increased population living in rural areas and the urban woodland interface may exacerbate the human and property risks of wildfires. Estimates of risks and mitigation risk reductions appear to have been based primarily on historical data on wildfire frequencies and size distributions. Many mitigations, especially hardening of lines, including covered conductors, and undergrounding, have a lifetime of 40 to 50 years. Estimates of future risk reduction from such long-term mitigations and the frequency of PSPS events without such mitigation should reflect not just the past, but also the best available estimates of future conditions and trends towards more frequent and larger wildfires over this time horizon.

7.3. Researchable question.

How should public safety power shutoff events and other utility activities with high customer impacts be treated in the RDF?

7.3.1. A statement of the issue.

The purpose of PSPS is to de-energize electric circuits when there is a significant chance of transmission or distribution lines sparking a wildfire in conditions of high wind and dry vegetation. The PSPS decision requires a difficult balance between two risks with major impacts on customers, the danger of wildfire versus the costs and safety impacts of a power shutoff. The RDF and RSE were developed as tools to prioritize risk mitigation projects. Are these methods applicable and sufficient to guide PSPS decisions and other utility activities with high customer impacts? How can the rationale for these decisions be communicated effectively to customers affected?

7.3.2. A review of relevant background material.

California utilities have pioneered the use of PSPS, so they have little to learn from elsewhere about best practices specific to this decision. But, of course, there is a wealth of methods and experience in making challenging high-stakes decisions with high public impacts and visibility from other fields. Some of these methods and experience already informed the development of RDF; notably, decision analysis and multi-attribute decision theory informed the formulation of the MAVF scheme.

RSE was developed as a metric to guide allocation of limited budgets to the most cost-effective risk mitigations. RSE was an appropriate guide to the value of projects needed to conduct the PSPS process, including setting up control systems and PSPS protocols, training staff, improving meteorology forecasting and condition monitoring, and developing effective customer communication plans. Over the last few years, the utilities have implemented and substantially refined these processes.

If the question is whether RDF and RSE provide an appropriate guide for individual PSPS decisions – rather than setting up the PSPS process -- the answer is no, or not quite. RSE focuses on the ratio of the risk reduction (the difference in MAVF scores before and after mitigation) to the mitigation cost using risk scores that are incommensurable with dollar costs. A more direct assessment of PSPS decisions requires a cost-benefit analysis to examine whether the benefits of PSPS or reduced wildfire risk outweigh the costs of the outages imposed on customers using commensurate measures, typically in dollars. Cost-benefit analysis is widely accepted and practiced by government agencies, often for high-stakes decisions of major public concern [Boardman et al. 2018; Sunstein 2019]. One example gives rise to the *social cost of carbon,* the cost of greenhouse emissions per ton implied by a sophisticated cost-benefit analysis of the tradeoffs between the costs of shifting the world to a lower carbon economy against the benefits in terms of reducing the effects of climate change [EPA 2017].

Multi-attribute decision analysis (the basis of the MAVF approach) is closely related to cost-benefit analysis but adds a more sophisticated treatment of uncertainty and risk attitude. Cost-benefit analysis typically uses explicit monetary trade-off values such as the value of lost load (VOLL), or value of a statistical life (VSL), and so on to combine different attributes. Given the great public sensitivity and visibility of risks addressed by RDF, it is understandable that the RDF framework agreed in the S-MAP settlement avoided making these trade-off values explicit. However, they are inevitably implicit in the MAVF scheme as we explain in section [MAVF], and as TURN [2020] has pointed out in a CPUC proceedings. In future, it may be desirable to be transparent about them (and as suggested in section [MAVF]) as required for cost-benefit analysis of PSPS. There has been some controversy about whether the benefits of PSPS exceed the costs. Early in this process, Dr. Mitchell for the Mussey Grade Road Alliance (an intervenor) presented a framework for an explicit cost-benefit analysis of this question, although he did not then have sufficient data to offer substantive results [Mitchell 2009]. He also made the interesting suggestion of using cost-benefit analysis to identify the optimal "trigger point" for de-energization as a function of forecast wind-speed, vegetation humidity, and other factors. More recently, Drs. Lesser and Feinstein (who also proposed the original MAVF framework) presented a detailed cost-benefit analysis of PSPS decisions, drawing on recent data on wildfire ignitions and consequences and the effects of PSPS events [Lesser & Feinstein 2020]. They concluded that the costs of outages usually outweigh the benefits in terms of reduced wildfire risk except when few customers are affected by the shutoffs.

S-MAP does not require utilities to perform an explicit cost-benefit analysis of PSPS decisions per se, and the RAMP submissions do not do so. Given the close relationship between the RDF and MAVF scheme and cost-benefit analysis, one might expect that the RSE for PSPS estimated in the RAMP submissions would cast light on this question. However, as we discussed, they cannot do so directly because the MRR has units of risk score that are incommensurate with the mitigation cost in dollars. In principle, it might be possible to render them commensurate applying the MAVF to mitigation costs as a contributor to the financial attribute in the same way it is applied to the costs of risk events. Alternatively, one might apply the MAVF inversely to the risk reduction score to estimate the monetary equivalent of the MRR for comparison against the mitigation cost in dollars. The nonlinear scaling functions impose some complications for such an analysis.

A simpler approach is just to treat the mitigation cost of PSPS as negligible relative to the benefits of reducing wildfire risks on the one hand and the costs of outages to customers on the other. Most of the PSPS mitigation cost has already been incurred by setting up the warning systems and response teams, so that the incremental cost is minimal. In that case, the positive MRR reported for PSPS by PG&E and SDG&E implies that the benefits exceed the costs. (SCE did not include outage costs, so their results do not apply.)

If we accept the validity of this approach, we may ask why Lesser and Feinstein [2020] come to the opposite conclusion, that PSPS is rarely cost-effective. One reason may be that Lesser and Feinstein use a much lower value for a value of a statistical life ($9.8 million in 2019$, based on values used by US EPA and Department of Transportation) than that implied by the RAMP submissions ($100 million to $500 million, as discussed earlier). Another reason may be that their report used data only up to 2019, and the utilities have made some significant refinements to PSPS to reduce the number of customers impacted. Moreover, the recent RAMP submissions evaluate additional planned mitigations designed to further reduce the impacts of PSPS, including better communication and earlier warnings to customers to help them prepare for outages, sectionalizing or segmenting circuits to allow more targeted shutoffs that reduce the number of customers affected, and providing or subsidizing batteries, generators, and establishing microgrids to improve resilience to outages, especially for high-risk customers. These mitigations reduce the impact of PSPS outages and so would be expected to improve the RSE and benefit-cost ratio.

While cost-benefit analysis and its cousin, multi-attribute decision analysis, are widely accepted and used by government agencies and, less often, by the private sector around the world, that does not mean they are widely understood or accepted by the public [Sunstein 2019]. For decisions like PSPS that impact customers very visibly, both from outages and wildfires, it is clearly a major challenge to explain them in ways that the public will understand and accept. Over the last forty years, there has been substantial research on the effectiveness of a wide variety of ways to communicate about risk [Balog-Way, McComas, Besley 2020]. Key findings from the rich literature on risk communication include the essential role of trust and transparency, framing, engagement with the audience, the challenges and opportunities of social media, and the communication of uncertainty [Morgan & Henrion 1990; Morgan, Dowlatabadi, Henrion et al. 2008; Fischhoff & Davis 2014]. No doubt, some of these findings have already influenced the ways in which the utilities have designed their communications about PSPS. However, there may still be further scope for improvement of this critical element of effective risk analysis and management.

7.4. Recommendations

Our PSPS related recommendations are shown in Table 22.

Table 22: PSPS related recommendations.

38. Perform parametric cost-benefit analysis of the "trigger" criteria for PSPS events, such as wind-speed and vegetation dryness, to evaluate the existing protocols and potentially refine the criteria in a way that increases the expected net benefit (or risk score).

8. Appendix A: Acronyms

AFN: Access and Functional Needs.

ATWACC: After Tax Weighted Average Cost of Capital.

CC: Climate Change.

CC: Covered Conductor.

CCF: Cross Cutting Factor.

CEC: California Energy Commission.

CEO: Chief Executive Officer.

CFF: Cross Functional Factor.

CMI: Customer Minute Interrupted

CoRE: Consequence of Risk Event.

CPUC: California Public Utilities Commission.

EPA: Environmental Protection Agency.

EPIC: Electric Program Investment Charge.

EPRI: Electric Power Research Institute.

EPSS: Electric Powerline Safety Settings.

EPIC: Electric Program Investment Charge.

ERR: Enterprise Risk Register.

FAA: Federal Aviation Administration.

FERC: Federal Energy Regulatory Commission.

FPI: Fire Potential Index.

GGP: Generator Grant Program.

GRC: General Rate Case.

HCFA: High-Cost Fund-A.

HFRA: High Fire Risk Area.

HFTD: High Fire Threat District.

IET: Independent Expert Team.

ILI: In-Line Inspections.

IOU: Investor-Owned Utilities.

IRT: Independent Review Team.

LoRE: Likelihood of Risk Event.
MARS: Mitigation Action Risk Spend.
MAUF: Multi-Attribute Utility Function.
MAVF: Multi-Attribute Value Function.
MaxEnt: Maximum Entropy.
MBL: Medical Baseline.
MGRA: Mussey Grade Road Alliance.
MRR: Mitigation Risk Reduction.
NPV: Net Present Value.
PG&E: Pacific Gas and Electric.
PHMSA: Pipeline and Hazardous Materials Safety Administration.
POI: Probability of Ignition.
PSPS: Public Safety Power Shutoff.
PTSD: Post Traumatic Statistics Disorder.
QM: Quality Manager.
R&D: Research and Development.
RAMP: Risk Assessment Mitigation Phase.
RDF: Risk Decision Framework.
ROI: Return on Investment.
RR: Risk Reduction.
RSE: Risk Spend Efficiency.
SAIDI: System Average Interruption Duration Index.
SAIFI: System Average Interruption Frequency Index.
SCC: Social Cost of Carbon.
SCE: Southern California Edison.
SCG: Southern California (SoCal) Gas.
SDG&E: San Diego Gas and Electric.
SDSC: San Diego Supercomputer Center.
SED: Safety & Enforcement Division.
SLR: Sea Level Rise.
SME: Subject Matter Expert.
SPD: Safety Policy Division.
tCO2e: Tons of CO2 Emitted.

TURN: The Utility Reform Network.

TWG: Technical Working Group.

UG: Undergrounding.

US: United States.

UTI: Utility Threat Index.

VMR: Value of Mortality Reduction.

VOLL: Value of Lost Load.

VOT: Value of Testing.

VSL: Value of a Statistical Life.

WMP: Wildfire Mitigation Plans.

WROF: Water crossings, unstable soil, erosion, heavy rains, and floods.

WRRM: Wildfire Risk Reduction Model.

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10. Appendix C- The Arithmetic of Uncertainty by Dr. Sam Savage

Calculations with uncertainties are referred to by mathematicians as Functions of Random Variables. Before the era of ubiquitous computer simulation, this was a difficult subject for most managers to understand, and typically triggered what I call Post Traumatic Statistics Disorder (PTSD). With recent versions of Excel, these formerly complex calculations of uncertainties are nearly as simple as calculations with numbers, so I prefer the arithmetic of uncertainty as a more appropriate and less threatening term.

The arithmetic of uncertainty requires five additional concepts beyond the Addition, Subtraction, Multiplication and Division of standard arithmetic. Any risk management framework must address each of these concepts explicitly, and preferably in layman's terms.

1. Risk is in the eye of the beholder.
2. Uncertainties cannot be expressed as single numbers.
3. Combinations of uncertainties.
4. Nonlinear formulas and uncertainties.
5. Interrelated uncertainties.

10.1. Risk is in the eye of the beholder

Risk is a poorly defined word that means different things to different stakeholders. If I flip a coin, there is uncertainty about whether it lands heads or tails, but there is no risk until someone bets on the outcome. And if you bet $1 that it is heads while I bet $100 that it is tails, our risks are very different and diametrically opposed. Given the diverse stakeholders impacted by the risk mitigation activities of the IOUs, an appropriate accounting of Risk Attitude (or Risk Tolerance) is one of the top priorities of this project and is discussed in the b ody of this report. The academic name for this subject is ***Utility Theory***, and the first rendition of MAVF was called Multi Attribute Utility Theory, which was no doubt modified due to the confusion it would have created in this industry. I will use the term Risk Attitude to describe the translation of an uncertainty into a given stakeholders' perceived risk. This first concept is the only one of the five addressed directly by MAVF.

10.2. Uncertainties cannot be expressed as single numbers

Uncertainty involves a range of outcomes with associated probabilities.

Averages: In risk management, uncertainty is often erroneously reduced to a single average outcome, which leads to a set of systematic errors that I call the Flaw of Averages[12]. For example, an average coin toss would be a static coin that had one half of a head and one half of a tail. There are many mathematical and graphical ways to express uncertainty that make it clear that more than one possible outcome may occur.

10.2.1. Graphs

Unlike averages, graphs can correctly display ranges of uncertain outputs. There are several standard graphs used in the context of risk management. The exceedance curve and explanation below (Figure 16) are taken from a 2016 report on S-MAP by Hubbard and Savage[13].

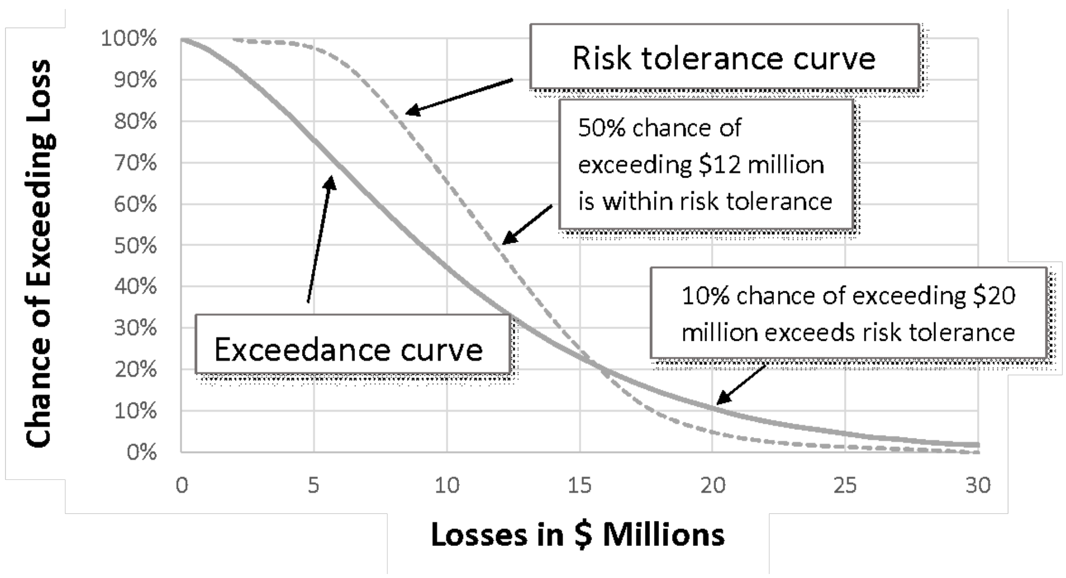


Figure 16: Loss exceedance curve.

A Loss Exceedance Curve is another particularly widely used method in quantitative risk analysis. It shows the chance that a loss exceeds some amount during a given period. This method also provides a convenient way to compare risks and risk tolerance. In the

[12] Sam L. Savage "The Flaw of Averages: Why We Underestimate Risk in the Face of Uncertainty" (John Wiley & Sons, 2009, 2012)

[13] "Assessment of Joint Intervenors' Multi-Attribute Approach Douglas W. Hubbard and Sam L. Savage October 21, 2016", https://www.cpuc.ca.gov/-/media/cpuc-website/files/uploadedfiles/cpuc_website/content/safety/risk_assessment/smap/joint-utilities-smap-whitepaper-v1-0-2016-10-21-final-hubbard-savage-1-.pdf

example [above], the loss is shown as a monetary amount each year. The risk tolerance curve explicitly states the acceptable level of a chance of a loss in a given year. In this case, it indicates that the organization can accept a 50% chance of a loss greater than $12 million in a given year but not a 10% chance of a loss greater than $20 million in the same period. The risk position shown indicates that the risks of larger losses are greater than what is acceptable to the organization.

10.2.2. Histogram

The histogram, a bar graph displaying the probabilities of various outcomes, is standard, as displayed on p.15 of PG&E’s 2020 RAMP Report (see Figure 17), and again in more context in Figure 19 below.

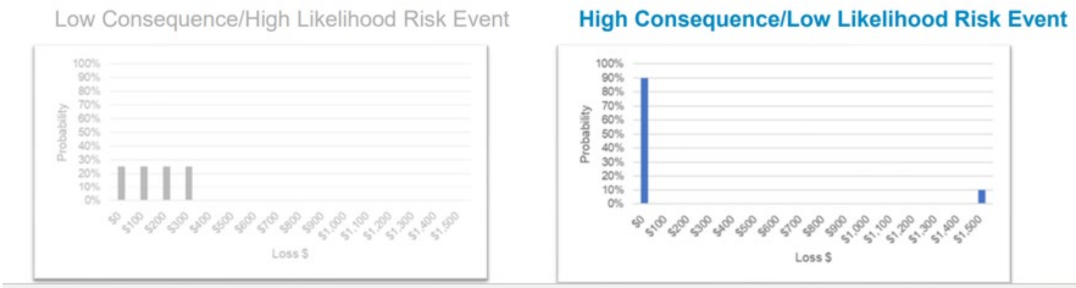


Figure 17: Two histograms with the same average from PG&E’s RAMP briefing.

The histogram displays uncertainty by indicating the chance that the outcome lies in various intervals. Hubbard & Savage describe the close relationship between histograms, cumulative charts, and exceedance graphs. They all contain essentially the same information, but are not actionable, in that they may not be used directly in the arithmetic of uncertainty. For example, one could not aggregate the total of the two risks displayed above based only on the histograms.

10.2.3. Computational Statistics

The industries of insurance and financial engineering have long employed the methods of computational statistics, which is based on simulation. They and others have pioneered the expression of uncertainties as the outcomes of a simulation (or in some cases historical data), as shown on page 22 of the PG&E 2020 RAMP Report (reproduced in Figure 11). This displays 10 trials of a safety risk consequence simulation and is most likely an illustrative graphic. As applied, it might involve hundreds or thousands of trials, but I will stick with 10 for this discussion. For most simulations, each trial is considered equally likely, so each of the numbers 12, 14 down to 15 would be expected to occur with probability of 1/10, (or if there were 1,000 trials, a probability of 1/1000). The other important representations of uncertainty may all be derived from the trials, but not the other way around. For, example, the average, which happens to be 11.1, would be calculated in Excel as:

Figure 18: Trials from a PG&E Simulation.

Trial	Sim. Natural Unit (EF)
1	12
2	14
3	8
4	5
5	12
6	8
7	10
8	14
9	13
10	15

=SUM(TRIALS)/10

Given the number 11.1, however, one could clearly not deduce the trials.

A histogram representation of the trials in might look like this (Figure 19)

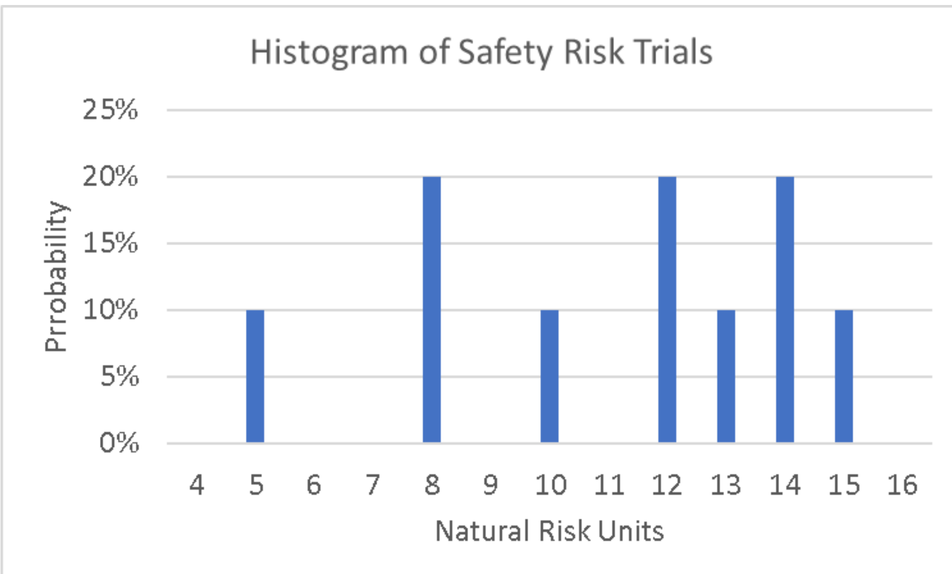


Figure 19: A histogram of the trials in figure 18.

By preserving the trials, it is also easy to estimate the chance of exceeding any threshold, say 12. The formula in Excel would be:

=COUNTIF(TRIALS,">12")/10

The chance is 40% in this case because four of the numbers in the column are greater than 12, which the formula first counts, and then it divides by the number of trials.

But most importantly, in computational statistics it is easy to perform the arithmetic of uncertainty by using the trials themselves in subsequent computations.

10.2.4. Combinations of Uncertainties

Uncertainties do not combine or aggregate like numbers. Consider a transformer with a 10% annual chance of exploding and injuring one worker. This is an average of 0.1 injuries per year. Now suppose that we have three such transformers. Averages may be validly added (that is they are additive) so, we have 3 x 0.1 = 0.3 is the average number of injuries per year across all three transformers. But other aspects of the risk are not additive. For example, if there was a 10% chance of a single injury with a one transformer, does that mean there is a 10% chance of three injuries when we aggregate the risk across the three transformers? The reduction to an average removes the ability to answer this. If the transformers fail independently, there would only be one chance in 1,000 of three injuries. The fifth concept below covers the case when they are not independent.

To visualize this situation probabilistically, imagine three wheels of *mis*fortune, one for each transformer, as shown below. Each wheel has an independent 10% chance of resulting in one injury. This special case has a mathematical solution beyond most managers' comprehension, and it is impossible to do in your head, but a Monte Carlo simulation can easily show that aggregating the three transformer risks is the equivalent of a single wheel of misfortune with a 72.9% chance of no injuries, a 24.3% chance of one injury, a 2.7% chance of two injuries and one chance in 1,000 of three injuries as shown in Figure 20.

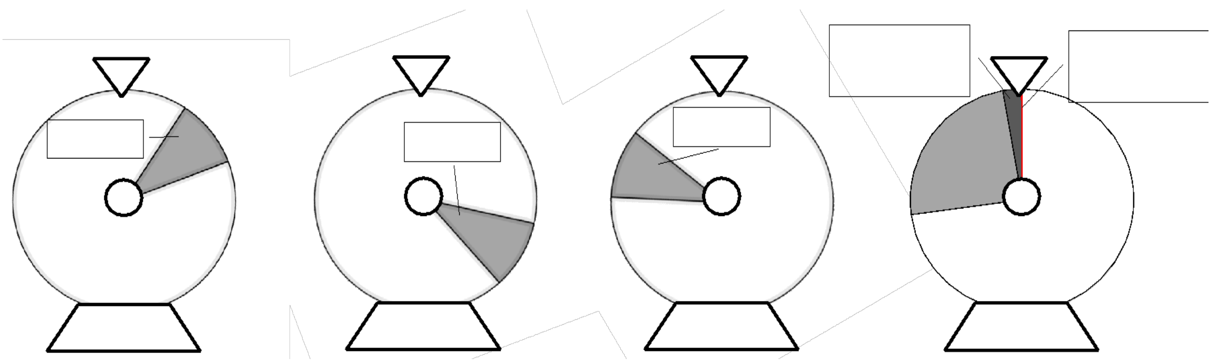


Figure 20: Aggregating risk across three independent wheels of misfortune.

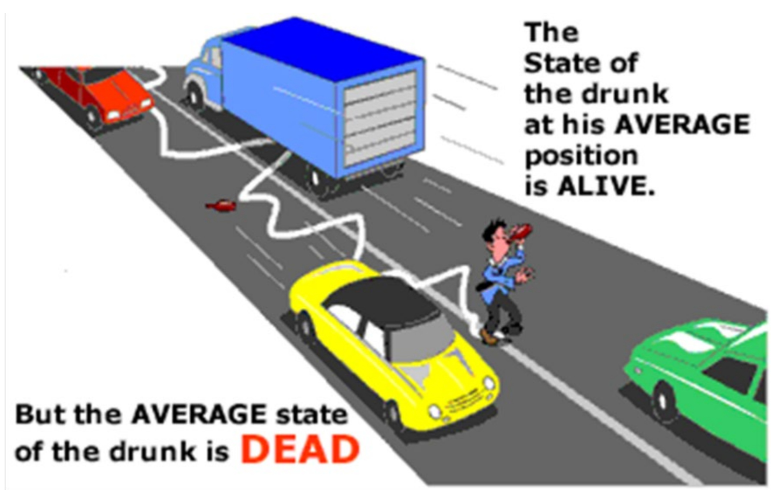
The technical term for this concept is ***Diversification of Risk***, which we encourage every risk manager to be familiar with. This subject is also governed by the ***Central Limit Theorem***, which implies that if we aggregated over hundreds of wheels of misfortune, that the total number of injuries would follow a bell-shaped curve. The word "diversification," a central principle of risk mitigation, does not appear in the Settlement Agreement.

10.2.5. Nonlinear Formulas and Uncertainties

This is one of the most insidious errors induced by using averages, and directly impacts the use of MAVF. As an introductory example, consider replacing ten segments of gas transmission line providing gas to a small city (Figure 21). To expedite the job, each segment will be replaced by its own team working in parallel with the others. Each team will finish its segment in six days, on average, with variation from team to team. So, we would expect the job to be done in six days, right? Wrong. This is the Flaw of Averages at its worst, and there is roughly only one chance in 1,000 of finishing in six days. Why? The line can't open until the last team finishes. With an average of six days, if each team has a 50/50 chance of finishing a little early or late, for them to all come in within six days is like flipping ten heads in a row on a coin.

Figure 21:Replacing ten segments of pipe.

The technical term for this version of the Flaw of Averages is ***Jensen's Inequality***, a term to avoid. It states that when averages of uncertainties are plugged into nonlinear formulas, they do not result in the average value of the formula. A sobering example of this error, which I have used in my books, involves a drunk wandering down the middle of a two-lane highway (Figure 22). If his average position is the center line, then …

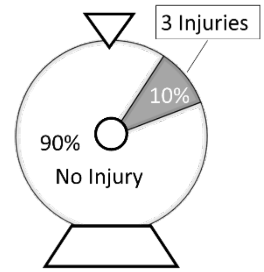


From "The Flaw of Averages: Why We Underestimate Risk in the Face of Uncertainty" by Sam L. Savage (John Wiley & Sons, 2009, 2012) Reproduced with permission

Figure 22: A Sobering Example of The Flaw of Averages.

MAVF attempts to avoid this problem by using nonlinearly scaled average scores instead of ordinary averages. But this leads to a different set of errors when the scaled scores are aggregated as shown in Appendix D.

10.2.6. Interrelated Uncertainties



The technical term here is ***Correlation*** or ***Statistical Dependence***. Returning to the transformers in concept 3 above, suppose that instead of failing independently, they failed in unison. That is, there is a 10% chance that they all fail and a 90% chance that none fail. The average injuries across all three is still 0.3, but now the chance of exactly three injuries goes up from one in 1,000 to one in 10, so even though the average stayed the same, the tail risk of three fatalities increased 100-fold. If they did not fail in unison but were nonetheless more likely to fail under the higher power demands of a heatwave, then the tail risk would increase to a lesser amount without necessarily affecting the average. Climate change, earthquakes, and power demand are examples of global factors that can induce correlation by impacting many assets at once and must be modeled appropriately. Two examples of a disastrous statistical dependency in risk management come to mind. First, during the Oakland Hills fire of 1991, the flames destroyed the powerlines to the pumping stations which were being used by the firefighters. Second, the backup generators at the Fukushima nuclear plant were placed in the basements, where they flooded when they were needed most. Earthquakes are rare and floods are rare, so does that mean that having both at once is very rare? Not when one is known to cause the other.

11. Appendix D - The Invalid Aggregation of Risk with Nonlinear Scoring.

11.1. Overview.

The basic problem is that if you aggregate risks that have been non-linearly scaled, you get invalid results. Consider for example a risk averse scaling that accentuates tail risk in fatalities. That is, a single fatality is scaled at 1, while ten fatalities are scaled at 10 each or 100. This is not an unreasonable risk attitude. Consider a regional airline comparing the risk of a passenger falling off entry stairs and suffering a fatal concussion vs. one of your planes crashing and killing all ten on board. The latter event could easily put you out of business, so it might be considered reasonable to scale the crash as 100 times worse than the stairway accident. This is an example of a convex scaling because the marginal penalty per fatality increases with fatalities.

Now consider two risks under the scaling of one fatality being worth 1 and ten fatalities being worth 100.

> Risk 1 – A single certain fatality.
> Risk 2 – One chance in ten of ten fatalities.

The scaled risk scores are calculated as

LoRE*Fatalities*Scale Factor.

or

Equation 1: Risk 1 score = Chance = 100%, fatalities = 1, Risk Score = 100%*1*1=1.

Equation 2: Risk 2 score = Chance = 10%, fatalities = 10, Risk Score=10%*10*10=10.

This is a valid reflection of being very risk averse to 10 deaths.

According to the Settlement Agreement:

> "For each Risk Event, the utility will subdivide the group of assets or the system associated with the risk into Tranches. Risk reductions from mitigations and risk spend efficiencies will be determined at the Tranche

> level, which gives a more granular view of how mitigations will reduce risk."[14]

So, now suppose that Risk 1 represents one of 10 identical Tranches of risk. We must sum up the risk of each Tranche to get the overall risk score, or as stated in the PG&E RAMP filing,

> "The Overall Risk Score for a Risk Event is a summation of the expected values that represent the individual tranche risk score. [15]" [16]

So, the ten Risk ones together (ten times Equation one) have a summed score of ten and Risk two has a score of ten, indicating that you are indifferent to either ten guaranteed fatalities or a 10% chance of ten fatalities, which is absurd.

11.2. Explanation of Weights, Nonlinear Scaling and Risk Attitude.

The body of this report addresses risk attitude and the weighting and scaling within MAVF in detail. Here I will attempt an intuitive explanation of these concepts as they relate to the potential of invalid risk aggregation. As a point of reference, weighting defines tradeoffs between various risk attributes, while scaling relates to risk attitude and can create problems in risk aggregation, as discussed below.

11.2.1. Risk Attitude.

If you own a $1 million house that has one chance in 4,000 of burning down each year, on average you would lose $1 million / 4,000 = $250 annually. But if you are risk averse, you might be willing to pay $500 in fire insurance to avoid any chance of losing $1 million. If you would pay $500, then you are paying double the average loss, or looking at it another way, you are scaling the value of the $1 million loss up by a factor of two. Someone more risk averse than you might pay $1,000 for insurance, a scale factor of four. Or a billionaire who is risk neutral might pay $250, for a scale of 1. So, we see that Risk Attitude may be measured by the degree to which you would scale a potential loss, which is how it is done in MAVF. Scaling may be linear, convex, or concave as described below. Any of these may reflect a valid risk attitude in a particular context for a particular stakeholder.

11.2.1.1. Linear Scaling.

Linear scaling, known as risk neutral, just increases risk proportional to the natural units. For example, 10 injuries would be considered 10 times worse than one injury.

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[14] point 14 of p. A-11 of the agreement.

[15] p. 13 of PG&E RAMP filing

[16] p. 13 of PG&E RAMP filing.

11.2.1.2. Convex Scaling.

Convex, or risk averse, scaling implies that as the natural units of risk go up, the risk goes up faster than the unit increase. For example, consider hours of power outage. A two-hour outage might be twice as bad as a one-hour outage, but an eight-hour outage, which ruins the food in a thousand freezers, might well be 100 times worse than a one-hour outage.

11.2.1.3. Concave Scaling.

Concave, or risk tolerant, scaling implies that as the natural units of risk go up, the risk goes up slower than the unit increase. For example, this makes sense in flooding risk for a single dwelling. Consider the risk of six inches of water and mud in your living room. Doubling the flood to one foot does not double the consequence. You would still have about the same cleanup bill.

11.2.2. Potential Problems with Scaling as implemented

Risk Attitude is a necessary aspect of risk management, but there are several problems with the scoring as implemented by the IOUs.

1) The utilities use different forms of scaling functions, which is inconsistent, but then apply their chosen form to all risks that they face, counter to the examples above of power outage and flood.

2) Scaled Risk Scores are aggregated by the IOUs, which leads to erroneous results.

Weighting and scaling must only be applied after any aggregation of risk across tranches of assets.

MAVF defines risk as:

LoRE x CoRE

where CoRE may be either linearly scaled in natural units, or, to reflect risk attitude, in nonlinearly (convex or concave) scaled units.

11.2.3. Linear Case Does Not Convey Tail Risk.

This is the scaling used by the Sempra IOUs, SDG&E and SoCalGas. Consider the hypothetical risk of the certainty of a single fatality. Then the risk in natural units according to the formula above, is:

Risk1 Score = LoRE (100%) x CoRE (1 fatality) = 1 fatality.

Consider a second risk event in which the likelihood is one chance in 10 and the consequence is 10 fatalities. According to the formula this yields the same risk score as the previous risk:

Table 23: Different risks with the same score.

Risk2 Score = LoRE (1/10) x CoRE (10 fatalities) = 1 fatality.

LoRE (Likelihood)	CoRE (Fatalities)	Risk Score
100%	1	1
1 chance in 10	10	1
1 chance in 100	100	1
1 chance in 7.753 billion	Entire population of earth	1

This method equates a 100% chance of a single fatality with one chance in 10 of 10 fatalities. In fact, it would also attach a risk score of one fatality to one chance in 100 of 100 fatalities or absurdly to one chance in 7.753 billion of killing all 7.753 billion people on earth (see Table 23). Low probability, high consequence events are called “tail risk,” which is completely masked by this approach.

Although these four risks are indistinguishable by the above measure, clearly, they would be viewed differently by most individuals, according to their personal risk tolerance. This demonstrates that linearly scaled MAVF does not recognize tail risk.

11.2.4. Invalidity of Aggregating Scores with Nonlinear Scaling.

11.2.4.4. Convex Scaling

PG&E addresses the issue of tail risk explicitly on p.15 of the 2020 PG&E RAMP presentation where they display two distinctly different risks, both with the same average (Mean) of $150 (Figure 23).

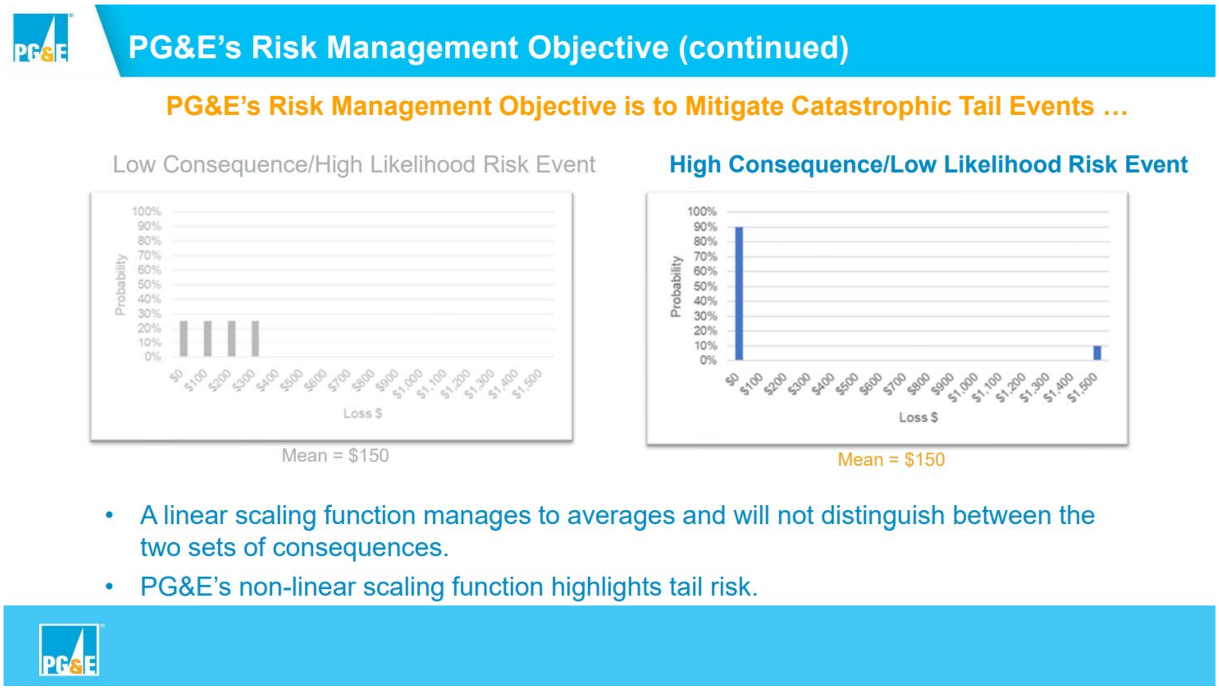

Figure 23: PG&E mitigation of tail risk.

PG&E uses a convex scaling function to create risk aversion to higher risks as shown on p. 16 of the PG&E RAMP presentation. This results in a scaled average, in which more weight is given to the tail risk or catastrophic region.

To explain this principle, consider the first two risks in Table 23, for which we have provided the histograms below. I will apply a particularly simple convex scaling for demonstration purposes, which is not identical with PG&E's, but will prove a mathematical point.

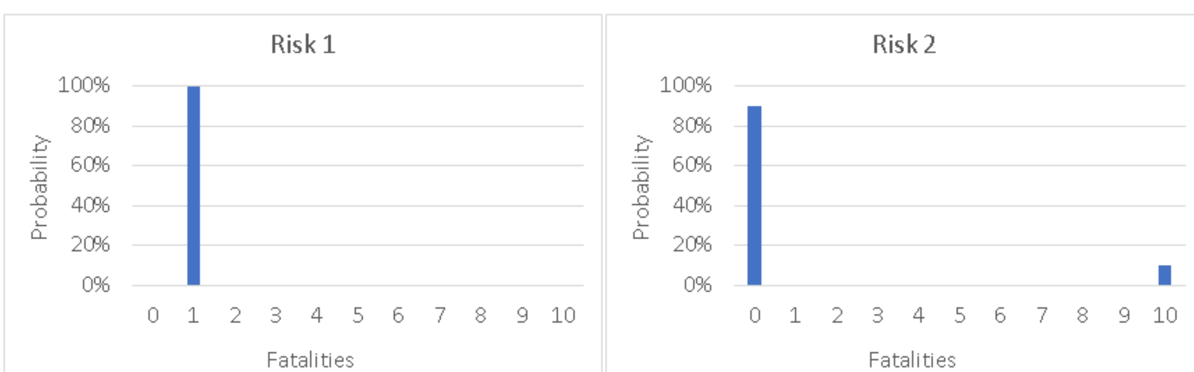

Figure 24:Histogram representation of two risks.

For our convex, risk averse scaling function we will assume that a single fatality is not considered to be catastrophic, and does not get additional impact, but that 10 fatalities are considered catastrophic and get scaled up by a factor of 10. The scaled MAVF risk scores and histograms would appear as below for the two risks.

Risk1 Scaled Score = LoRE (100%) x Scale (1) x CoRE (1 fatality) = 1 scaled fatality.

Risk2 Scaled Score = LoRE (1/10) x Scale (10) x CoRE (10 fatalities) = 10 scaled fatalities.

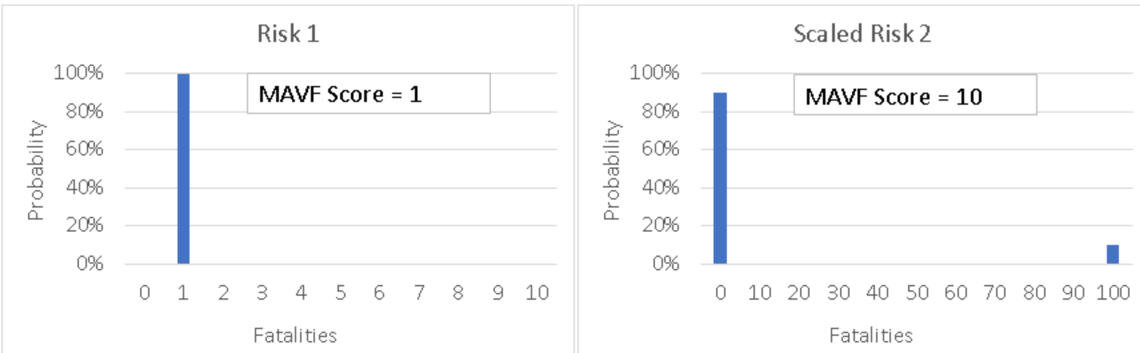

Figure 25: The histograms of two risks.

So far, so good. This reflects the risk attitude that ten fatalities are 100 times worse than one fatality, which could be a valid risk attitude.

But when nonlinear (convex or concave) risk scores are aggregated across tranches, serious errors can occur.

Now imagine that Risk1, one certain fatality, represents a single tranche of Risk Event1 out of a total of ten identical tranches. Then the "summation of the expected values" is 10 x 1 = 10 fatalities for the Overall Risk Score for the aggregated Risk Event. That is, the sum of 10 Risk1s has the same risk score of 10 as Risk 2, which provides the absurd result that ten certain fatalities have the same risk score as a 10% chance of 10 fatalities as shown in Table 24.

Table 24: Scaling and Aggregation can Equate a 100% and 10% chance of ten fatalities.

Risk	LoRE (Likelihood)	CoRE (Fatalities)	Scaled Risk Score
Ten Aggregated Risk1s	100%	10	10
Risk2	10%	10	10

It is even more glaring when we look at the actual unscaled histograms of the aggregated Risk1s vs the single Risk2 as shown below (Figure 26), which according to MAVF would be equivalent.

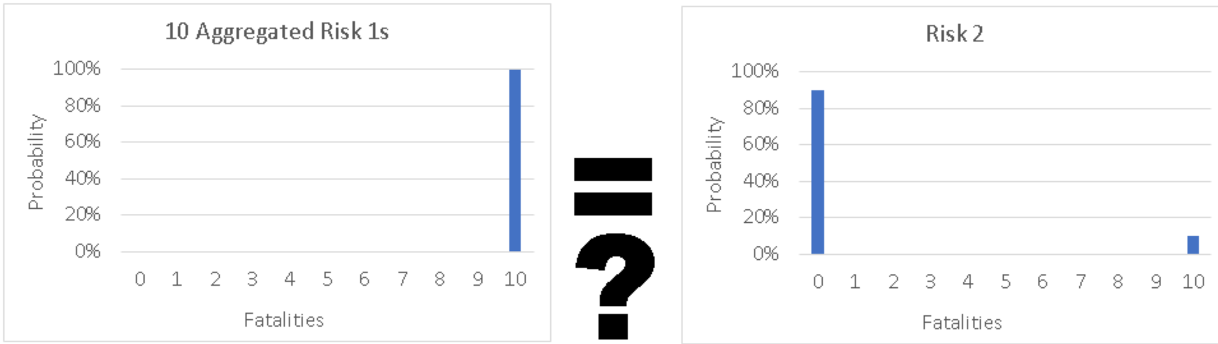

Figure 26: These histograms are not equivalent.

Imagine how this would confound Risk Spend comparisons. Suppose that all ten Risk1s could be fully mitigated for $1,000,000 and that Risk2 could be mitigated for $999,999. Based on the Risk Spend Efficiency, to save a single dollar, a utility would choose to mitigate Risk 2 with a 10% risk of ten fatalities instead of mitigating the Aggregated Risk1s with 100% chance of 10 fatalities.

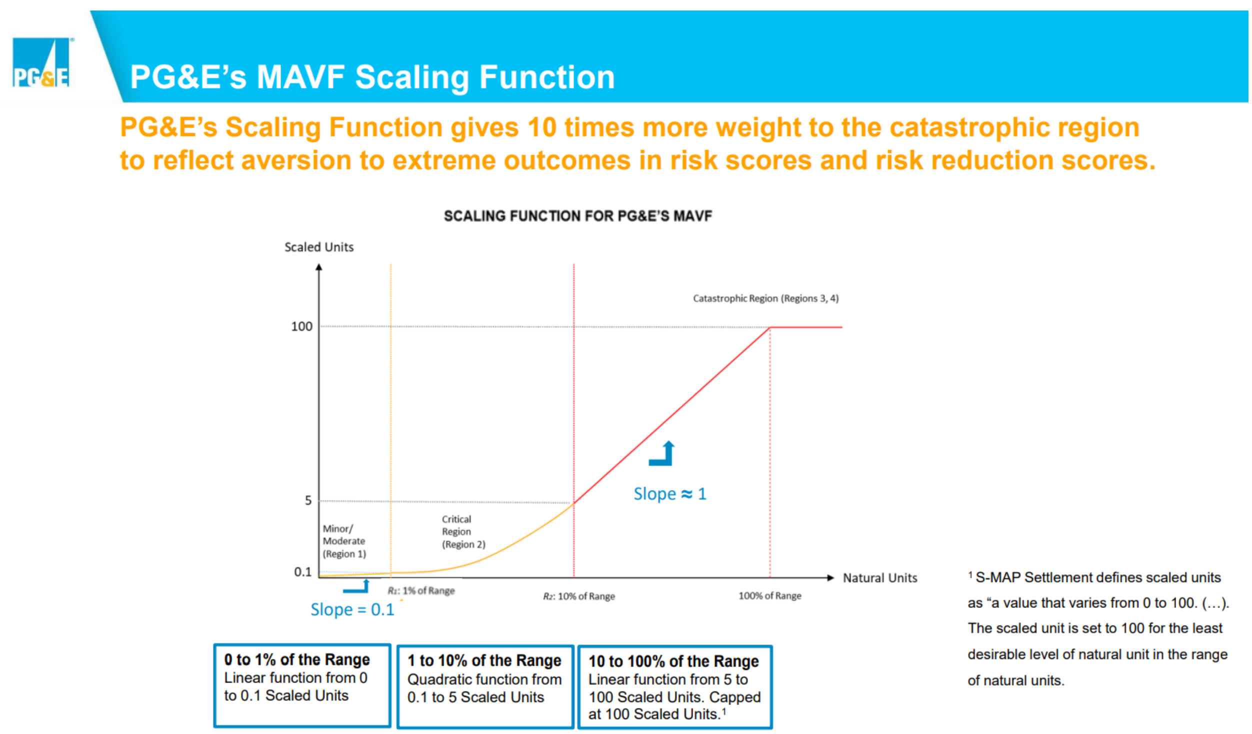

Figure 27: PG&E's convex scaling function.

11.2.4.5. *Concave Scaling*

SCE Uses a Concave Scaling Function, as shown in Figure 28 from P. 24 of their 2018 RAMP Presentation for the case of Serious Injury.

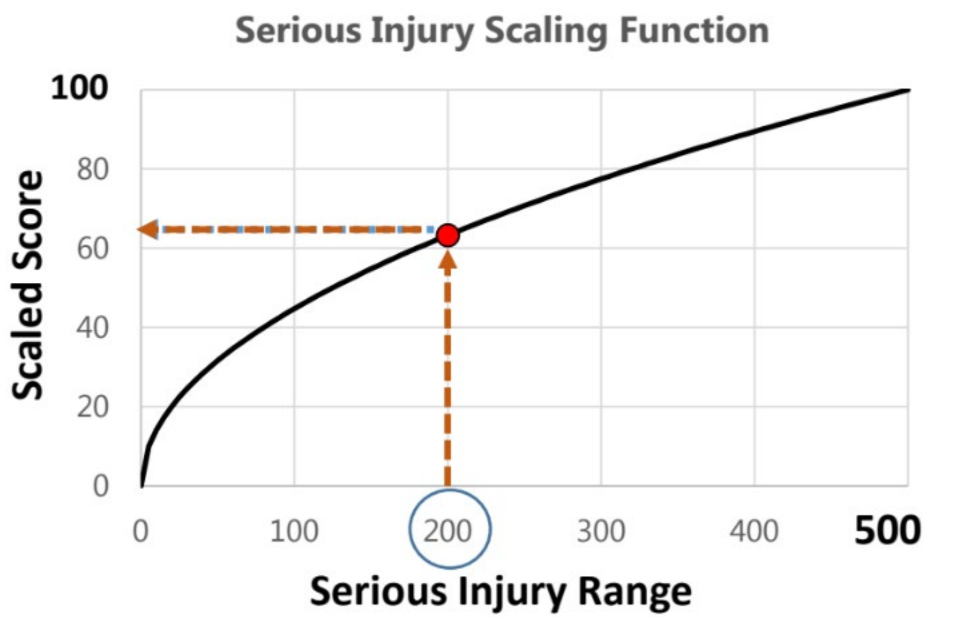

Figure 28: SCE's concave scaling function.

Whereas a convex scaling function puts more emphasis on larger natural units, a concave function puts more weight on the smaller units, for example the first 6 inches of flooding, rather than the larger units, the second 6 inches of flooding.

We will now return to the first two risks in Table 9, but this time apply a concave scaling, which also demonstrates the invalidity of aggregating risk scores. This time a single fatality is again scaled to 1, but each of the 10 fatalities of Risk2 are scaled as 0.5. The MAVF scaled risk scores and histograms would appear as below (Figure 29) for the two risks.

Risk1 Scaled Score = LoRE (100%) x Scale (1) x CoRE (1 fatality) = 1 scaled fatality.

Risk2 Scaled Score = LoRE (1/10) x Scale (0.5) x CoRE (10 fatalities) = 0.5 scaled fatalities.

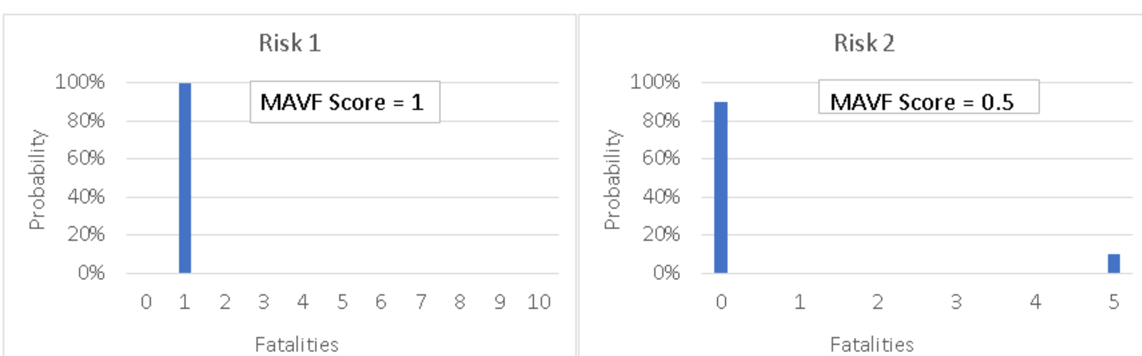

Figure 29: Risk 1 and risk 2 with concave scaling.

This reflects the risk attitude that 10 fatalities are only five times (0.5 x 10) as bad as a single fatality, which, again could be a valid risk tolerance. But now suppose Risk Event 1 is found by aggregating 10 of Risk 1 for total risk score of 10. And Risk Event 2 is found by aggregating 20 of Risk 2, again for a total risk score of 10. Risk Event 1 and Risk Event 2 would be considered equivalent. But Event 1 guarantees 10 fatalities, and Event 2 has an average of 20 fatalities and 12% chance of at least 10 fatalities as shown on the right. It is hard to imagine a Risk Attitude in which these two risks would be considered equivalent.

Figure 30: Another histogram illustration.

11.3. Conclusion

Risk Aggregation is central to enterprise-wide risk management and is the foundation of the insurance industry and modern portfolio theory, where assets are not evaluated individually, but only as part of a portfolio. Aggregation is particularly critical when one is evaluating various portfolios of mitigation projects over tranches of utility assets such as pipe segments or electric transmission lines. A risk mitigation system must be agile and interactive, allowing decision makers to quickly swap tranches in and out of mitigation project portfolios and immediately observe the aggregated risk. Within the current framework, such aggregation may not even be valid. Furthermore, in searching the related documents, I found few references to aggregation so there are no guardrails to warn risk managers, intervenors, or regulators of potentially erroneous results. However, given what appears to be solid underlying risk management practices at the IOUs, leading up to aggregation, we intend to research potential improvements in this area in the second phase of this project. This will explore the applicability of scenario optimization approaches traditionally applied to portfolios in insurance and finance, where instead of applying MAVF at the tranche level it is applied to evaluate the portfolio. It is hoped that this approach will not only be more valid, but also simpler for the IOUs to implement.

12. Appendix E: Estimating the implied VMR

Consider a risk event, E, that causes F fatalities and \$C of financial loss (and no other consequences). We compute the combined score for the Consequences of the Risk Event (CoRE) is:

$$CoRE (E) = W[F] \times ScaleF(F[E]) + W[C] \, ScaleC(C[E])$$

Where:

> W[F] and W[C] are the attribute weights for fatalities and costs respectively.
> F[E] and C[E] are the fatalities and costs respectively of risk event E.
> ScaleF(.) and ScaleC(.) are the scaling functions for fatalities and costs respectively.

Suppose event E1 results in F1 fatalities (and zero costs or other consequences) and event E2 results in costs C2 (and zero fatalities or other consequences), and both have the same CoRE:

$$CoRE [E1] = CoRE [E2]$$

Where:

$$CoRE [E1] = W[F] \times ScaleF(F1) = CoRE [E2] = W[C] \times ScaleC(C2).$$

We can then compute the cost C2 that is equivalent to the fatalities F1:

$$W[F] \times ScaleF(F1) = W[C] \times ScaleC(C2) \qquad [1]$$

For simplicity, we start with the MAVF with linear scaling functions used by SoCalGas and SDG&E. In this case, the weights are:

$$W[F] = 60\%, W[C] = 15\%,$$

and scaling functions are:

$$ScaleF(F1) = F1/20, ScaleC(C2) = C2/500M,$$

Substituting these into [1], we get

$$60\% \times F1/20 = 15\% \times C2/500M$$
$$C2 = 500M/15\% \times 60\% \times F1/20 = 100M \times F1$$

Thus, the cost C2 is $100M times the number of fatalities, implying a VMR of $100M per fatality avoided.

13. Appendix F: Stochastic Libraries and Modularity

Modular systems are those which may be broken into separate components, increasing both their flexibility and ability to evolve. Non-modular systems resemble sandcastles, which are difficult to modify, or maintain, and may collapse under their own weight. Modular systems are like Lego blocks, which allows structures to be replaced, or new blocks to be developed for special purposes.

In the decision sciences, a common modularity is to delineate models as *descriptive*, *predictive*, or *prescriptive*. Models of the first type describe the current state of the world, models of the second type predict the future state of the world and models of the third type prescribe the best course of action based on the first two. The connective tissue holding such models together is numerical data passed from one to another.

A descriptive model might explain the current state of a tranche of aging utility assets. A predictive model would forecast the future states of the assets over time. Finally, a prescriptive model would specify the most risk spend efficient maintenance interval based on weights applied to such attributes as safety risk, reliability risk, etc.

One area in which modularity is difficult is that of models that simulate uncertainty. The problem is that instead of being connected by numbers, the various components of a simulation model are connected by potentially thousands of random outcomes of various uncertainties. And unlike numbers, uncertainties may be interrelated or linked. For example, a predictive model of wildfire would include uncertain inputs for both humidity and temperature, and although both are uncertain, high temperatures are statistically linked to low humidity. The idea of basing computations on databases of coherent Monte Carlo trials dates back at least to 1991[i]. In such a system, one column of data would represent uncertain temperature, and another uncertain humidity, and the two columns of data would be statistically linked, with higher temperatures generally associated with lower humidity.

This approach has been used in large monolithic systems with self-contained stochastic databases to optimize financial portfolios and balance risks in books of insurance. But as computer storage and power have grown, it has been possible to create cross-platform standalone stochastic libraries that may be shared between programs.

In 2006 the energy firm, Shell, created a library of simulated outcomes of potential petroleum ventures, which was used to choose exploration projects[ii]. Although it took a matter of hours to generate the library, the results were read into an interactive Excel model, which allowed high level management to quickly explore numerous efficient portfolios of projects. To prepare the Shell executives to make better portfolio decisions, they were given a training session at which they were introduced to a small demonstration version of the full portfolio model.

The demonstration model is available here, with the first 15 of 1,000 trials of its stochastic library displayed below. The far-right column simulates whether or not political disruption has occurred in region 4. This is equivalent to a risk event in the RSE framework. To be coherent, a stochastic library must preserve statistical relationships between variables. Note that on trial 11, such an event occurs, and that this in turn creates large losses in Ventures 4 and 4a, which are in region 4. It also increases the price of gas in region 1, which was supplied by region 4, which in turn also increases the value of Venture 5, which is an alternative source of gas to Region 1.

Table 25: Example stochastic library.

	Venture 1	Venture 2	Venture 3	Venture 4	Venture 4a	Venture 5	Venture 6	Venture 7	Venture 8	World Oil Price	Region 1 Gas Price	Region 6 Gas Price	Region 8 Gas Price	Disruption in Region 4
Trial 1	20.73	33.24	-111.63	51.51	51.51	-143.87	-42.14	-52.14	127.30	31.57	14.08	24.00	18.34	0
Trial 2	28.77	79.93	-112.27	-17.00	-17.00	-109.23	156.14	146.14	-20.00	32.38	16.38	24.49	18.25	0
Trial 3	-20.00	26.60	176.43	215.99	215.99	-20.51	38.69	28.69	18.69	21.70	22.30	23.94	20.82	0
Trial 4	40.70	32.16	-93.44	190.02	190.02	37.03	-32.15	-42.15	-20.00	33.57	21.00	21.28	20.94	0
Trial 5	299.06	3.17	179.90	189.31	189.31	36.24	97.03	87.03	-20.00	59.41	20.97	17.12	20.99	0
Trial 6	145.20	-42.57	-104.75	66.49	66.49	-12.90	284.22	274.22	264.22	44.02	22.81	21.04	19.32	0
Trial 7	48.76	-6.40	128.89	158.74	158.74	-63.45	178.13	168.13	158.13	34.38	19.44	17.85	18.44	0
Trial 8	36.64	8.40	-64.68	52.85	52.85	53.67	-34.18	154.81	-20.00	33.16	21.76	17.34	25.05	0
Trial 9	23.43	-1.54	210.55	216.28	216.28	-20.29	-40.78	-50.78	130.28	31.84	22.31	17.77	22.53	0
Trial 10	-20.00	59.45	217.93	171.99	171.99	17.19	19.58	9.58	-20.00	19.96	20.10	22.44	22.90	0
Trial 11	-20.00	64.02	-112.79	-230.00	-230.00	598.88	86.44	-79.80	-20.00	26.04	46.54	22.90	18.17	1
Trial 12	26.34	19.50	-82.91	131.47	131.47	-27.39	153.48	-49.33	133.48	32.13	18.07	18.45	22.44	0
Trial 13	148.20	22.72	-76.86	23.94	23.94	4.74	287.52	11.60	-20.00	44.32	19.53	20.89	23.31	0
Trial 14	-20.00	-7.77	-83.05	-8.08	-8.08	-98.94	-134.28	-144.28	-154.28	5.97	17.07	15.97	22.42	0
Trial 15	247.26	56.65	-108.23	32.97	32.97	20.03	396.49	386.49	-20.00	54.23	20.23	23.24	18.82	0

In 2006, running such models in Excel took specialized add-in software, but since then there have been two major improvements in Excel performance.

In 2010, the Data Table function in Excel became powerful enough to process stochastic libraries without any additional software as described in a 2012 article in Analytics Magazine. This was a major breakthrough, which led to applications to risk management at PG&E, which are ongoing. The second breakthrough occurred in 2020, when Excel did a general release of Dynamic Arrays as described in this 2018 preview article. This significant evolution in its calculation engine, improves scalability and speed, in particular when it comes to accessing stochastic libraries. In some ways, Excel can now perform calculations in a similar manner to the statistical language R.

We have created a demonstration of the power of Dynamic Arrays in calculating Risk Spend Efficiency curves based on 100 hypothetical risk mitigation projects in four areas. To demonstrate the modularity of this approach, the model allows the user to switch between either of two libraries containing 1,000 trials for each of the 100 projects. One can imagine that the two libraries represent data that evolves from time period to time period. Although in the demonstration, the libraries are contained in the same file as the calculations and dashboard, the libraries can also be stored in the cloud, and accessed by dashboards written in Excel, R, Python, or the analytical engine of your choice, each producing identical results. Also, tests indicate that interactive results are possible with up to 10,000 trials on each of 1,000 projects.

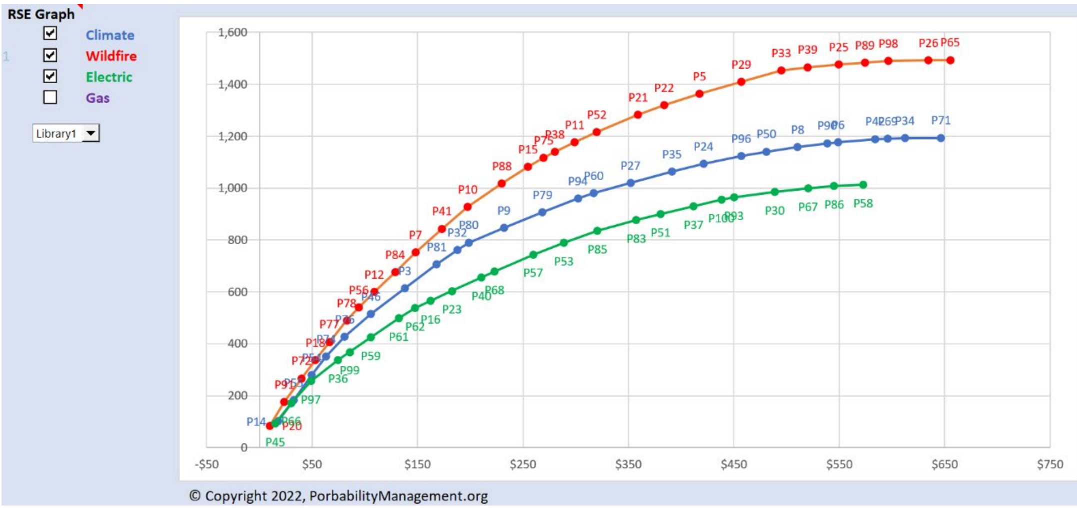

Figure 31: Sample RSE curves.

Dynamic Array RSE Model.xlsx contains no macros or add-ins and allows the user to select each of four groups of **non-interrelated** projects and instantly see a graph of the RSE ranking. Computations for interrelated projects would be more complex, but this is a well understood problem with standard solution methods. This model will be explained and distributed at the March 1st workshop.

14. Appendix G: Stochastic Portfolio Simulation and Noise

One potential problem with our proposed approach to portfolio simulation, in which risk mitigations are individual removed to observe the impact on RSE, would be that the small incremental change in the overall risk score could be dwarfed by the size of the total portfolio and lost in the noise (random fluctuations) associated with that overall portfolio score. It's true that if we were proposing ordinary simulation, simulating the portfolio first with the mitigation and then without the mitigation would be a problem. This is because the simulation introduces its own uncertainty and the uncertainty in the portfolio might swamp the effects of the mitigation. This uncertainty would be introduced for both the pre and post mitigation simulations and would add a lot of noise (Figure 32).

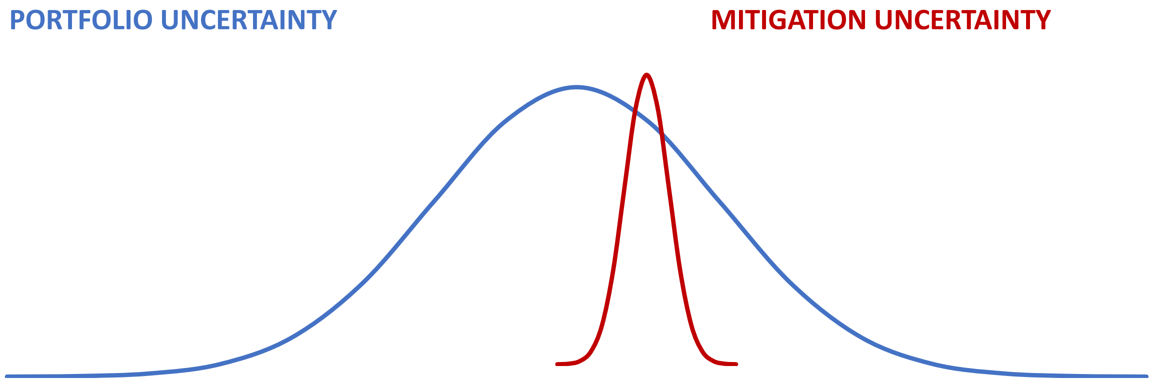

Figure 32: Portfolio uncertainty obscuring risk uncertainty.

But with Stochastic Libraries the simulation has been frozen to a single set of numbers, so there is no random portfolio uncertainty, and the relative impact of the mitigation may be clearly captured (Figure 33).

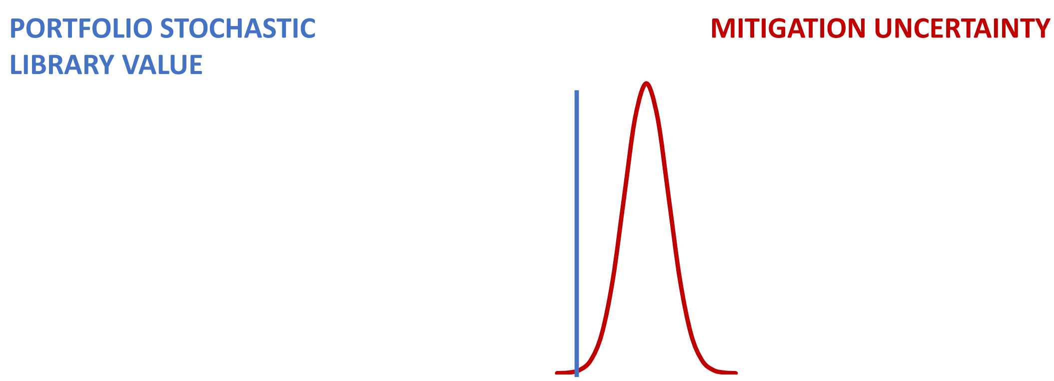

Figure 33: Known portfolio characteristics exposes individual risk uncertainty.

As an analogy, if we need to determine a small number, say, 0.01, it doesn't matter if we know it has been added to 1,000,000. That is, we simply take 1,000,000.01 and subtract 1,000,000 to get 0.01. Even the latest approach to storing virtual stochastic libraries is accurate to one part in about 10^15. Beyond that we must be aware of roundoff errors.

There is a secondary issue as well here. There is no need to use the portfolio approach with mitigations that are statistically independent. There the stochastic libraries allow each mitigation to be simulated at any level of granularity, and then aggregated up to any courser level of granularity.

An important step will be to partition the mitigations into sets that are independent and mutually dependent, with only the latter requiring the portfolio approach. Note that dependence may be due either to external global factors such as climate change, or internal effects such as choosing between mutually exclusive mitigations. But at the end of the day, in this manner all mitigations of either type may be summed up to determine total RSE and may be analyzed at any level of granularity desired.

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[ii] Probability Management, Sam Savage, Stefan Scholtes and Daniel Zweidler, OR/MS Today, February 2006, Volume 33 Number 1