WARP to Resilience
Weather Adapted Resource Planning

RESILIENCE FRAMEWORK MEMO

Submitted on April 25, 2025*

This memo is an interim work product submitted to the California Energy Commission under EPIC agreement number EPC-22-001. It has been edited lightly for clarity. Memo content is subject to review and revision, and it does not necessarily reflect all aspects of the project team's final approach, methodology, or results.

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WARP to Resilience aims to advance California's analytical tools for electricity resource planning to incorporate the impacts of climate change and environmental extremes on electricity supply and demand. As part of its effort, the study team will develop a novel model to evaluate the future resilience of electricity service to California's ratepayers.

The term "resilience" lacks a standard and actionable definition in California's grid planning processes. This gap represents a significant institutional barrier to coordinated, effective, and efficient resilience investment planning throughout the state. Importantly, this gap prevents meaningful measurement of resilience impacts and quantification of the tradeoffs of alternative resource investment strategies.

This memo outlines a framework for defining resilience such that it can be quantified and measured in a resource plan, and a strategy for refining and embedding that definition in the state's resource planning processes. The framework and adoption strategy build upon best practices in resilience planning evolving across the nation, and upon the significant thought leadership of California's grid planning community to explore resilience concepts and needs, including under the CPUC's Resiliency and Microgrids proceeding (Rulemaking 19-09-009).

Contents

Literature Review of Resilience Definitions and Use

We reviewed industry literature on the definition of resilience with a focus on how the term has been used in federal and state regulatory contexts, and in state or utility integrated resource plans (IRP). Our objective in this literature review is to extract the key elements of a resilience definition needed to meaningfully quantify and measure the resilience of an electricity grid resource portfolio.[1] In order to do so we need to understand the evolution of the term over time, identify lessons learned in resilience definitions, and identify current best practices in resilience planning.[2]

Federal and State Definitions

"Resilience" in the U.S. energy sector relates to several types of catastrophic system failures. In the early 2000s and following the tragedy of terrorist attacks on September 11, 2001 ("9/11"), national concerns heightened over protecting critical infrastructure such as communications infrastructure. At the same time, the nation saw a renaissance of concern over energy security, including (but not limited to) concerns over reliance on external fuel supply and supply chains. This concern eventually surfaced as a key risk consideration in some utility electricity resource plans, for example, see (Newell et al. 2010). As the then-nascent .com economy rapidly grew, along with trends towards digitization and automation, a new set of risks related to cybersecurity entered the resilience stage. Additionally, in the last 10 years or so, since the early/mid 2010s, climate change-related hazards have become increasingly apparent through a growing record of extreme weather events.

In 2009 the National Infrastructure Advisory Council (NIAC) released a report focused on critical infrastructure and with recommendations on how to integrate resilience into a comprehensive risk management strategy. In that report the NIAC defined resilience as:

> *Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.* (NIAC 2009)

Several years later the Presidential Policy Directive on Critical Infrastructure Security and Resilience (PPD-21) was issued, with guidance for all federal agencies. The resilience definition in PPD-21 mirrors the NIAC report to describe, generally, what a resilient system does:

> *The term 'resilience' means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.* (The White House 2013)

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[1] We use resource portfolio in both in terms of IRP resource portfolio solutions and in the broader grid planning sense, to include bulk generating resources and storage, distributed generation and storage, transmission wires, distribution wires, and demand-side management.

[2] For further reading on resilience definitions, we highly recommend (Jasiūnas 2021).

Elements of these definitions subsequently propagated through the federal landscape. In 2018 the Federal Energy Regulatory Commission (FERC) offered a resilience definition at the start of a proceeding to evaluate the resilience of the bulk power system:

> *The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such events.* (FERC 2018)

We observe that some federal entities that are closer to planning and technical applications, such as the national labs, translate resilience concepts from infrastructure resilience into local or community resilience.[3] The National Renewable Energy Laboratory (NREL), for example, developed a 2019 resilience roadmap that builds upon the same basic concepts and defines resilience as:

> *The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions through adaptable and holistic planning and technical solutions.* (NREL 2019)

In addition to emphasis on aging infrastructure and extreme weather, NREL's roadmap presents details of a community resilience planning pilot in Colorado.

Federal definitions include some refinements and distinctions in resilience concepts that are important for application—but some ambiguities remain. Initial concepts that emerge include:

- Evolving from 2009 NIAC report, a better distinction between the hazard/event and the system that needs to be resilient against it
    - E.g., language shifts from "reduce magnitude of events" to "withstand and reduce magnitude of events" to "withstand, respond to, and recover rapidly from events"
- Consistency on what the resilient system does: it withstands, absorbs, recovers from, adapts to
- Suggestion that the system that needs to be resilient performs some critical function—although the exact function is not specified
- A distinction between critical infrastructure resilience and community resilience
- A sense that the resilience hazard or event is uncontrollable within the boundaries of the system planning problem and disruptive to the system, although descriptions of the hazard and its severity are typically highly conceptual
    - E.g., hazards may be described as "disruptions," "changing conditions," or "deliberate attacks, accidents, or naturally occurring threats or incidents"
    - However, through the timeline of resilience definitions we see a growing record and prominence of weather-driven events and conditions as key hazards to the energy system

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[3] The concept of more specific site- or customer-level resilience, and its relationship to infrastructure and community resilience, is not addressed as much in the Federal and State literature and is best demonstrated through new-build communities such as Babcock Ranch in Florida (Dean 2022) and Shadow Mountain in California (KB Home 2022).

State-level resilience definitions offer more clarity on hazard and event characteristics, and on the specific undesired outcomes of a resilience failure. As with the national lab reports we reviewed, we interpret this level of specificity as a necessity of planning and technical applications.

In a 2013 report on the topic of resilience in regulated utilities the National Association of Regulatory Utility Commissioners (NARUC), which represents state public service commissions, defines resilience as:

> *…robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event.* (Keogh and Cody 2013)

A California Public Utilities Commission (CPUC) staff paper in 2020 discusses the issue in depth, including disruptions in the context of equipment and electricity service outages, and defines resiliency as:

> *…the ability to mitigate the impact of a large, disruptive event by any one or more of the following mechanisms: 1. Reducing the magnitude of disruption; 2. Extending the duration of resistance; 3. Reducing the duration of disruption; 4. Reducing the duration of recovery.* (CPUC 2020)

These definitions underscore the importance of what a resilient system does in response to a resilience hazard or event, and further clarify the "system's" key function is to deliver electricity. The system's ability to function with and without resilience attributes is well-represented in the "resilience trapezoid" presented in the CPUC staff paper and adapted from the work of a group of energy system researchers (for example, *see* Ding et al. 2017). However, the exact delivery point of service differs by report or case study, or it is sometimes unclear.

A 2022 report by NARUC and the National Association of State Energy Officials (NASEO) provides the following commentary on state regulator resilience-related efforts: "…expenditures have been guided by imprecise approaches that fail to account for the impacts of outages or anticipate [high-impact low-frequency] events such as Winter Storm Uri" (Rickerson et al. 2022). In doing so, NARUC and NASEO refine the nature of resilience hazards, and they begin to fold in language on the need to balance the tradeoffs of resilience investments. They add, "New approaches to analyzing the costs and benefits of resilience investments, such as microgrids, can enable more efficient use of ratepayer and taxpayer resources to deliver better outcomes." This perspective on resilience is particularly important in a resource planning context where the planning framework relies heavily on benefit/cost analyses.

CPUC Rulemaking 19-09-009 and the 4-Pillar Methodology

The work products and policy direction reflected in CPUC Rulemaking 19-09-009, the Resiliency and Microgrids proceeding, are a major consideration in our model development for two reasons:

1. Their work exploring resilience concepts—in particular, materials developed by the Resiliency and Microgrids Working Group (RMWG)—reflects significant thought leadership in resilience best practices and a sophisticated framework for resilience planning. Their planning framework, dubbed the "4 Pillar Methodology," is geared towards application and it is the among most specific and detailed frameworks we reviewed. Despite being developed within the Resiliency and Microgrids proceeding, 4 Pillar Methodology is also designed to be technology-neutral and to be broadly applicable to a variety of resilience planning efforts.

2. Synergizing with their work is essential for adoption of our model and integration of our model in the state's resource planning processes. The CPUC oversees and guides the integrated resource plans of all load-serving entities within the investor-owned utility footprints, and has a large base of public participants. Within the CPUC, the RMWG and other public participants in the Resiliency and Microgrids proceeding are at the heart of developing a resilience planning framework and definition of resilience that we believe will eventually bridge all other grid planning proceedings and efforts.

We have been fortunate to connect with the CPUC Resiliency and Microgrids team, thanks to their initiative, and that of our CEC Commission Agreement Manager, to explore a collaboration opportunity. The CPUC Resiliency and Microgrids team has provided significant guidance and feedback to our resilience framework, both in terms of refinements for better incorporation of best practices and in terms of refinements to better facilitate adoption and integration of our model in the state's planning processes.

On March 21, 2023 CPUC Commissioner Shiroma and the Resiliency and Microgrids team hosted a 3-hour public workshop in which we presented our resilience framework.[4] Through audience polls, Q&A, and a brainstorming exercise, public participants shared their perspectives on resilience and on our definition of resilience which we have also considered carefully in developing this resilience framework memo. In subsequent public information sessions we further explored resilience metrics and methodologies for quantifying and integrating those metrics in grid planning processes.

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[4] This and other related work by the CPUC Resiliency and Microgrids team are available at https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/infrastructure/resiliency-and-microgrids/resiliency-and-microgrids-events-and-materials.

WECC-Wide Integrated Resource Plans

In recent years, climate change has become an increasingly pressing issue, highlighting the need for a more resilient energy infrastructure. The integrated resource planning (IRP) process, by design, has the bird's eye view on system needs. IRP is in a unique position to incorporate resilience needs and value into grid planning and support investment decisions at the system level.

To get a better understanding of the range of interpretations of "resilience" in current grid planning efforts, we reviewed 20 utility IRPs across the WECC footprint which account for over 75% of the region's electric load. Of those reviewed, 4 IRPs were CPUC-regulated.

Our review focused on maturity of the resilience definitions in the latest plans and extent of climate change impacts explicitly considered in the planning studies.

Below we summarize key themes in a few examples.

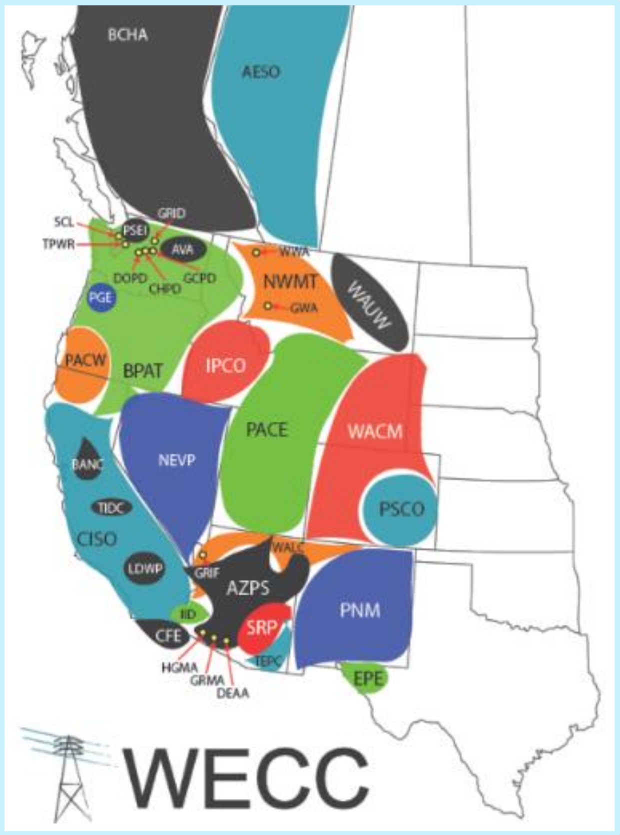


Figure 1: Map of WECC balancing authorities.

California Load Serving Entities (LSEs)

- Public Utilities Code Section 454.52(a)(1)(G) requires IRPs to:

  "Strengthen the diversity, sustainability, and resilience of the bulk transmission and distribution systems, and local communities."

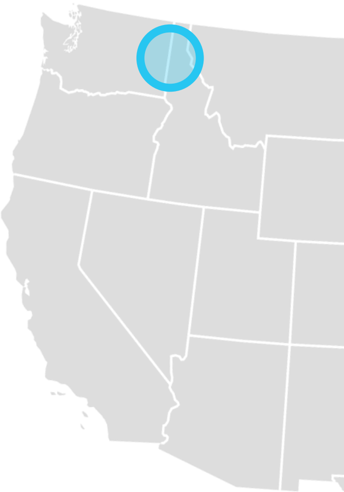
- In the latest 3 large IOU IRPs reviewed, this is addressed by a diverse resource portfolio that supports grid reliability and emission targets, and in that portfolio, energy storage is highlighted as a flexible resource that improves resilience.
  - However, without a clear and standardized definition of "resilience", the IRP requirement above is subject to a wide range of interpretations, and thus, difficult to address systematically.
- Several parallel efforts are ongoing to improve customer and community resilience but not integrated into IRP analyses.
- Climate risks are increasingly recognized, but the effects are not (yet) fully included in the LSEs' planning process.

Los Angeles Department of Water & Power (LADWP)

- 2022 Power Strategic Long-Term Resource Plan (SLTRP) sets its core objectives as: power reliability, resiliency, affordability, and environmental justice/equity.
- It provides a clear distinction between reliability and resilience:
  "While grid reliability is centered around having sufficient resources to adequately meet load while accounting for commonly-expected events (e.g. equipment failure, short-duration outages), resilience focuses on high-impact, low-frequency events that are often unexpected and can result in long-duration outages."
- Their working definition of resilience is:
  "The ability of a power system to anticipate, absorb, adapt, and rapidly recover from a certain set of high-impact, low-frequency events, and to supply sufficient capacity, energy, and services to its customers at all times of the year while managing societal impacts and meeting policy objectives."
  - The SLTRP address resilience through sensitivity analysis on extreme events, focusing on major transmission outages like the 2019 event caused by wildfires.
  - It also points to future approaches that can utilize Value of Lost Load and/or social burden metrics.

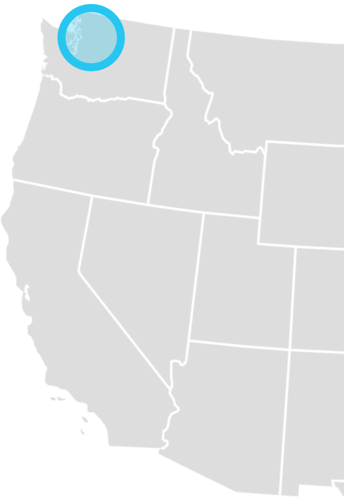
Avista Corp.

- In Washington state, the Clean Energy Transition Act (CETA) requires:
  "equitable distribution of energy benefits and reduction of burdens to vulnerable populations and highly impacted communities; long-term and short-term public health, economic, and environmental benefits and the reduction of costs and risks; and energy security and resiliency"
  - The act doesn't define what "resiliency" is.
- Avista's 2021 IRP considers resilience as the ability to quickly recover from an outage, measured by CAIDI based on average duration that customers are offline in an outage event.
- Their ongoing 2023 IRP effort has a broader definition of energy resilience as the ability to adapt to challenging conditions from disruptions.
  - Scoping discussions on which resilience topics to be evaluated in the IRP vs. other planning forums.
  - Resilience captured in two metrics: (1) Energy Availability based on CAIDI, energy storage capacity, planning reserve margin, and (2) Generation Location as % of gen in WA or connected to Avista.



Puget Sound Energy (PSE)

- Also in Washington state, under Clean Energy Transition Act (CETA) requirements.
  - PSE's IRP includes a Clean Energy Action Plan (CEAP) under a long-term view.
  - Their Clean Energy Implementation Plan (CEIP) develops 4-year targets for solutions proposed in the IRP/CEAP, considering equitable distribution of customer benefits and feasibility of implementation.
- In CEAP, PSE pursues energy security and resiliency investments such as microgrids or infrastructure hardening at locations that could include highly impacted communities, transportation hubs, emergency shelters, and areas at risk for isolation during significant weather events or wildfires.
- In their 2021 IRP, PSE's customer benefit indicators for portfolio analysis include "Energy Resilience" measured in capacity of distributed storage added.
  - It also considers: "System enhancements that will improve resiliency, such as the ability to deliver electricity via a second line, possibly from another substation, to make the grid more self-healing."



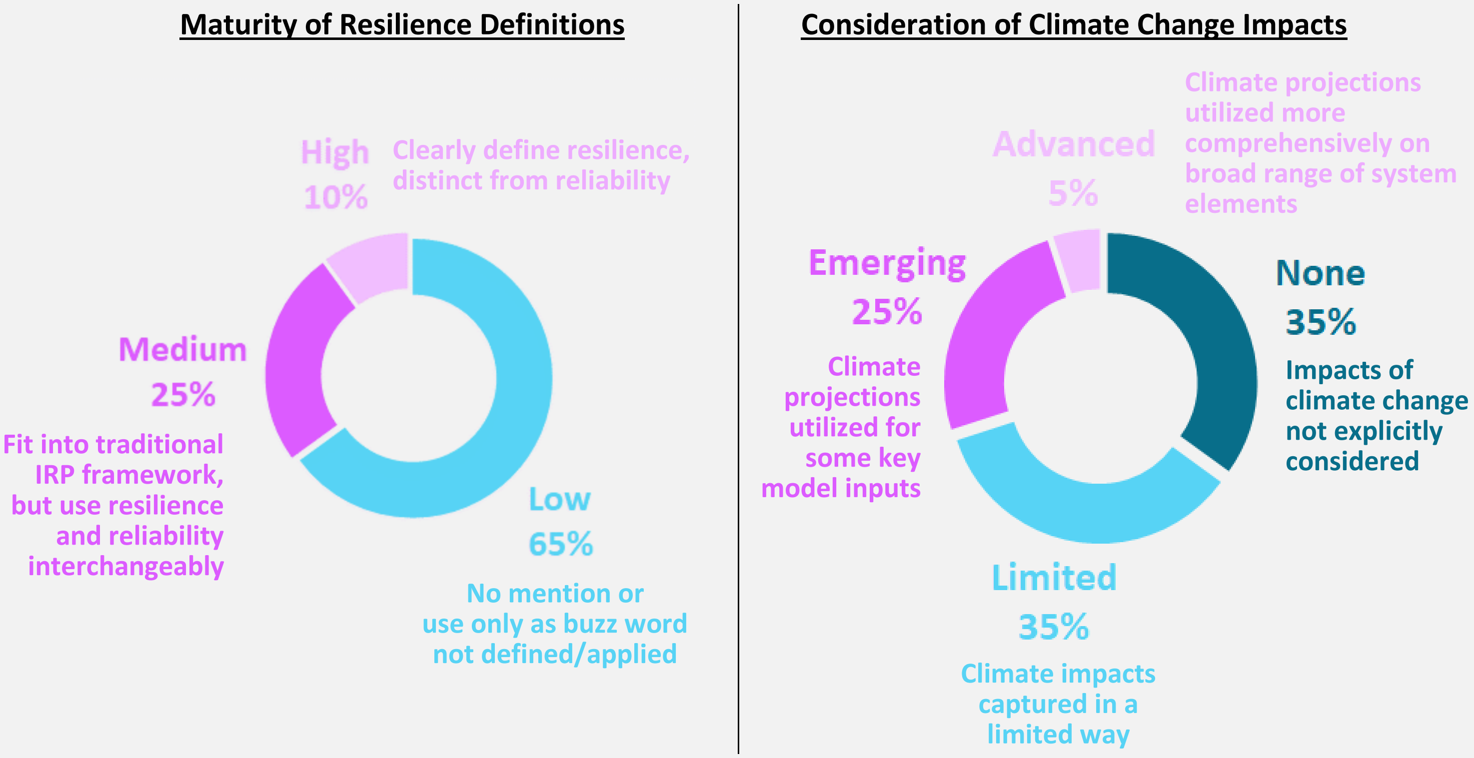


Figure 2: Summary of IRP survey results.

The two figures above summarize the findings of our survey.

Of the 20 plans we reviewed across the WECC, around 2/3 either did not mention resilience at all or they used it as a buzz word without defining or measuring it. In 25% of the resource plans, resilience fit into a more traditional IRP framework in which it is discussed primarily in the context of system reliability. These plans included examples of certain types of projects or programs improving grid resilience, but without being tied to a specific definition or set of metrics. Only a couple of the IRPs included a clear, actionable, definition of resilience.

Climate change is amplifying weather extremes and creating new normals, as is increasingly recognized in the IRP studies. About 1/3 of the IRPs we reviewed still do not explicitly consider the effects of climate change. Among the remaining 2/3 that recognizes climate change-induced risks to the electric system, the approaches to incorporating climate change impacts into IRP studies are evolving:

- Some rely on historical trends and extrapolate them, with more weight on recent events;
- Some run one-off sensitivity cases or scenarios (deterministically) to explore needs under certain types of extreme weather events;
- Others are starting to more systematically bring in long-term climate projections when developing key modeling inputs;
- So far, the primary focus has been temperature effects on electric demand, but some planners are now starting to also look into impacts of weather on supply availability.

Key Elements of the Resilience Evaluation Model Architecture

Key Elements of a Resilience Definition

Based on our literature review we identified the following 5 key elements of a resilience definition needed for resilience planning applications in California's grid planning processes:

1. What is the critical function or service that must be preserved?
2. What is the system providing that function/service?
3. What are the key hazards that can disrupt the systems' ability to provide those functions/services?
4. Where are the known failure points on the system that would disrupt that function/service?
5. What are the most concerning sets of hazards and failure points, reflecting risk tolerances on impact vs. probability?

These key elements must be clearly specified in order to identify the necessary architecture and output metrics of a planning model that measures resilience.

Proposed Definition of Resilience

We reviewed descriptions of about two dozen catastrophic events across the U.S. that had major impacts on the ability of electricity infrastructure to function. Event types include operations-related (1963 and 2003 Northeast blackouts), hurricanes (e.g., Hurricanes Irma and Maria in 2017), winter storms (e.g., Winter Storm Uri in 2021 and Winter Storm Elliot in 2022), other extreme cold events (e.g. cold snaps in 2011 and 2018), heat waves and extreme heat events (e.g., 2011, 2020, and 2022 heat waves), wildfires (e.g., 2007, 2019, and 2020 events in California), wildfire smoke (e.g., megafires in 2020 in California), and extreme drought (e.g., 2012 drought in California).

For each event we collected information to help answer the 5 questions above. We also compared a national resilience perspective to a California-specific perspective. Combining (a) our literature review with (b) this event-based research, (c) the *WARP to Resilience* focus on climate resilience, and (d) our own expertise in grid planning needs and objectives, we conclude:

1. Critical function or service: This is the minimum level of electricity service to end-use customers needed to access other services needed by the customer for survival and livelihood, such as food, safe shelter, medical care, heating/cooling, communications, ability to work/study, and transportation. The level of electricity service must recognize that interruptions are heterogeneous in the severity of impact depending on the characteristics and circumstances of (a) the service interruption (outage), and (b) the customer.

   We emphasize that heterogeneity in the severity of outage impacts depending on the outage and the customer is particularly difficult to capture in any outage (or loss of load) metric. We will discuss that further in future work products, and from a resilience model design perspective.

2. System (providing that function/service): The electricity grid, including all grid domains (transmission, distribution, customer), and from generation fuel supply to the end-use customer.

3. Key hazards: These are environmental and weather conditions that can significantly increase electricity demand, reduce electricity supply, limit delivery of electricity to customers, and/or coincide with stressors to other (non-electricity) services that compound the impact of electricity service interruptions. For California specifically, these include extremes in heat, cold, drought, wildfires, storms, winds, floods, and wildfire smoke.

4. Known failure points: We observe failures at points across the entire system. For California specifically, failures tend to occur as (a) insufficient generating capacity, (b) unplanned wires (transmission and/or distribution) outages and de-rates, or (c) planned wires outages to manage wildfire risks (via Public Safety Power Shutoffs and Enhanced Powerline Safety Settings).

5. Most concerning sets of hazards and failure points: On a national scale, hurricanes are among the most destructive to the electricity grid. Hurricanes Katrina (2005) and Harvey (2017) are the highest and second highest cost disasters on record, respectively (NOAA 2023). Most electricity system destruction occurs at the distribution and customer level and recovery of electricity service can be a lengthy process. In Puerto Rico, for example, 1.2 million (75%) households were on outage for more than a month—some for almost a year—following Hurricanes Irma and Maria in 2017 (Marsters and Houser 2017; Hoyos 2018).

   Winter storms are also highly disruptive and hazardous from a national perspective. Winter Storm Uri (2021) resulted in the Uri the "largest controlled firm load shed event in U.S. history" (FERC). In Texas, 69% people experienced an outage, lasting for days on average. In terms of electricity infrastructure, generators and generator fuel supply are the key failure points in winter storms and cold snaps. Impacts can be compounding and cascading in areas with a high dependency on natural gas for both heating and for electricity production as these weather conditions simultaneously drive (1) spikes in electricity demand, (2) generator equipment failures and inability to produce even with fuel sufficiency, and (3) disruptions in fuel operations and allocation of fuel to generators.[5]

   In California specifically, the major hazards are more varied and known failure points span the entire system of electricity infrastructure. The most concerning hazards and failure points are:

   a. Heat waves, that are known to result in insufficient generation and rotating blackouts affecting hundreds of thousands of customers lasting several hours;

   b. Extreme wildfires, that are known to result in (a) wires (transmission or distribution) outages that can leave millions of customers on outages for several days at a time, and (b) customer property destruction that yields more extensive customer outages;

   c. Drought, as a compounding factor that heightens the severity of heat waves and wildfire weather, and that reduces the amount of generating capacity available;

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[5] On the second point, for example, see (FERC and NERC 2011).

d. Storms and floods, that are known to result in (a) wires (especially distribution) outages that can leave hundreds of thousands of customers on outages for several days at a time, and (b) customer property destruction that yields more extensive customer outages;

e. Extreme smoke, that is known to force transmission outages and de-rates on major interties on the bulk grid, with the customer outage impact a known unknown; and

f. Cold snaps, largely as a known unknown that could conceivably threaten California's generation and battery fleet under novel future weather patterns.

Our working definition of resilience is therefore the following or something similar:

> *Resilience in the electricity sector is the ability to provide a minimum level of electricity service to end-use customers needed by the customer for survival and livelihood; even in an emergency situation that stresses the electricity system such as extremes in heat, cold, drought, wildfires, storms, winds, floods, and wildfire smoke; and considering known and knowable failure points on the electricity system such as generator fuel supply and generation sufficiency, transmission and distribution, and customer-sited resources.*

The specific language and wording of this definition has evolved—and will continue to evolve—through the course of this study.

Implications for the Architecture of a Resilience Evaluation Model

Given this definition of resilience, our resilience evaluation model will need to have the following characteristics:

1. Critical function or service: The model will need to analyze and calculate end-use customer outages for each relevant outage type and customer type. For example, if 1 MWh outage in the commercial sector is more impactful to customers than 1 MWh outage in residential homes, then the model will need to calculate and distinguish outages by customer sector. Definition of "relevant" outage and customer types is in-progress and we will discuss this in more depth in future work products. For now, we observe the following:

   a. **Value of Lost Load (VoLL)** studies provide a rich conceptual framework for expressing heterogeneous outage impacts in dollar terms (*see*, for example, (Gorman 2022)), but actual measured or estimated values are extremely limited. Even for studies within California, results are indicative or directional at best, and do not appear to be broadly applicable to all California electricity customers. So, we face a major data limitation to expressing outages in dollar terms.

   Even with sufficient VoLL data available, we learned from public participants that expressing outages in dollar terms in our model, at this stage of California's grid planning framework, is likely to be counterproductive. The metric asserts value tradeoffs that not all may agree with, e.g., that it is generally better to serve x# of commercial customers than y# of residential customers. The metric also implies absolute spending thresholds—

e.g., outages once every 5 years cost a community $z so they should spend that much on a mitigation solution—that are not necessarily appropriate given (a) unavoidable flaws in VoLL measurement and estimation that may bias those thresholds up or down, and (b) different outage risk tolerances and discount rates of different communities and public participants.

Public participants helped us better understand the role and diversity of community perspectives and planning, and that it would be more productive at this time to produce metrics that better support the discussion of tradeoffs and risk tolerances, rather than a metric like VoLL that asserts those tradeoffs and risk tolerances. For example, if an alternative resource portfolio better serves x# of commercial customers at the expense of y# of residential customers, then show those numbers (rather than VoLL) so the grid planning community can discuss: “Is that an acceptable tradeoff?”

As a result, we are inclined to adjust our original work plan, and we now plan to initially produce outage metrics that are not processed into dollar terms. The outage metrics will be grouped by relevant outage and customer characteristics; and how we define those groups and relevant characteristics will be guided by the VoLL literature. At this time we still plan to include implied breakeven VoLL calculation functionality in the model in case it is useful.

b. **Vulnerability studies** also provide a rich conceptual framework for expressing heterogeneous outage impacts—but through geographic, community, and customer segmentation. Vulnerability studies offer a promising data source that is more comprehensive across California customers than the VoLL research and more reflective of the diversity of California’s landscape and communities. Examples of vulnerability studies are (a) CalEnviroScreen’s metrics on pollution and socioeconomic burdens, and identification of disadvantaged communities; (b) the California utilities’ Climate Adaptation Vulnerability Assessments (CAVAs) developed under CPUC Rulemaking 18-04-019; (c) and Sandia National Laboratories’ ReNCAT model that produces a social burden metric. Combined with guidance from VoLL literature, national and California-focused vulnerability studies are likely to provide a way for us to better distinguish the communities and customers that experience the most severe outage impacts.

In 2024 the CPUC Resiliency and Microgrids team formally engaged us to lead a study with Spatial Informatics Group, LLC (SIG), under CPUC RFP #22NC1091, with a goal to develop an equitable resilience index. Shortly after study launch, and in collaboration with the CPUC and their public participants, the study team explored many other state and national vulnerability studies. We started data review with CalEnviroScreen, and with the Public Health Alliance of SoCal’s Healthy Places Index (HPI), but found additional studies and data sources more reflective of the breadth of indicator categories needed for our resilience planning application. We identified data sources spanning indicators of community-specific:

- Health and wellbeing;
- Socioeconomic condition;

- Built environment infrastructure and resources;
- Natural environment infrastructure and resources; and
- Natural hazards.

Key references identified in this research include (Brockway et al. 2021), (CPUC Staff 2020), (Dugan et al. 2023), and (Sparti et al. 2023).

This CPUC equitable resilience index study is currently on hold, and it is unclear to us at this time if its final index can be developed in time to incorporate into our resilience evaluation model for this study. Pending those results—and based on the initial data collection work for the CPUC equitable resilience index study—we plan to incorporate the Federal Emergency Management Agency's (FEMA) National Risk, Social Vulnerability, and Community Resilience indices to demonstrate incorporation of community-specific characteristics and how they can be used to prioritize the impact of outage outcomes in our model.[6]

c. **Demand data:** Applicability of information from VoLL and vulnerability studies is limited by the availability of sufficiently granular demand data. Distinction of outages within versus outside of disadvantaged communities in our model, for example, will be difficult if demand data are only available by broad utility planning areas. In collaboration with the CEC's R&D and Energy Assessment Divisions we are pursuing several options for alignment of our model's demand data to the required granularity of output metrics.

2. <u>System</u> (providing that function/service): The model crucially will need to represent failures in electricity supply across all grid domains, failures in delivery across major transmission interties, failures in delivery through distribution sections, and the weather-sensitivity of demand. Failures in generator fuel supply will depend on weather variables, including reductions in sun, water, and wind, that impact the performance of both generators and energy storage. Fossil and other fuel supply interruptions may be modeled stochastically via generator forced outage rates that depend on weather conditions.

3. <u>Key hazards</u>: The model will need to reflect a variety of possible environmental and weather conditions that can significantly increase electricity demand, reduce electricity supply, or limit delivery of electricity to customers. We plan for the model's first stochastic variable to be a full year (8,760 consecutive hours) weather variant. We are working with CEC's R&D and Energy Assessment Divisions, and the Analytics Engine team, to develop a comprehensive library of weather variants for each planning year.

4. <u>Known failure points</u>: The model will need to include relationships between (a) the drawn weather variant and (b) impacts on supply and demand levels. From there, the model will iteratively test for insufficient generating capacity and wires (transmission and/or distribution) outages and de-rates. Subject to further refinements, we expect the model's basic logic will likely be:

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[6] https://hazards.fema.gov/nri/

a. Draw a weather variant (with the caveat that the underlying distribution of weather variants is our best guess at the probability distribution of what could happen)
b. Estimate demand given that weather variant
c. Estimate supply availability (bulk grid and distributed) given that weather variant
    i. Estimate based on solar/water/wind conditions, e.g., solar insolation, winter precipitation, wind speeds
    ii. Apply probabilistic forced outages or de-rates to both generation and transmission interties that may vary by environmental conditions, e.g. by extreme temperatures
    iii. Apply deterministic transmission and distribution outages which is a function of weather variables, such as PSPS when a fire weather index is high and wind speeds exceed a certain threshold
    iv. Estimate likely storage operations and resulting states of charge
d. Test for supply sufficiency at three levels:
    i. Bulk grid: using a load shed process consistent with CAISO's emergency operating procedures, determine the need for rolling blackouts
    ii. Apply the same test to major load pockets within California, indicated by how we select key intrastate transmission interties
    iii. For distribution areas on outage, apply a similar test to those local areas (i.e., originally estimated demand in (b) versus available distributed supply in (c)
e. Report outage results

5. <u>Most concerning sets of hazards and failure points</u>: The model will need to include parameters that reflect failure rates that depend on the hazard. SCE in its 2022 CAVA, for example, assumes generator de-rates when ambient temperature exceeds 115 degrees Fahrenheit. Parameterization of our demand and supply assumptions is in-progress.

Application in California's IRP and System Planning

The IRP and bulk grid planning ecosystem in California is very rich and requires coordination among many parties. The figure below highlights key interactions under the current planning process. Among the state agencies, the CEC is charged with preparing a comprehensive demand forecast, as a part of their annual Integrated Energy Policy Report. Their demand forecast is used by the CPUC's IRP studies and flows into CAISO's transmission planning process (TPP).

The IRP is a multi-year process which starts with a CPUC study to develop the "least-cost" resource portfolio options, while meeting two key objectives:

- **System reliability** based on planning reserve margin and need assessment that corresponds to a 1 day in 10 years loss of load expectation; and
- **Electric-sector GHG emission reductions** consistent with the target range set by the California Air Resources Board.

LSEs use the CPUC's analysis for guidance to develop their individual IRPs and file the plans with the CPUC to show compliance with their IRP requirements under the Public Utilities Code 454.52(a)(1), which includes to "[s]trengthen the diversity, sustainability, and resilience of the bulk transmission and distribution systems, and local communities" among other requirements.

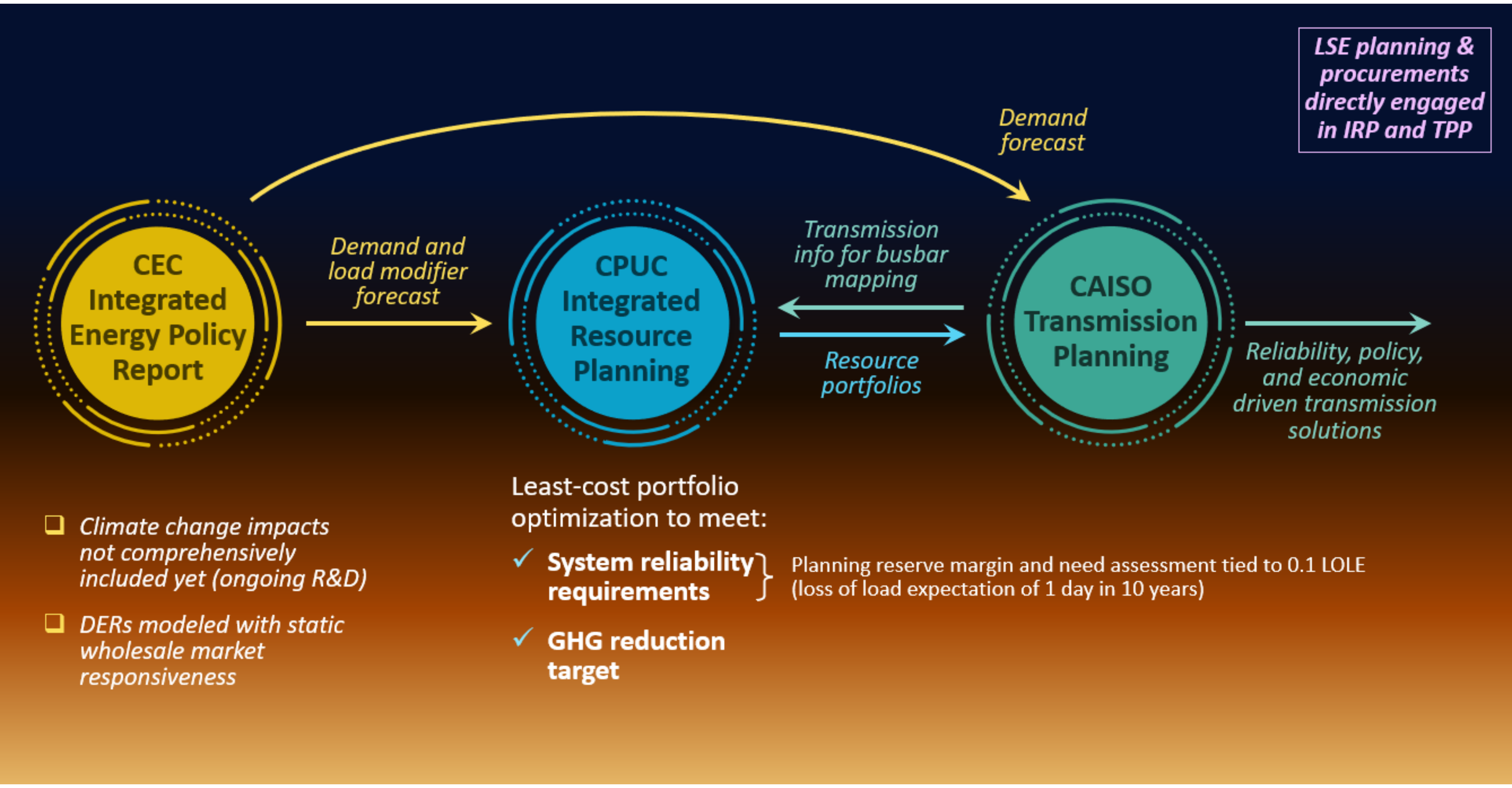
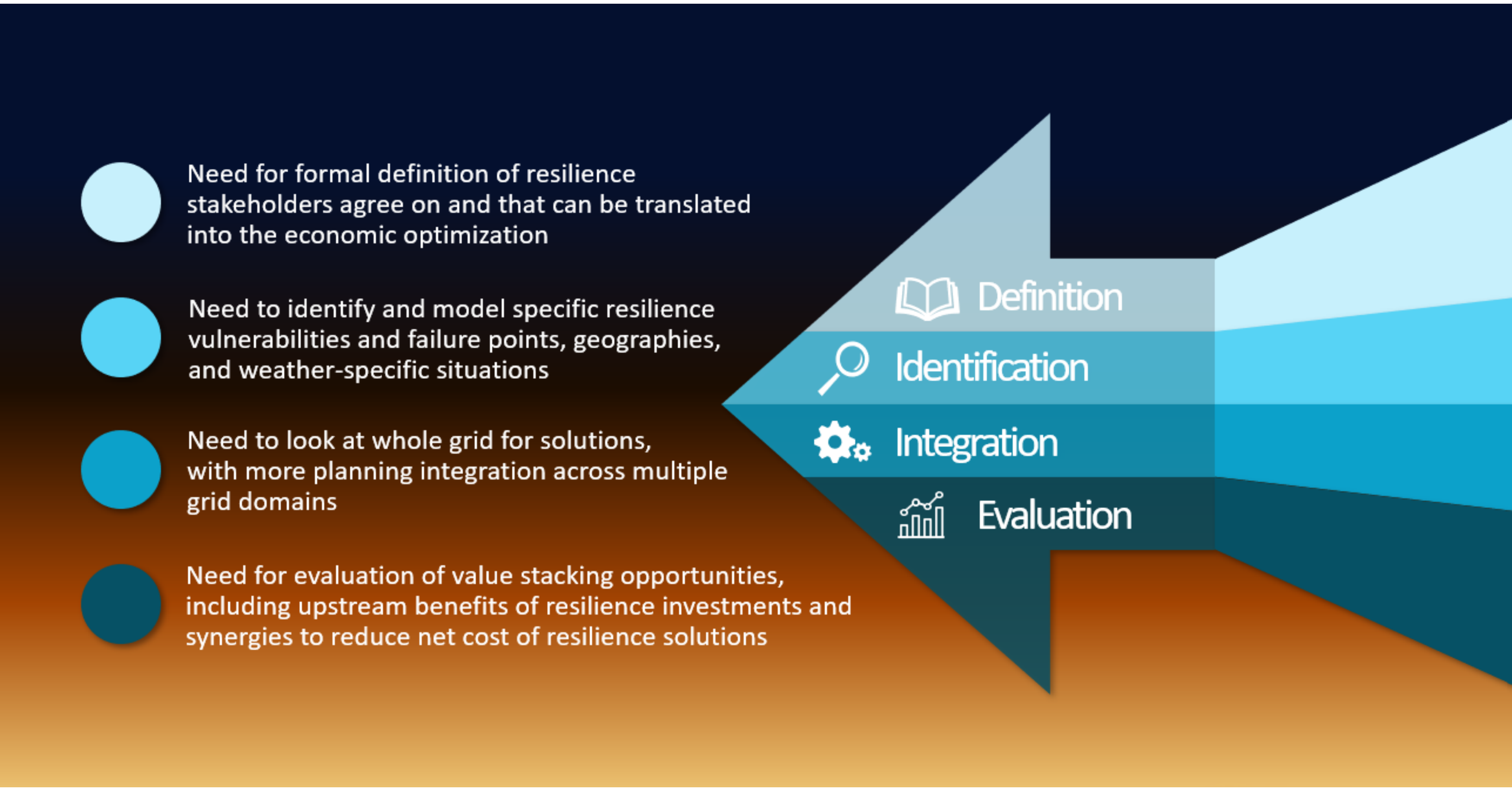


Figure 3: Overview of current IRP and bulk-grid planning in California.

We identify that the current process has four gaps that needs to be addressed for incorporating resilience in resource planning, as described below:

- **Common definition of resilience and a set of metrics** that grid planners agree on and can be translated into the IRP's portfolio optimization;
- **Identification and modeling of key resilience vulnerabilities and potential failure points** across the grid and geographies, while considering weather-specific situations and concurrent & compounding events;
- **Exploration of the whole grid for solutions with more planning integration** across grid domains including bulk grid and distributed resources;
- **Comprehensive evaluation of the resilience impacts** while considering the multiple use and value stacking opportunities.

Environmental hazards impact all parts of the grid, so many of the resilience mitigation measures must be closer to the customer and communities at risk. Traditional resilience solutions, like diesel generators are installed for back-up power and provide only downstream benefits to the customers they serve. However, today's resilience solutions include resources like storage (or hybrid solar+storage) that are very flexible: they can also provide upstream benefits and support clean energy transition. Bulk grid planning needs to consider contributions of these resources and their ability to stack grid and customer benefits. Value stacking is also important when evaluating local resilience solutions because it can reduce net cost to provide resilience and impact economic feasibility and ranking of mitigation measures.



Need for formal definition of resilience stakeholders agree on and that can be translated into the economic optimization

Need to identify and model specific resilience vulnerabilities and failure points, geographies, and weather-specific situations

Need to look at whole grid for solutions, with more planning integration across multiple grid domains

Need for evaluation of value stacking opportunities, including upstream benefits of resilience investments and synergies to reduce net cost of resilience solutions

Figure 4: Resilience-related gaps in IRP planning.

The figure below illustrates a potential framework on how to integrate resilience into resource planning. At the heart is a comprehensive resilience assessment, which taps into several related but currently disconnected efforts.

1. Bring in resilience definition and set of societal metrics/tools from the CPUC's Resiliency and Microgrids effort;
2. Bring in information on vulnerability profiles and guidance on climate scenarios from various utility-led efforts, such as CAVA, RAMP, and WMP;
3. Utilize high-resolution climate projections and scenarios and re-parametrize electric demand forecast and supply availability assumptions to reflect climate change impacts and extreme weather conditions, probabilistically; and
4. Bring in resource portfolios from the current IRP studies and evaluate resilience of those portfolios.

Outputs of the resilience assessment would include loss of load and customer outage metrics, with details by location, load priority, type of hazard, and grid failure mode.

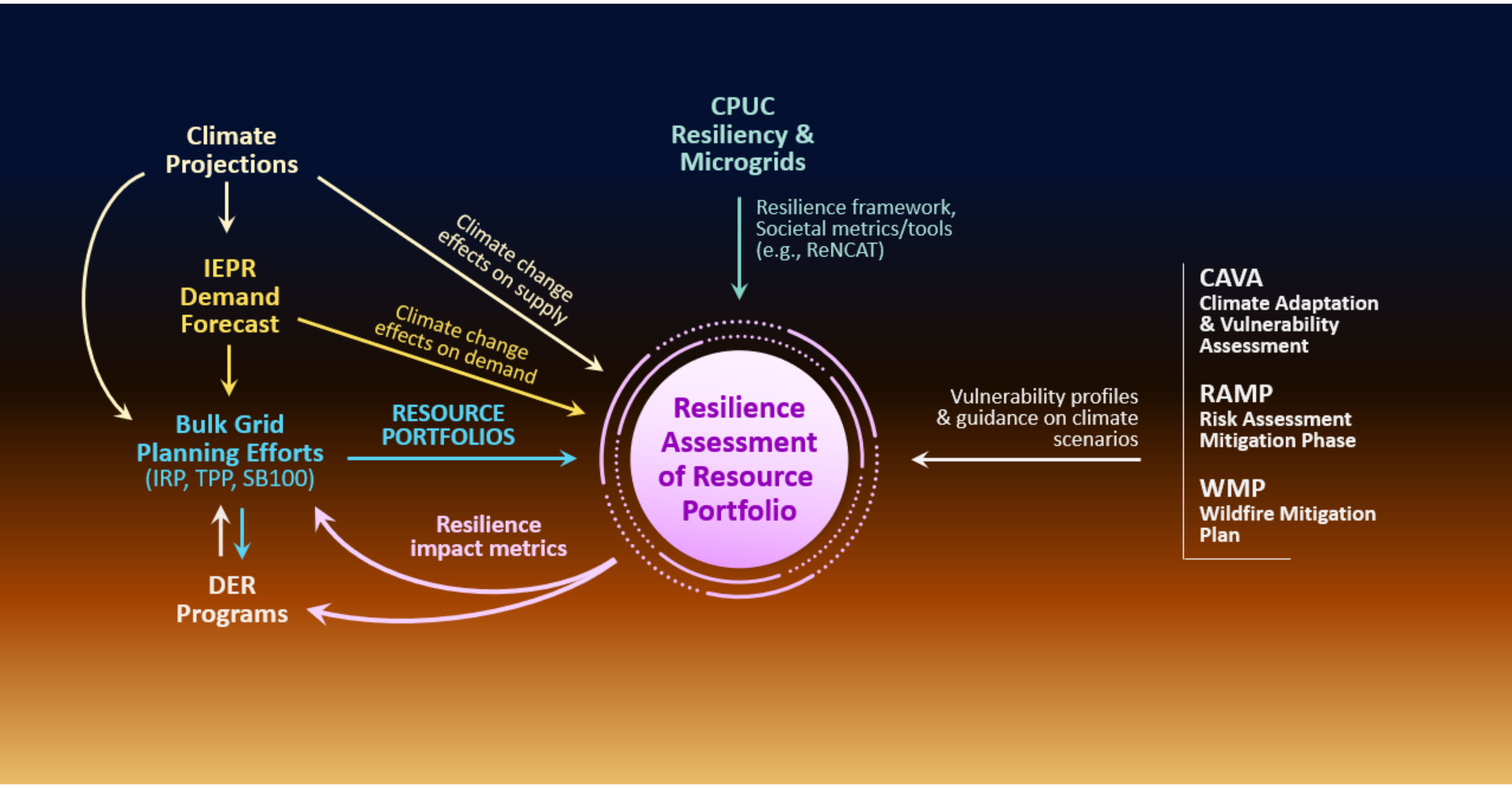


Figure 5: Illustration of how to integrate resilience into the current resource planning process.

Key Elements of an Integration Strategy in California

Public participant buy-in to our resilience framework and integration with the state's grid planning processes is crucial to the success of the *WARP to Resilience* study. California has a complex grid planning construct that is highly innovative and recognizes gaps in resilience planning, yet wrestles with deep institutional barriers that prevent a cross-cutting issue like resilience from being fully addressed. At this time we find the key elements of a strategy to integrate our work in California's grid planning include work to:

- Continue to build off of CPUC 4 Pillar Methodology, and work with the CPUC Resiliency and Microgrids team and their public participants to develop a definition of resilience that includes specific resilience assessment metrics that can be used in IRP
- Through our model, connect and leverage elements of various grid planning processes with a consistent resilience evaluation framework including:
    - Input vulnerability profiles, and corresponding model outputs, based on the CPUC and utility CAVA, RAMP, and wildfire mitigation work
    - Input climate data and demand methodologies from the CEC's work
    - Input resource portfolios from the utility IRPs, CPUC resource plans, CEC and other state agency SB 100 studies, and CAISO transmission plans
    - Output metrics that inform both bulk grid planning efforts and distributed resource planning efforts
- Include model functionality for LSEs to compare resilience results of their resource plans to the CPUC's baseline Reference System Plan
- As part of the IRP proceedings, demonstrate the model's results for an LSE plan that clearly improves resilience; as part of that demonstration facilitate discussion of resilience tradeoffs of different resource portfolios, and of how different LSEs might have different views on those tradeoffs, the risk profiles of hazards and grid failures, and the appropriate investment strategy.

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