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LBNL EPIC 5 Research Concept Input

Please see attached. Thank you!

Additional submitted attachment is included below.

Electric Program Investment Charge 2026–2030 (EPIC 5) Research Concept Proposal Form

The California Energy Commission (CEC) is currently soliciting research concept ideas and other input for the Electric Program Investment Charge 2026–2030 (EPIC 5) Investment Plan. For those who would like to submit an idea for consideration, please complete this form and submit it to the CEC by **August 8, 2025**. More information about EPIC 5 is available below.

To submit the form, please visit the e-commenting link: https://efiling.energy.ca.gov/EComment/ECommentSelectProceeding.aspx and select the Docket **25-EPIC-01**. Enter your contact information and then use the "choose file" button at the bottom of the page to upload and submit the completed form. Thank you in advance for your input.

1. Please provide the name, email, and phone number of the best person to contact should the CEC have additional questions regarding the research concept:

Alecia Ward
Lawrence Berkeley National Laboratory
Leader, Program and Business Development, Energy Technologies Area
award@lbl.gov, 510-486-4540

2. Please provide the name of the contact person's organization or affiliation:

   Lawrence Berkeley National Laboratory

Lawrence Berkeley National Lab (LBNL) is pleased to present the following concepts in response to the public comment period for strategic goals and strategic objectives in the EPIC 5 investment plan.

We are very thankful to the California Energy Commission for your leadership, for recognizing the needs of the battery industry in California, and for providing the support to develop the technologies, tools, and analysis that will help California to meet its energy needs.

The concepts included in this document represent the multiple topics and areas that LBNL researchers work on including residential, commercial, and industrial buildings energy efficiency, DER integration, demand response and flexibility, light, medium and heavy duty transportation, energy generation and storage technologies, grid modernization and wildfire impacts to name a few. Within these varied topics, the concepts included represent a breadth of capabilities at the lab such as technology development, integration, scale-up and validation, technoeconomic and life cycle analysis, modelling and valuation.

The main themes across the submitted concepts can be summarised as follows:

- Concepts that build on California Energy Commission funding in previous investment plans and address gaps or identify further needs for research and development, scale-up or integration for achieving specific goals and outcomes for California within the context of the evolving electric grid. Examples include feeder level forecasting for residential load growth from new electric loads and identification of neighborhoods with the greatest opportunity for upgrading aging equipment, and new approaches for energy savings, demand flexibility and peak load reduction from small and medium businesses sectors.

- Concepts that propose new and advanced technologies with a focus on process efficiency and cost reduction such as AI tools for performance validation and verification, AI for home energy audits and targeting, planning and implementing retrofits, AI and automation for improving energy operations of commercial buildings and AI for localized risk mapping from flood, drought and wildfires on grid infrastructure. Other advanced and novel technologies include digital twin and controls to accelerate the development and deployment of low-emission technologies in energy-intensive industrial sectors, mobile back-up, and demand flexibility and demand response solutions for industrial loads including data centers.

LBNL has provided ~80 concepts in this document that are organized by the 13 *primary* strategic objectives that they best align with. Concepts that respond to more than one strategic objective have been noted in the main text of the concept. Several projects funded by California Energy Commission over past EPIC investment plans have benefited from collaboration with DOE funded research. Given the evolving landscape of federal investments in research, we have also identified opportunities for EPIC 5 in this context.

Each concept responds to questions three through eight of the *Electric Program Investment Charge 2026–2030 (EPIC 5) Research Concept Proposal Form* using the following numbering and heading convention:

Question 3	i. Brief Description
Question 4	ii. Breakthroughs
Question 5	iii. Outcomes
Question 6	iv. Metrics
Question 7	v. References
Question 8	vi. Strategic Goal
	vii. Support for Goal
	viii. Concept Contributed By

A. Reducing M/HDV charging infrastructure costs

1. Large-Scale Intermodal Freight System Optimization to Enhance Affordability, Efficiency, and Air Quality in California

   i. Description: California's freight transportation system—spanning truck, rail, marine, and intermodal hubs—is a major consumer of energy and a significant source of air pollution, particularly in communities near freight corridors and ports. However, the affordability, efficiency, and environmental performance of this system can be substantially improved through coordinated planning and optimization across transportation modes and fuel types.

      This project proposes a California-centric, large-scale intermodal freight system optimization framework that builds on Lawrence Berkeley National Laboratory's (LBNL) existing tools and capabilities. These include multimodal freight demand modeling, infrastructure simulation and optimization, and advanced transportation operations analysis.

   ii. Breakthroughs: The proposed framework will: Reduce infrastructure costs for medium- and heavy-duty (MHD) electric truck charging by identifying optimal siting strategies, leveraging synergies across intermodal connections, and coordinating charging infrastructure with other transportation investments.

      Evaluate and optimize across multiple fuel types (e.g., electricity, hydrogen, diesel) to ensure cost-effective deployment strategies that reflect California's varying freight operations and energy goals.

      Quantify and reduce air pollution and associated health burdens by incorporating emissions and air quality metrics into the optimization alongside energy use and operating cost.

      Leverage real-world freight network and operations data, including datasets previously collected by the team, to formulate intermodal vehicle routing problems (VRPs) grounded in California's specific freight patterns.

      Use SynthFirm, an open-source agent-based firm and supply chain simulator developed by LBNL, to generate detailed freight demand scenarios for California's industrial sectors.

iii. Outcomes: By advancing cost-effective fuel-type optimization and pollution reduction strategies, this project will benefit California electricity ratepayers through more efficient grid planning, reduced infrastructure costs, and improved public health.

iv. Metrics:

a. Affordability Metrics (Quantitative): These indicators evaluate the financial impact on infrastructure development, operations, and ratepayers.
   1. Capital cost savings from optimized siting of MHD electric truck charging infrastructure (e.g., $ per charging site avoided or reduced).
   2. Total cost of ownership (TCO) comparisons for various fuel and mode combinations ($/ton-mile).
   3. Electricity infrastructure investment deferral value ($ saved through avoided or postponed grid upgrades).

b. Air Quality and Health Metrics (Quantitative): These evaluate the environmental and public health benefits.
   1. Reductions in emissions of key pollutants
   2. Health impact reduction, estimated through metrics like premature deaths avoided, hospital admissions reduced, or DALYs (disability-adjusted life years) using tools like BenMAP or InMAP.
   3. Emissions intensity per ton-mile, by fuel type and mode (g pollutant/ton-mile).

c. Operational Feasibility and Resilience (Qualitative and Quantitative): These reflect real-world applicability and robustness.
   1. Stakeholder satisfaction or support from industry, utilities, local governments, and communities (surveys, interviews).
   2. Feasibility scores for infrastructure deployment scenarios (scored on technical, and market acceptability and readiness).

v. References:

a. Xu, X., Yang, H.-C., & Ravulaparthy, S. (2024). *Firm Synthesizer and Supply-chain Simulator (SynthFirm) v1.0* (1.0). https://doi.org/10.11578/dc.20240621.2

b. Xu, X., Yang, H.-C., Jeong, K., Bui, W., Ravulaparthy, S., Laarabi, H., Needell, Z., & Spurlock, C. A. (2024). Teaching Freight Mode Choice Models New Tricks Using Interpretable Machine Learning Methods. *103rd Transportation Research Board (TRB) Annual Meeting*.

c. Preble, C. v., Cados, T. E., Harley, R. A., & Kirchstetter, T. W. (2018). In-Use Performance and Durability of Particle Filters on Heavy-Duty

Diesel Trucks. *Environmental Science & Technology*, acs.est.8b02977. https://doi.org/10.1021/acs.est.8b02977

vi. Strategic Goal: Transportation Electrification

vii. Support for Goal: This project will support reducing M/HDV charging infrastructure costs through optimal infrastructure siting, load split with other freight modalities, and peak demand shaving under efficient freight shipment scheduling. This project will also boost the benefits of EVs for disadvantaged communities that are close to freight facilities and disproportionately affected by higher emissions from diesel trucks, rails, and vessels. The proposed work will support local-level decarbonization through boosting EV adoption in the freight sector and reducing emissions produced by businesses.

viii. Contributors to This Concept Include: Xiaodan Xu, Ling Jin, Haitam Laarabi, Tom Kirchstetter

2. Easing EVSE Projects into the MHDV Space

i. Description: Electric vehicle supply equipment (EVSE) projects are highly complex technical projects that require significant consideration and investment beyond the simple costs of purchasing and installing the equipment. Work on light-duty public EVSE completed jointly by LBNL, NREL, and INL resulted in the identification of a set of barriers to EVSE projects in the light-duty vehicle (LDV) space that represent significant impediments to successful projects, either by adding unpredictability to project budget and timelines, increasing project costs, or simply making projects infeasible (which can happen due to a variety of issues). This framework was developed based on stakeholder interviews across a spectrum of stakeholder types (including state and local governments, utilities, EVSE installers, and site operators) to understand some of the 'invisible' issues with these projects that may not appear on a budget sheet. This framework can be used to tackle the primary barriers faced by EVSE projects, and to develop solutions to those barriers. We propose to extend this framework for easing EVSE projects into the medium- and heavy-duty vehicle (MHDV) space and developing it further to propose solutions to systematic issues in MHDV project processes.

ii. Breakthroughs: Soft costs in EVSE projects have been studied by LBNL, NREL, INL, and others for several years. We have found that these costs can significantly impact the overall costs of these projects, and in some cases can account for more than 60% of overall project costs. This represents a significant pain point for installers and prospective owners/operators, to the point of cancelling what would otherwise be projects with a high potential to create a positive impact for EV drivers. Furthermore, other barriers (such as compliance hurdles, or working on projects in areas that lack significant institutional knowledge) can create drags on a project that, while not directly appearing on a project budget, can nonetheless cause fiscal and operational issues, either immediately or in the future. By conducting interviews to understand the landscape of MHDV EVSE project barriers, we believe this research would be the first such effort to systematically frame these issues in the MHDV space. Furthermore, this framework is intended to develop and propose realistic solutions to ease these pain points and improve the outcomes of MHDV EVSE projects, reducing costs and increasing deployment throughout California.

iii. Outcomes: A successful project would begin by developing a map of project barriers and their underlying causes. For LDV EVSE projects, we have identified 5 main 'root causes' of project barriers: Compliance, Knowledge, Administrative Overhead, Technical Limitations, and Direct Monetary Costs. This research concept would apply this same framework to MHDV EVSE projects (adjusting as needed in response to stakeholder interviews) to provide insight into the greatest pain points of MHDV EVSE projects in California.

This map of barriers would then be used to identify high-potential methods to ease the pain points identified by stakeholder interviews in MHDV projects. By identifying key barriers and their root causes, it is possible to understand where and how these issues overlap, and develop systematic solutions to systematic issues that can have a greater impact on MHDV EVSE deployment.

These outcomes have the potential to significantly impact the MHDV space significantly by easing the process of installing EVSE, allowing EVSE to be installed in more places for less money. This in turn should lead to an increase in consumer choice for MHDV operators to adopt efficient vehicles into their fleets in ways that align with the state's energy policy goals.

iv. Metrics:

a. Quantitative measures of impact may include:
   1. Reduction in average time to project completion
   2. Reduction in project unpredictability (for both cost and time)
   3. Metric around the supply, demand and EVSE market dynamics
   4. Development and use of educational materials for policymakers and local contractors regarding steps to improve successful outcomes for MHDV EVSE projects
   5. Decreased time to obtain necessary project permits
b. Qualitative measures of impact may include:
   1. A standardized framework for understanding MHDV EVSE project barriers
   2. Stakeholder satisfaction with and adoption of project outputs
   3. Stakeholder satisfaction with proposed solutions to project barriers
   4. Further scientific study of MHDV EVSE projects based on this work

v. References:

a. Benoliel P, et al. Soft costs and EVSE – Knowledge gaps as a barrier to successful projects. Applied Energy 2025; 389 (2025) 125749. https://doi.org/10.1016/j.apenergy.2025.125749
b. Nelder C, Rogers E. Reducing EV Charging Infrastructure Costs. 2019. https://doi. org/10.13140/RG.2.2.26490.03525

vi. Strategic Goal: Transportation Electrification

vii. Support for Goal: This project would support transportation goals by providing direct pathways to reduce MHDV EVSE costs. Additionally, by fully engaging stakeholders in a variety of locations, it is possible to focus solutions on various communities making the greatest impact. This project would also provide policymakers with educational materials to assist them in maintaining a solid knowledge base for the rapidly evolving technology market of EVSE.

viii. Contributors to This Concept Include: Margaret Taylor, Peter Benoliel, Sydny Fujita

B. Overcoming barriers to EV benefits in DVCs

1. Integration of Distributed Fiber-Optic Sensing for Battery Modules in EVs
   i. Description: We propose that EPIC investigate the integration of Distributed Fiber-Optic Sensing (DFOS) for real-time, high-resolution monitoring of lithium-ion battery modules in electric vehicles. By embedding fiber-optic sensors into cells and modules and coupling them with advanced signal-processing and machine-learning analytics, this approach would detect early-stage degradation, thermal hotspots, and mechanical strain both during manufacturing (for inline quality control) and in-service operation (for predictive maintenance and second-life repurposing). Techno-economic pilot studies across various chemistries, pack designs, and duty cycles would evaluate sensor integration pathways, data accuracy, durability, and cost-benefit trade-offs in California's EV manufacturing and charging ecosystem. EPIC funding is essential to support these pre-competitive demonstrations and comprehensive techno-economic analyses—steps required to de-risk the technology, and inform next-generation battery management systems.
   ii. Breakthroughs: The proposed DFOS-enabled battery monitoring concept overcomes key technical and market barriers that currently limit faster, wider scaling of these critical technologies:
      a. Conventional battery management systems (BMS) rely on external voltage/temperature measurements, leaving internal hotspots and mechanical strain undetected until failure. The embedding of fiber-optic sensors delivers sub-module spatial resolution (<10 cm) and temperature accuracy (±0.1 °C), as well as strain sensitivity (<10 με), enabling early detection of thermal run-away precursors and mechanical fatigue.
      b. OEMs and pack integrators have hesitated to add sensors due to packaging constraints and cost. By leveraging low-cost fibers and existing laser-interrogation hardware in the charging station, this approach targets system integration costs lower than the advanced BMS hardware.
      c. High-fidelity spatiotemporal datasets during charge/discharge cycles are scarce, hindering predictive-maintenance algorithms. DFOS pilot data will fill this gap, informing machine-learning models that forecast remaining useful life (RUL) and enabling second-life repurposing.
      d. EV OEMs, fleet operators, and warranty providers will gain actionable insights for quality control (inline defect detection) and in-service health

diagnostics. Cell-manufacturers can tighten process controls, while recycling and second-life providers can better assess state-of-health and increase battery life cycles.

iii. Outcomes: If successful:
   a. Reduce failure rates & warranty costs: Early-stage anomaly detection can cut unexpected cell/module failures by ≥30%, translating into multi-million-dollar savings for OEMs and reducing ratepayer burden via lower warranty reserves.
   b. Extend pack lifetime: By mitigating thermal and mechanical stresses, packs could achieve a 20–25% increase in cycle life, lowering the levelized cost of transportation (LCOT) by an estimated 10%.
   c. Facilitate scaling: Greater confidence in battery reliability and safety will boost consumer acceptance.
   d. Environmental & circular economy gains: Prolonged pack lifetimes and optimized second-life deployment will reduce raw-material demand and end-of-life waste, aligning with EPIC's principles by delivering longer-lasting mobility solutions across all communities.
   e. Develop a method to qualify the condition of the batteries in a way that works as a battery "passport" supporting a robust secondary market.

iv. Metrics: To quantify the impact, we can:
   a. Temperature and strain detection accuracy: (target: <±0.5 °C, <20 με)
   b. False-alarm rate (<5%) and true-positive detection sensitivity (>95%)
   c. Incremental cost per pack less than $100 in the battery side and count in cost per sensor data
   d. Extension of cycle life in accelerated aging tests

v. References:
   a. DOE report on "Battery Testing, Analysis and Design", 2014. https://www.energy.gov/sites/prod/files/2014/05/f15/APR13_Energy_Storage_e_IV_Battery_Tstg_Design_2.pdf
   b. NREL report on "Electric Vehicle Lithium-Ion Battery Life Cycle Management", 2023, https://docs.nrel.gov/docs/fy23osti/84520.pdf
   c. Research article "The future of battery data and the state of health of lithium-ion batteries in automotive applications", 2024, https://www.nature.com/articles/s44172-024-00299-w

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Transportation Electrification

vii. Support for Goal: The proposed concept will advance transformational energy technologies by pioneering inline and in-service DFOS that fundamentally enhance battery safety and performance. Improve battery reliability and resilience through proactive health monitoring. Increase affordability by lowering total cost of ownership via extended battery life and reduced warranty/maintenance expenses. Promote environmental quality and lower costs with data-driven lifecycle management that minimizes raw-material usage and waste through optimized second-life applications.

i. Contributors to This Concept Include: Linqing Luo, Yuxin Wu

2. Transportation for Emergency Services and Public Use

   i. Description: The proposed concept aims to strategically deploy a reliable, resilient, and accessible network of electric vehicle supply equipment (EVSE) for both emergency services and public use. Leveraging advanced agent-based modeling (BEAM CORE), the concept will identify optimal charging station locations, charger types, and deployment strategies to ensure operational reliability for critical municipal fleets (e.g., Sheriff, Fire, EMT) while supporting broader consumer choice. The goal of the concept is to enable local jurisdictions managing fleet turnover to use electric vehicles without compromising public safety and operational reliability while extending the benefits of such choices to local communities broadly.

      EPIC funds are essential to support this concept because current market-driven EVSE deployments do not adequately address the unique needs of emergency service fleets, especially regarding resilience, disaster preparedness, and access. EPIC funding will enable cutting-edge modeling, robust stakeholder engagement, and comprehensive assessment of impacts on grid reliability, air quality, and public health—outcomes that are not feasible through traditional funding sources or commercial investments alone.

   ii. Breakthroughs: This concept will drive technological advancement by addressing critical barriers faced by local jurisdictions managing turnover of their emergency service fleets. Technically, the unpredictable and mission-critical usage patterns of emergency vehicles mean that existing depot-based charging solutions are insufficient; this project will pioneer new planning methodologies for distributed, resilient charging infrastructure that can ensure 24/7 operational readiness, even during disasters or grid outages. Market barriers are also significant, as standard infrastructure planning rarely accounts for the unique needs of emergency services. The project will directly address customer pain points such as uncertainty around range, charging access, and the potential impact on emergency response times, while also improving access to charging for the public. By setting clear cost and performance targets—such as achieving greater than 99% charger reliability for emergency use, maintaining or improving current response times, and reducing total infrastructure costs by 15% compared to ad hoc siting—the proposed concept will demonstrate the feasibility and value of optimized deployment. The concept will address data gaps by integrating real-world emergency fleet operational data, resilience analysis under grid stress, and stakeholder needs into advanced planning models, delivering actionable insights for municipal planners, utilities, and workforce partners. Ultimately, the beneficiaries of this work will include emergency responders, local governments, utilities, workforce development agencies, and the broader public, all of whom will gain from improved reliability, access, and environmental outcomes.

iii. Outcomes: Reduce Costs: Lower infrastructure investment needs via optimized siting and shared use, and reduce operational costs through efficient charging strategies.

Improve Performance: Ensure reliable emergency response with electric fleets, even during grid disruptions.

Scalability: Provide a replicable planning framework for local jurisdictions, counties, and agencies with electric fleets.

Ratepayer Benefits: Enhance public safety, grid reliability, affordability (by reducing redundant investments), improve environmental quality (through improved air quality), and access (by ensuring all communities have reliable charging for emergency vehicles).

Workforce Development: Support local jobs and training in EV infrastructure installation and maintenance.

iv. Metrics:

a. Quantitative Metrics:
    1. Number and geographic distribution of new EVSE installed for emergency and public use.
    2. Charger uptime and reliability statistics, especially for emergency-designated chargers.
    3. Emergency response times before and after EVSE deployment.
    4. Reduction in criteria pollutant emissions.
    5. Cost savings from optimized infrastructure deployment.

6. Number of workforce trainees/certifications generated.

b. Qualitative Indicators:

1. Stakeholder satisfaction (municipal, utility, and local stakeholder feedback).
2. Resilience performance during simulated or actual grid outages/disasters.

v. References:

a. Spurlock, C.A., et al., Behavior, Energy, Autonomy & Mobility Comprehensive Regional Evaluator: Overview, calibration and validation summary of an agent-based integrated regional transportation modeling workflow, Lawrence Berkeley National Laboratory Report, 2024 https://ses.lbl.gov/publications/behavior-energy-autonomy-mobility modeling workflow, Lawrence Berkeley National Laboratory Report, 2024 https://ses.lbl.gov/publications/behavior-energy-autonomy-mobility

b. Laarabi, L., et al., A Modeling Framework for Behavior, Energy, Autonomy and Mobility (BEAM), Lawrence Berkeley National Laboratory Report, 2024 https://ses.lbl.gov/publications/modeling-framework-behavior-energy

vi. Strategic Goal: Transportation Electrification

vii. Support for Goal: Transportation Electrification: The proposed concept supports EPIC 5 Transportation goals by developing a data-driven, replicable framework for strategically deploying resilient and accessible EV charging infrastructure that meets the unique needs of both emergency service fleets and the public. Using advanced agent-based modeling, the project ensures operational readiness for critical services, integrates grid and disaster resilience, and prioritizes access. By engaging local stakeholders and workforce partners, this concept not only accelerates emissions reduction and air quality improvements but also reduces infrastructure costs, supports local job creation, and provides actionable insights that can be scaled across California to maximize ratepayer benefits.

viii. Contributors to This Concept Include: Haitam Laarabi, Zach Needell, Xiaodan Xu, Anna Spurlock

3. Strategic Lifecycle Management of Plug-in EVs

i. Description: This concept seeks to explore how California can more strategically manage the lifecycle of plug-in electric vehicles (PEVs) after they come off lease, with a focus on maximizing in-state benefits from used vehicles and second-life battery reuse. California's robust EV market leads to a growing outflow of lightly used PEVs to other states through wholesale auction channels, influenced in part by differing state incentive structures and auction price dynamics. At the same time, promising demonstrations—such as Element Energy's grid storage project using second-life Nissan Leaf batteries—highlight the untapped value of these vehicles for local grid resilience and affordability goals.

This research will analyze the vehicle and battery end-of-life pathways for PEVs leaving California, identify levers to increase in-state retention or repurposing, and model the tradeoffs between used vehicle affordability, in-state emissions reductions, and stationary storage potential. EPIC funds are needed to support this cross-sectoral, data-intensive work because of its relevance to multiple California priorities, but its low likelihood of being funded by private industry.

ii. Breakthroughs: This concept offers several important advancements in the intersection of transportation, grid resilience, and circular economy strategies. First, it will generate new insights into the post-lease lifecycle of EVs, including how wholesale auction dynamics and cross-state policy differences influence the flow of used vehicles out of California. Second, it will model novel pathways for recovering and reusing second-life batteries in stationary storage applications—helping bridge transportation and energy sectors in support of local resilience.

The project also pioneers an integrated policy analysis framework that incorporates market data, lifecycle emissions, grid value, and consumer access considerations to evaluate tradeoffs between keeping used EVs in-state, exporting them, or recycling their components. By focusing on real-world implementation levers—such as auction price dynamics, OEM lease agreements, and state resale incentives—the work advances practical understanding of how to retain technology value within California while expanding affordability and access.

iii. Outcomes: This work will generate actionable insights to guide California policymakers, program administrators, and local stakeholders and organizations in making more strategic use of end-of-lease electric vehicles and their batteries. The project will produce:

a. A detailed analysis of current post-lease EV flows out of California, with quantified estimates of lost economic, environmental, and grid resilience value
b. A set of key program design options (e.g., auction interventions, resale incentives, battery recovery agreements) that could increase the availability of affordable used EVs within California
c. Modeling of second-life battery use cases for stationary storage, including identification of promising applications in grid-constrained or fire-prone areas
d. Tradeoff analysis highlighting the implications of different end-of-life pathways for EVs and batteries, including environmental quality, affordability, and circularity considerations
e. Practical recommendations for state agencies and utilities on how to align battery reuse with energy resilience objectives.

Collectively, these outcomes will help California retain greater long-term value from its early EV market leadership, while expanding access to EV and energy storage benefits broadly.

iv. Metrics: This concept proposes a mix of quantitative and qualitative metrics to evaluate success, with a focus on creating actionable program design elements that enhance affordability for ratepayers:

a. Estimated increase in availability of affordable used EVs, derived from modeling various interventions (e.g., feebates, state-level auction incentives, and resale conditions).
b. Potential second-life stationary storage capacity (in MW and MWh) from PEVs that would otherwise leave the state, with geographic overlays identifying grid resilience opportunities.
c. Estimated reductions in household transportation and energy burden under scenarios of improved in-state EV retention and battery reuse.
d. Qualitative documentation of program design options and tradeoffs across economic, affordability, consumer choice, and circularity dimensions, developed using stakeholder interviews and scenario modeling.
e. Preliminary estimates of avoided upstream emissions and mining impacts, based on reduced need for virgin battery materials if second-life batteries are reused in California-based grid applications.

v. References: This concept builds on multiple strands of emerging evidence and demonstration activity. First, significant volumes of EVs are expected to come off lease in California in the coming years, with nearly 80% of new EV sales occurring through leases in some quarters (Axios, July 2025). The resulting surge in post-lease vehicle availability has implications for both the used vehicle market and second-life battery applications, but California currently lacks a coordinated strategy for leveraging this resource in-state. Second, recent large-scale demonstrations are proving the technical and economic viability of second-life battery systems. The 50 MWh / 13 MW pilot by Element Energy and NextEra Energy Resources (DOE Award DE-FOA-0002680, Project ID ELT307) is the first utility-scale deployment of second-life EV batteries in the U.S. It incorporates advanced module-level power electronics and adaptive battery management systems to safely extract 15+ additional years of grid service from repurposed EV batteries. This supports California's goals for energy storage deployment, lithium resource stewardship, and reduced reliance on virgin materials.

Third, market dynamics suggest many used EVs leave California due to auction-based lease returns, affecting the availability of affordable EVs for many in-state consumers. Preliminary findings from Zhao (2024), Helveston's lab at George Washington University, and researchers at UC Davis (e.g., Hardman & Tal, 2021) indicate that auction pricing, state-level incentives, and consumer awareness all play roles in determining whether used EVs stay local or are exported across state lines. These factors create both opportunity and policy uncertainty that merit structured evaluation.

Fourth, retaining used EVs in California can make transportation more accessible to lower-income households, reduce transportation energy burdens, and improve air quality. Recovered batteries, in turn, can support local resilience if deployed as stationary backup storage. The proposed research addresses this by analyzing the economic tradeoffs, grid-storage potential, and distributional impacts of various end-of-life EV management pathways.

vi. Strategic Goal: Transportation Electrification

vii. Support for Goal: This concept directly supports EPIC's transportation goals by developing and supporting the secondary market for electric vehicles while improving resilience. By identifying ways to retain used EVs and recover second-life batteries for in-state reuse, the concept maximizes the return on prior public and private EV investments.

The work also strengthens the state's energy related circular economy by connecting transportation and grid sectors through second-life battery applications—especially where energy affordability, reliability, and air quality are ongoing concerns. Finally, the proposed analysis aligns with multiple state initiatives, including the Scoping Plan, the Integrated Energy Policy Report (IEPR), and the CPUC-led proceedings on related topics, by offering actionable insights on infrastructure, accessibility, and emissions reduction strategies. This also addresses the strategic objective G - Impacts research from new generation and storage.

viii. Contributors to This Concept Include: Margaret Taylor, Peter Benoliel, Sydny Fujita

4. Automated Vehicle Control Technologies

i. Description: With the development and deployment of (partially or fully) automated vehicle control technologies, more and more vehicles have Advanced Driver Assistance Systems ranging from Adaptive Cruise Control (ACC) capability up to fully autonomous vehicles such as ROBOTAXIs. All those ACC technologies are based on radar, lidar, and/or video cameras. There is no vehicle-to-vehicle communication (V2V). All the control systems have some delays in target detection and control response which is at least 1 second. Scenarios where multiple such vehicles are following each other in tandem or convoy as an example, the delay will accumulate from the downstream (the 1st vehicle) to the upstream (the nth vehicle) in the convoy. If the 1st vehicle takes any action, the 5th or 6th vehicle will not be able to sense it until 6-7 seconds later. This likely causes significant safety, mobility, energy consumption and emissions concerns. Therefore, it is imperative for the federal and state governments to support research and deployment of Connected Automated Vehicles (CAVs) through V2V and Cooperative Driving Automation (CDA) through V2X. Our previous research indicated that CDA applications can potentially save energy for transportation systems by as much as 15 – 20% or more, with significantly improved mobility, emissions reductions and safety. We also field tested on Transport Canada Test Track through 3 Class A truck platooning and partially demonstrated this technology in Washington DC in 2017. We seek additional funding to validate and scale this concept in California as an early adoptor of autonomous driving technologies such as Waymo and Robotaxi.

ii. Breakthroughs:

   a. The overall barriers that prevent wider adoption of electric transportation systems include but are not limited to:

      1. lack of wireless communication connectivity among vehicles (V2V) and between vehicles and traffic management systems (V2X)
      2. lack of refined traffic detection systems from the infrastructure side

3. lack of automated Active Traffic Management systems in urban and suburban areas
4. lack of integrated network level traffic management systems.

b. CDA application research, development, and deployment intends to overcome the barriers above. The breakthrough of the proposed technology will lead to significant energy savings, emissions reductions, as well as mobility and safety improvements in all traffic levels.

iii. Outcomes: The key technologies to support CDA application in traffic include:

a. V2X technology and deployment
b. Cooperative Perception to integrate vehicle-based sensors and roadside/infrastructure based sensors through V2X in real-time
c. Vehicle automation through cooperative driving with V2V and V2X
d. CDA through integrated control of vehicles and traffic from infrastructure for arterial and freeway corridors to achieve overall network traffic optimization. More specifically, we propose a technology innovation research to partially support CDA applications in simulation and sensitivity analysis with improved V2X modeling and network mixed traffic (with manually driving, partial AVs and full AVs) for energy savings and mobility and safety improvements. This tool is particularly important for evaluating algorithms and technologies for CDA applications before field implementation and deployment. If this concept is successful, a simulation tool will be available to simulate wireless communication systems (V2X) for network traffic with ACC and CAVs integrated. This will strongly support the development and deployment of V2X and will speed up the application of CDA technologies in transportation systems to improve safety, reliability, affordability, environmental goals, and consumer choice.

iv. Metrics: The metrics to evaluate the impacts of this concept would be: percentages of energy savings, traffic mobility improvement and emission reduction with this technology compared to the status quo traffic situations.

Evaluation Methods: Through microscopic mixed traffic simulation, field tests and demonstration.

v. References:

a. B. McAuliffe, M. Lammert, X. Y. Lu, S. Shladover and A. Kailas, Influences on Energy Savings of Heavy Trucks Using Cooperative Adaptive Cruise Control, SAE International, 2018-01-1181
b. H. Liu, Shladover, S. E., Lu, X., and Kan, X. 2018. Vehicle Fuel Efficiency Improvement via Cooperative Adaptive Cruise Control Operations. Journal of Intelligent Transportation Systems
c. H. Liu, A. Kurzhanskiy, W. Hong, and X. Y. Lu, Investigating Impacts of Arterial Cooperative Driving Automation Applications on Traffic Flow via X-in-the-Loop Experiments, to appear in Transportation Research Part-D, August 2025
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e. Hao Liu, A. Kurzhanskiy, W. Hong and Xiao-Yun Lu, Integrating vehicle trajectory planning and arterial traffic management to facilitate eco-approach and departure deployment, Journal of Intelligent Transportation Systems - Technology, Planning, and Operations, published online (https://doi.org/10.1080/15472450.2024.2369988): 24 Jun 2024
f. H. Liu, X. Y. Lu, and S. Shladover, Mobility and Energy Consumption Impacts of Cooperative Adaptive Cruise Control (CACC) Vehicle Strings on Freeway Corridors, Transportation Research Record, Transportation Research Record, 0(0) 1–13, 2020, DOI: 10.1177/0361198120926997
g. H. Liu, A. Kurzhanskiy, W. Hong, and X. Y. Lu, Investigating Impacts of Arterial Cooperative Driving Automation Applications on Traffic Flow via X-in-the-Loop Experiments, to appear in Transportation Research Part-D, August 2025
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vi. Strategic Goal: Transportation Electrification, Climate Adaption, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: This concept will leverage DOE investments in co-simulation developed in the CDA project EEMS119. We propose to further improve V2X modeling that includes factors such as building and other roadside infrastructure blocking the field-of-view as well as model more realistic V2X scenarios while including some field testing, data collection and analysis.

viii. Contributors to This Concept Include: Xiao-Yun Lu

C. Smart systemwide planning tools for new load

1. EnergyPlus Development and Maintenance

    i. Description: EnergyPlus is a foundational tool for California's energy goals. Title 24 Compliance software CBECC-COM relies on the EnergyPlus simulation engine, and numerous past and future EPIC projects have and will continue to heavily depend on EnergyPlus simulations. Additionally, modeling novel and complex HVAC systems might require modifying the source code to add new features or enhance existing ones. However, as federal funding priorities shift, funding for EnergyPlus is likely to diminish. By strategically investing EPIC funds in targeted EnergyPlus development and maintenance, CEC can facilitate more accurate, accessible, and California-specific modeling of advanced energy systems, including changes in electricity demand, demand flexibility, and resilience. This investment will enable and accelerate compliance with Title 24, support innovations in new technologies, and solidify California's energy leadership. As an open-source infrastructure, improvements to EnergyPlus will benefit the state's entire energy ecosystem, from policymakers to practitioners to the public.

    ii. Breakthroughs: The proposed EnergyPlus software development would fill critical data and information gaps in modeling California's next-generation buildings and distributed energy resources. Currently, EnergyPlus lags behind technological advancements in adding electric loads to buildings, demand flexibility strategies, microgrid integration, and other emerging technologies relevant to California's unique weather patterns, codes, and policy landscape. By enhancing EnergyPlus to address these needs—including new modules for advanced heat recovery, thermal storage, demand response, DERs, and Title 24 workflows—this project will enable more precise and accessible analysis for a wide range of stakeholders.

        The primary beneficiaries include California building designers, engineers, technology developers, utilities, policymakers, researchers, and local stakeholder organizations. Each of these groups will be able to use enhanced EnergyPlus capabilities to design, validate, and implement innovative, accessible, and grid-supportive solutions while supporting commercial development and workforce development across the state.

    iii. Outcomes: If this project is successful, California's buildings and distributed energy sectors will gain an enhanced, open-source EnergyPlus platform tailored to the state's unique weather patterns, policy, and grid needs. This will lower technology and ratepayer costs by enabling more accurate, efficient design and deployment of advanced energy solutions, and by streamlining compliance and program participation. At scale, these improvements will accelerate the adoption of affordable, reliable, and advanced energy technologies across California, maximizing the impact of ratepayer investments. The project directly supports EPIC's guiding principles by improving safety (through resilience modeling), reliability (via grid-integration features), affordability (by reducing design and compliance costs), environment, and by ensuring all stakeholders have access to state-of-the-art modeling tools.

iv. Metrics: We will evaluate project impact through a combination of quantitative and qualitative metrics. Quantitative metrics include: number of California projects and organizations using enhanced EnergyPlus features, reduction in modeling costs and time, estimated emissions and energy savings enabled, utilization rate by various segments of the population, and projects. Qualitative metrics include: conducting case studies highlighting how the improvements enable advanced, cost-effective, and affordable energy solutions across the state. These metrics will be regularly reported to the CEC and used to refine project priorities and outreach.

v. References:

1. Energy and GHG modeling benefit with EnergyPlus: EnergyPlus models can be used as an operational digital twin and achieve electricity saving of 18% https://www.sciencedirect.com/science/article/pii/S0360132325002768.
2. Resilience modeling benefits with EnergyPlus: EnergyPlus analysis helps decision-makers justify building upgrades by showing resilience co-benefits boost economic returns beyond just energy savings https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160758875_5956a5e4-da26-492f-ae22-398894e88471.pdf.

3. EnergyPlus-modeled weatherization upgrades offered $250/year per household (1–3¢/kWh saved) in resilience benefits by cutting backup electricity demand during outages. This value is based on the avoided cost of backup systems needed without such upgrades https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722163149047_48c1e985-b1af-461d-8242-ee16a1ae8b1e.pdf.
4. Grid-integration modeling benefits with EnergyPlus: EnergyPlus modeling indicates that implementing building efficiency and flexibility measures could prevent up to 742 TWh of annual electricity consumption and 181 GW of daily net peak load by 2030 across contiguous U.S. https://www.sciencedirect.com/science/article/pii/S2542435121002907#sec2
5. Decarbonization modeling benefits: EnergyPlus simulates and selects optimal energy efficiency, electrification, and renewable technology upgrades, achieving up to 97% energy consumption savings and reducing long-term energy bills.https://www.sciencedirect.com/science/article/pii/S0360132325002768

vi. Strategic Goal: Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Climate Adaptation

vii. Support for Goal: EPIC's support for EnergyPlus development is crucial for achieving a number of California's strategic goals. This is accomplished by accurately modeling baseline and intervention scenarios, including changes in consumer choice for electrical service, energy and emission reduction retrofits, and resilience measures. Such modeling helps quantify the energy and emissions reduction potential of interventions at individual building, city, and state levels, guiding phased retrofit strategies for buildings and regions with high savings potential.

viii. Contributors to This Concept Include: Tianzhen Hong, Yujie Xu

2. A Digital Platform Linking Building and Transportation Systems for Integrated Urban Analysis

i. Description: The proposed concept is the development of an Integrated Energy and Emissions Urban Platform, which is a digital solution that links building and transportation systems for comprehensive, high-resolution urban analysis. By integrating two advanced tools (BEAM CORE and CityBES), the platform will simulate and analyze daily traveler activity, building occupancy, energy consumption, and emissions across both transportation and building sectors. The purpose is to provide city planners, utilities, and policymakers with actionable insights to optimize energy use, reduce emissions, and inform accessible and effective energy investments.

EPIC funds are essential to support this concept because current market solutions do not offer integrated, high-resolution modeling of building and transportation energy interactions, nor do they provide the granularity needed for California's ambitious energy goals. EPIC support will enable the development, demonstration, and validation of this integrated platform, bridging critical data and analysis gaps that impede the state's progress toward its energy goals.

ii. Breakthroughs: This concept directly addresses several barriers that impede California's energy goals by enabling technological advancements and integration across urban systems. Currently, technical barriers exist because urban analysis tools are siloed, lacking interoperability between transportation and building energy models, which prevents accurate modeling of cross-sector impacts, such as how telecommuting or electric vehicle adoption shifts grid loads at specific locations and times. Market barriers further hinder progress, as city agencies and utilities lack accessible, actionable data to inform investments in electrical energy infrastructure, distributed energy resources, and grid upgrades at the neighborhood level. In addition, planners and policymakers are unable to evaluate the full impact of policies on emissions, energy demand, and accessibility outcomes due to fragmented data sources and insufficient modeling tools. By integrating high-resolution, spatially explicit data and enabling "what-if" scenario analyses, the proposed platform will provide a breakthrough in supporting effective deployment of energy solutions. It will empower cities and utilities to anticipate and manage local grid impacts from emerging trends, such as EVs and remote work, thereby reducing costly over- or under-investment in infrastructure and accelerating technology adoption.

iii. Outcomes: If successful, this research will enable more precise, data-driven investments in an energy infrastructure that meets the state's goals by equipping cities and utilities with integrated, actionable insights, ultimately reducing both technology and ratepayer costs through optimized resource allocation. The platform will enhance grid reliability and resilience by allowing stakeholders to anticipate and effectively manage load shifts resulting from an increase in electricity demand and evolving travel patterns, while simultaneously supporting environmental goals by identifying and prioritizing interventions that yield the greatest emissions reductions. Furthermore, the platform will provide granular data to uncover and address differences in energy use, air quality, and infrastructure investment across various neighborhoods. At scale, widespread deployment of this innovation could empower all California cities and utilities to coordinate building and transportation efforts, accelerating progress toward the state's goals. Overall, the concept aligns with EPIC's guiding principles by improving safety through reduced air pollution, enhancing reliability and affordability through targeted investments, and promoting environmental quality by enabling emissions reductions.

iv. Metrics:
   1. Quantitative:
      1. Accuracy of modeled vs. observed energy/emissions data
      2. Reduction in planning/analysis costs and time
      3. Emissions reductions or grid impact mitigation measures enabled by platform-informed decisions
      4. Number of cities/utilities/agencies adopting the platform
   2. Qualitative:
      1. User satisfaction and perceived value
      2. Case studies demonstrating improved outcomes

v. References: Electrical cost impacts from heat pump installations - https://www.energy.ca.gov/sites/default/files/2025-06/CEC-500-2025-026.pdf

vi. Strategic Goal: Transportation Electrification, Building Decarbonization

vii. Support for Goal: The proposed Integrated Energy and Emissions Urban Platform will accelerate transportation goals by leveraging high-resolution agent-based modeling to simulate individual travel behaviors, vehicle technology adoption, and daily activity patterns across cities. By mapping EV ownership and charging demand to specific neighborhoods and buildings, the platform enables utilities and city planners to anticipate localized grid impacts, optimize charging infrastructure deployment, and assess the air quality and public health benefits of reduced transportation emissions. The platform also supports scenario analysis of emerging trends, such as telecommuting and shared mobility, empowering decision-makers to design smarter policies and make better investments that maximize the benefits while ensuring grid reliability and accessibility.

For buildings, the platform integrates detailed building energy modeling with dynamic occupancy and activity data, providing accurate forecasts of energy use and emissions at the building and district levels. This enables cities and utilities to identify optimal opportunities for expansion of electrical load, energy efficiency retrofits, and distributed energy resource deployment, tailored to actual usage patterns impacted by changing travel behaviors. The platform's granular analysis also highlights differences in energy use and infrastructure access, ensuring that efforts are effective, and that they advance California's goals.

viii. Contributors to This Concept Include: Haitam Laarabi, Kaiyu Sun, Ling Jin, Xiaodan Xu, Tianzhen Hong

3. Dashboard for AI and Digital Infrastructure for Data Centers

   i. Description: California's growing data center footprint is essential to powering AI and digital infrastructure, but it is increasingly vulnerable to compound hazards such as wildfire, extreme heat, drought, and flooding. The proposed development of data centers also poses increasing demands and competition on energy, water, and land resources. California needs to invest in better planning tools as it comes to siting and implementing these data centers to more holistically evaluate resilience strategies, such as water-smart cooling systems and battery storage, and assess regional economic and environmental trade-offs.

      EPIC funds are essential to support this concept because the risk and adaptation potential of data centers under weather extremes are understudied. Such funding can support producing public dashboards, and resilience heatmaps, and siting guidance to inform stakeholders and planners, ensuring that California's AI and digital infrastructure remains resilient.

   ii. Breakthroughs: The advances of this project can be summarized in the modeling framework, planning insights, and operational-ready output. The project will offer a cutting-edge AI-assisted and data-driven integrated hazard and resource risk modeling for data centers by combining weather extremes forecasting (wildfire, heat, flood, drought) with localized water, land, and grid constraints. Meanwhile, to improve our understanding of modeling the resilience trade-offs of deployment for datacenters, the second part of the modeling will provide systematic simulations and analysis to quantify the costs, benefits, emissions, and environmental and infrastructure risks for datacenters in varied hazard scenarios. By applying the modeling framework, this project can further provide planning insights that focus on how resilience investments can reduce energy and resource burdens and infrastructure vulnerabilities. The final breakthrough of this project will be the first-of-kind public dashboard of heatmaps and other visualizations with guidance for data center siting and operations.

iii. Outcomes: Identify high-risk data center clusters where weather extremes and natural hazards affect operational continuity and resilience. Analyze the regional resource competition and trade-off, as well as their environmental and economic impacts, for datacenter operations. Model the resilience and cost-effectiveness of adaptation measures. Provide risk and resilience maps to utilities, decision-makers, and policy-makers to co-benefit local interests with data center deployment. Deliver a public-facing and operational dashboard to demonstrate the available information, resource demands, and risk analysis for data center operation.

iv. Metrics: Quantitative metrics: a comprehensive spatial dataset and modeled outputs based on risks from extreme weather, environmental impact, and vulnerability for a data center. Qualitative metrics: stakeholder feedback from utilities, developers, and local communities on the dashboard's usefulness for planning and investment.

v. References:

1. Chen, S. (2025). Data centres will use twice as much energy by 2030—Driven by AI. *Nature*. https://doi.org/10.1038/d41586-025-01113-z

2. Ren, S. (2025, June 11). *The Hidden Environmental and Public Health Impacts of AI* [AAAI 2025 Presentation]. Datacenter Impacts on Municipal Energy, Water, and Air Systems, Center for Scientific Evidence in Public Issues. https://www.aaas.org/events/datacenter-impacts-municipal-energy-water-and-air-systems

vi. Strategic Goal: Climate Adaptation

vii. Support for Goal: This concept directly supports the EPIC's goal by equipping planners and decision makers with data-driven tools to assess and mitigate risks to California's digital infrastructure.

viii. Contributors to This Concept Include: Newsha Ajami, Beichen Zhang

4. Ongoing Measurement-Based Methane Emissions Monitoring System
   i. Description: Methane emissions from California’s natural gas value chain have significant implications for the emissions intensity of natural gas-fired electricity generation and direct natural gas consumption in buildings. A growing body of scientific literature suggests that these emissions are significantly underestimated in many contexts. An ongoing measurement-based methane emissions monitoring system within the state would help with tracking in order to inform numerous electric power and building fueling decisions. This concept proposes expanding the SUMMATION network, which leverages multi-tier measurements of methane emissions from flux towers, remote sensing, and ground-based systems, transforming the current scientific study into a user-friendly dashboard with highly granular, up-to-date information about methane emissions from the state’s natural gas infrastructure. Without EPIC funds, this project will sunset in mid-2026 and would simply result in scientific publications, rather than a user-friendly tool.
   ii. Breakthroughs: Many decision-makers in California regularly perform emissions-informed benefit-cost analysis to assess the impact of introducing new technologies in electricity generation and within buildings. Existing methods typically rely on past estimates of the methane emissions intensity of natural gas, which recent studies suggest is highly conservative. A user-friendly tool bringing the latest science to the fingertips of decision-makers would strengthen California’s emissions reduction efforts in innumerable ways.
   iii. Outcomes: If successful, this work would benefit numerous stakeholders. Analysts performing emissions-informed benefit-cost analysis would see substantial efficiency gains, as their underlying numbers would more accurately reflect reality. In addition, insights from the tool would provide granular visibility into the components of the natural gas value chain that currently emit the most, providing substantial opportunities for achieving low-cost emissions reductions within the sector.
   iv. Metrics: Adoption rates of our online tool, e.g. visits to an online web portal. Citations to the tool in documents related to California energy decision-making, e.g. government reports. One could qualitatively or roughly assess the emissions impact of using up-to-date methane emissions information compared to legacy numbers in technology decision-making processes.
   v. References:

1. Sherwin, E.D., Rutherford, J.S., Zhang, Z., Chen, Y., Wetherley, E.B., Yakovlev, P.V., Berman, E.S.F., Jones, B.B., Cusworth, D.H., Thorpe, A.K., Ayasse, A.K., Duren, R.M., Brandt, A.R., 2024. US oil and gas system emissions from nearly one million aerial site measurements. Nature 627, 328–334. https://doi.org/10.1038/s41586-024-07117-5
2. Jeong, S., Millstein, D., Fischer, M.L., 2014. Spatially Explicit Methane Emissions from Petroleum Production and the Natural Gas System in California. Environ. Sci. Technol. 48, 5982–5990. https://doi.org/10.1021/es4046692
3. Moyes, A.B., Dos Santos, A.L.D., Reichl, K., Biraud, S.C., 2025. Dense and varied regional methane sources characterized using a tiered, dual-tracer measurement strategy. Atmos. Environ. 354, 121270. https://doi.org/10.1016/j.atmosenv.2025.121270
4. Sherwin, E., Kruguer, J., Wetherley, E.B., Yakovlev, P.V., Brandt, A., Deiker, S., Berman, E.S.F., Biraud, S., 2025. Comprehensive Aerial Surveys Find a Reduction in Permian Basin Methane Intensity from 2020-2023. https://doi.org/10.2139/ssrn.5087216
5. Varon, D.J., East, J.D., Pendergrass, D.C., Chen, Z., Sulprizio, M., Gautam, R., Barkley, Z.R., Cardoso-Saldaña, F.J., Reidy, E.K., Kamdar, H., Sherwin, E.D., Biraud, S.C., Jervis, D., Pandey, S., Worden, J.R., Bowman, K.W., Maasakkers, J.D., Kleinberg, R.L., 2025. Seasonality and declining intensity of methane emissions from the Permian and nearby US oil and gas basins.

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: Natural gas currently represents ~35% of California's in-state electricity generation and provides heat to nearly 80% of homes in the state, alongside many commercial and industrial buildings. Amid ongoing efforts at the state level to determine cost-effective paths toward lower emissions in the electric power system and within buildings, a user-friendly tool providing access to accurate and granular information about the emissions intensity of natural gas within the state would provide invaluable insights informing innumerable decisions.

viii. Contributors to This Concept Include: Evan Sherwin and Sebastien Biraud

5. Accelerate Adoption Of Advanced Controls In Small And Medium Commercial Buildings

i. Description: Small and medium commercial buildings (SMBs) make up the vast majority of the commercial building stock and nearly half of all commercial building energy use nationwide. Despite their significance, SMBs remain largely overlooked in the deployment of advanced controls and demand flexibility (DF) solutions. Recent market research indicates that interest exists: 73% of SMBs expressed willingness to participate in demand response (DR) programs, and 74% showed interest in electrifying non-electric operations. Yet adoption of enabling technologies is still low—less than 15% of SMBs have any building automation, and only 5% use networked thermostats. Proven technologies like networked thermostats and advanced rooftop units (RTUs) and heat pump controls can deliver 10–20% energy savings and enable valuable DR participation, but this market remains largely untapped.

Title 24 requires RTUs 4.5 tons or larger to have economizers and FDD, expanding these advanced controls to existing buildings represents a major untapped opportunity. There is also an opportunity to document and analyze real-world deployment and performance of FDD requirements under Title 24, through field studies that can inform future policy and best practices. Recent updates to the state's energy code (CEC 2025) also encourage replacing end-of-life RTUs with heat pumps in existing schools, offices, libraries, and retail buildings—creating a key opportunity to pair these upgrades with advanced controls for greater energy efficiency and demand response.

Upgrading controls in existing SMBs is a significant untapped opportunity, and proven technology options are available; the main barriers are market-driven, such as: limited awareness among owners, lack of contractor training and incentives, concerns about vendor lock-in and subscription costs, and perceived uncertainty about technology longevity. There is also a lack of standardized, real-world data on DR performance and product interoperability, making it difficult for stakeholders to confidently invest.

We propose that EPIC invest in a targeted initiative to accelerate adoption of advanced controls—including RTU/heat pump controls, networked thermostats, grid-interactive solutions, and code-compliant FDD —across California's SMBs. Example activities include lab testing and/or field validation of demand-flexible controls and RTU FDD, performance benchmark data, enhanced monitoring & diagnostic capabilities, and multi-stakeholder engagement (surveys and/or working groups with utilities, HVAC contractors, owners, technology vendors) to develop comprehensive solutions. This work will generate actionable, vendor-neutral data on energy and DR performance, and may explore pathways for technology standardization and contractor certification, modeled after successful lighting controls certification programs. EPIC funding is critical to overcome persistent market barriers and unlock scalable energy and grid benefits for California's SMB sector.

ii. Breakthroughs: This initiative will overcome key barriers to California's energy goals by addressing both technical and market gaps that limit adoption of advanced controls and DR/DF in SMBs (a huge untapped market). Field validation will generate the first standardized, real-world data on energy savings, DF performance, and interoperability of RTU, heat pump, and networked thermostat controls—including insights on the field-observed performance and outcomes of Title 24's economizer and FDD requirements.

By benchmarking solutions and exploring standardization and contractor certification pathways, the project will reduce uncertainty, lower integration costs, and support broader, future-proof adoption. The work will also identify workforce training needs, helping to build contractor competence and owner confidence.

These advancements will benefit building owners, contractors, utilities, and technology vendors—enabling informed investment, better program design, and increased participation in DR and efficiency programs. Ultimately, this project will accelerate the deployment of advanced energy technologies in SMBs, directly supporting California's energy and grid reliability goals.

iii. Outcomes: If this research is successful, it will drive widespread adoption of advanced controls and demand response solutions in SMBs, unlocking 10–20% energy savings and enabling significant new DR/DF capacity. Clear, real-world performance data and streamlined pathways for standardization and contractor certification will lower technology costs, reduce installation risks, and make it easier for owners and contractors to invest in and maintain these solutions.

At scale, these innovations can transform California's SMB sector into a flexible, energy-efficient backbone for the state's grid—reducing peak demand, supporting reliability, and avoiding costly infrastructure upgrades. Ratepayers will benefit from lower utility bills, improved building comfort, and increased access to utility programs and incentives. By targeting market barriers and supporting workforce development, the project will also make advanced controls more accessible to small businesses and other local stakeholders, supporting EPIC's principles of affordability, reliability, environmental quality. Ultimately, this initiative will deliver persistent value to California's ratepayers while advancing the state's energy goals.

iv. Metrics:

1. Quantitative Metrics:

    a. Estimates of statewide increase in energy impact (%, Mwh) and demand response (DR) capacity (MW) achieved in SMB market sectors
    b. Utility program participation rates (controls EE upgrades and DR program participation)
    c. Number of contractors trained or certified through new pathways
    d. Number of field sites and case studies documented

2. Qualitative Metrics:

    a. Stakeholder feedback from building owners, contractors, and utilities on usability, value, and confidence in advanced controls
    b. Documentation of real-world interoperability and performance of FDD requirements under Title 24
    c. Lessons learned and best practices for scaling adoption in varied SMB settings

v. References:

1. Less than 15% of SMBs have any form of building automation system (BAS) installed and only 5% use inter-connected thermostats.
   - CBEC 2018: https://www.eia.gov/consumption/commercial/data/2018/index.php?view=microdata
2. Networked thermostats and advanced controls (including for RTUs/heat pumps) can deliver 10–20% energy savings and enable DR participation
   - "Going Big on Small Buildings: Spotlight on efforts to improve controls for packaged rooftop HVAC units" 2024 ACEEE Summer Study on Energy Efficiency in Buildings: https://www.aceee.org/sites/default/files/proceedings/ssb24/pdfs/20240722163106359_e248936e-7852-4c5b-8784-31af1d738e4a.pd
3. Title 24 requires that all RTUs 4.5 tons and larger with economizers in California be equipped with economizer fault detection and diagnostics

(FDD) systems: https://www.energy.ca.gov/rules-and-regulations/building-energy-efficiency/manufacturer-certification-building-equipment/economizer-fdd

4. Barriers to adoption: Lack of contractor training, vendor lock-in worries, subscription costs, and uncertain technology lifetime "Commercial Building Sensors and Controls Systems: Barriers, Drivers, and Costs" NREL 2022 Research Highlight: https://docs.nrel.gov/docs/fy22osti/82750.pdf

vi. Strategic Goal: Building Decarbonization

vii. Support for Goal: This initiative supports CEC's goals by ensuring that SMB electric loads, to the extent possible, are paired with advanced, grid-interactive controls, while also reducing peak coincident demand across the large installed base of conventional dual-fuel RTUs. This pairing maximizes efficiency, provides demand flexibility, and prevents unmanaged peaks that could otherwise increase grid costs.

1. Objective C – Smart Systemwide Planning Tools for New Load: Field-validated data on energy use, load shapes, and demand response from SMBs will improve forecasting of new electric loads and support integration with utility capital planning and operations.

2. Objective E – Innovative Approaches for Difficult-to-Decarbonize Sectors: It's difficult to achieve California's energy policy goals with respect to the SMB segment due to low building owner staff resources, high concern over risks of any added complexity, and the slow pace of adoption of new technologies for the HVAC contractor workforce. De-risking integrated heat pump and advanced controls retrofits reduces lifecycle cost and emissions, creating a replicable pathway to achieve the state's energy policy goals with cost-parity to other available options.

3. Objective K – Providing Data Input into a Value of DER Framework: By generating vendor-neutral DR and load flexibility performance data, the project will provide critical input for utility DER valuation and grid planning, supporting integration of flexible SMB loads into California's evolving grid architecture.

By generating vendor-neutral performance data, developing standardized installation and training pathways, and demonstrating grid-interactive benefits, the project will accelerate cost-effective, scalable decarbonization for California's SMB sector. This also addresses the strategic objective E - Innovative Approaches for Difficult-to-Decarbonize Sectors.

viii. Contributors to This Concept Include: Eliot Crowe and Jessica Granderson

6. Energy Planning Tools To Reflect Spatially Targeted, Flexible Demand-Side Strategies

   i. Description: This concept proposes the development and integration of demand-side strategies, including passive retrofits, thermal zoning, localized heating/cooling, and behavior-informed energy use, into urban-scale building models and load forecasting tools. By capturing flexible, spatially targeted demand profiles, this approach enables to evaluate both load growth and suppression potential under constraints of affordability, resilience, and occupant comfort. It will also incorporate dynamic passive cooling and heating strategies that respond to real-time demand response signals and changing environmental conditions. Examples include automated shading, night ventilation, targeted room conditioning, and adaptive operation based on occupancy or use intensity. Together, these strategies reduce the energy required to maintain comfort, improve alignment between building performance and grid capacity, and avoid the need for costly infrastructure upgrades. When deployed across the building stock, this framework supports California's goal of achieving 100% carbon-free building emissions through smarter, spatially aware, and human-centered energy use.

   ii. Breakthroughs: This concept enables energy planning tools to reflect spatially targeted, flexible demand-side strategies. Current models assume static, whole-building operation, missing opportunities to capture behavioral demand flexibility- passive performance, sub-zonal conditioning, and behavior-driven load reduction. By integrating these factors into urban-scale modeling, the concept reveals how low-cost, occupant-responsive strategies can shape load profiles, reduce peak demand, and improve comfort. It fills a critical data gap by generating sub-zonal, adaptive demand profiles, allowing planners, utilities, and aggregators to evaluate passive and behavioral strategies for the grid. These are often overlooked despite their affordability and effectiveness.

   iii. Outcomes: If successful, this concept will deliver a scalable framework that improves demand forecasts by integrating passive, behavioral, and sub-zonal strategies into energy planning. It enables more accurate modeling of load reduction and peak shifting, reducing the need for costly mechanical systems and infrastructure upgrades.

iv. Metrics:
   1. Reduction in peak hourly load per household through passive or localized strategies
   2. Reduction in total annual energy demand compared to baseline full-space conditioning
   3. Improvement in comfort hours maintained within safe thresholds without mechanical cooling/heating.
   4. Deferred or avoided infrastructure costs modeled via revised demand projections.

v. References:
   1. Behavioral flexibility in demand response: A comparison of energy communities and individual prosumers based on real consumption and flexibility data https://www.sciencedirect.com/science/article/pii/S0378778825000763
   2. Prioritize energy sufficiency to decarbonize our buildings https://www.nature.com/articles/s41562-023-01752-0
   3. Load Flexibility: Keeping Users in the Loop with "Invisible" Technologies, CalFlexHub publication https://calflexhub.lbl.gov/wp-content/uploads/sites/41/2024/08/Load-Flexibility-Keeping-Users-in-the-Loop-with-Invisible-Technologies.pdf

vi. Strategic Goal: Building Decarbonization, Distributed Energy Resource Integration

vii. Support for Goal: This concept aligns with California's goals of building decarbonization and distributed energy resource (DER) integration by reducing energy demand and enabling flexible, grid-responsive operation. By modeling spatial and temporal flexibility, the concept supports more effective integration of DERs like solar and storage, improving load matching and reducing grid strain. This also addresses the strategic objective L - Reducing feeder/circuit peaks.

viii. Contributors to This Concept Include: Jeetika Malik, Max Wei, Kaiyu Sun, Tianzhen Hong

D. Reducing cost of whole-home electrification

1. Capturing Non-Energy Impacts

i. Description: Capturing the Non-Energy Impacts (NEIs) of Energy Upgrades: This project aims to integrate non-energy impacts (NEIs) into household decision-making and policy development. While NEIs are increasingly recognized, they are often described qualitatively, limiting their use in analysis and planning. This research will focus on developing methods to quantify NEIs of residential and commercial retrofits for buildings, with a focus on resilience, affordability and health, enabling their inclusion in cost-benefit evaluations and policy frameworks. EPIC funding is critical, as both the building industry and policymakers currently lack the technical tools and data needed to effectively incorporate NEIs in policy and analysis. Moving to quantification of NEIs is an innovative and groundbreaking R&D effort that has not previously been undertaken that will help to unlock the full value of California's energy goals.

ii. Breakthroughs: As California pursues energy related goals, energy savings alone often fail to motivate households and businesses to invest in retrofits. Incorporating NEIs into broader decision-making is essential, particularly for cost-constrained consumers.

With increasing extreme weather and power outages, homes lacking adequate thermal performance and air filtration pose heightened risks for occupants. This concept proposes integrated research to assess and quantify NEIs of residential and commercial building retrofits, focusing on resilience, health, and consumer choice. We will identify retrofit strategies that improve thermal comfort, Indoor Environmental Quality (IEQ), acoustics, and lighting while reducing energy burden impacts. These are co-benefits often overlooked despite their potential to lower public health costs and enhance well-being.

Using field data and economic modeling, research could consolidate health-related metrics (harm budgets, DALYs) to estimate NEIs, address data gaps, and support evidence-based policy. This work aims to demonstrate how retrofit investments can yield significant non-energy returns while advancing building performance, resilience, and accessibility, including potential reduction of insurance premium costs.

The project directly supports Senate Bill 96 by addressing technical and market barriers hindering energy retrofit adoption. It targets a major gap in the energy transition: lack of data and valuation tools for NEIs, including health, comfort, and resilience benefits that are often excluded from cost-benefit analyses, limiting investment in retrofit technologies.

iii. Outcomes: If successful, this research will increase the number of buildings retrofitted to meet the state's energy goals. The specific research outcomes will include calculation procedures to quantify NEIs such as improved IEQ, thermal comfort, and occupant health. By measuring these co-benefits using metrics like disability-adjusted life years (DALYs) and harm budgets, the project will support more comprehensive cost-benefit analyses, unlocking new financing opportunities, such as through insurers or public health agencies, and ultimately reducing costs for ratepayers over time.

    At scale, the findings can inform voluntary consensus standards, as well as utility programs to prioritize strategies that enhance resilience and accessibility. This will improve safety during extreme weather events like heatwaves, wildfires, and power outages, reduce reliance on mechanical cooling, and lower health-related burdens. Ultimately, this quantification of the NEIs will drive investments that better serve ratepayers, boost adoption of the sorts of building resilience measures and energy upgrades that deliver ratepayer benefits which are aligned with EPIC's goals.

iv. Metrics: The proposed research will use a combination of quantitative and qualitative metrics to evaluate its impacts.

    Quantitatively, the project will assess changes in IEQ (e.g., temperature, humidity, PM, VOCs, noise levels, etc.), health-related metrics such as DALYs, harm budgets, and harm intensity, as well as reductions in energy burden and insurance risk. Economic modeling will quantify the value of non-energy benefits, including avoided healthcare costs and improved productivity.

    Qualitatively, the research will incorporate occupant surveys and interviews to capture lived experiences related to thermal comfort, perceived air quality, noise, lighting, and well-being.

    Additional indicators include adoption rates of retrofit measures, stakeholder engagement levels, and accessibility. Together, these metrics will provide a comprehensive evaluation of the project's effectiveness in advancing resilient, accessible, and health-promoting building energy and resilience strategies.

v. References: The following references provide background information:

1. Lozinsky, C. H., Casquero-Modrego, N., & Walker, I. S. (2025). The health and indoor environmental quality impacts of residential building envelope retrofits: A literature review. Building and Environment, 112568.
2. Casquero-Modrego, N., Antonopoulos, C., Fuentes, T. L., McCord, K. H., & Walker, I. S. (2025). Decarbonizing residential buildings in the United States: A comparative analysis of households and construction professionals. Energy Research & Social Science, 120, 103908.
3. Jones, B., Morantes, G., Molina, C., Sherman, M., & McGrath, J. A. (2025). Harm from indoor air contaminants: protection by exposure limit values. International Journal of Ventilation, 1-11.
4. Morantes, G., Jones, B., Molina, C., & Sherman, M. H. (2023). Harm from residential indoor air contaminants. Environmental science & technology, 58(1), 242-257.

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Building Decarbonization, Climate Adaptation

vii. Support for Goal: By quantifying NEIs and integrating them into cost-benefit analyses, the project helps justify and accelerate the adoption of energy-efficient technologies in both residential and commercial buildings.

In terms of resilience, the research prioritizes retrofit solutions that enhance resilience to extreme heat, wildfire, and power outages (conditions increasingly common in California).

By demonstrating how retrofits can simultaneously reduce emissions, enhance resilience, and improve public health, the project contributes to achieving EPIC’s emissions-related goals.

viii. Contributors to This Concept Include: Núria Casquero, Iain Walker, Max Wei

2. Affordable and Resilient Cooling Strategies for California’s Residential Sector

i. Description: This concept proposes the development and demonstration of affordable, resilient cooling strategies tailored to California’s residential sector, with a focus on solutions that maintain thermal safety during extreme heat and grid disruptions while minimizing energy demand and infrastructure costs. A few example strategies to be explored include "Cool

Rooms" and a modular, plug-and-play “Heat Resilience-in-a-Box” solution. This research initiative will explore and validate cost-effective, resilient electrical topologies and equipment packages to support “cool room” operation and plug and play modular cooling solutions for low-power emergency modes such as low-voltage, touch-safe DC-powered cooling packages like compact air conditioners paired with small-scale solar and battery storage. Designed for both retrofit and new construction, these systems will provide thermal refuge during grid stress events while minimizing energy costs and avoiding the need for costlier electrical service upgrades. These systems will reduce peak electricity demand, improve resilience to outages, and enhance energy affordability in hot weather and/or during power interruptions during increasingly frequent heat waves.

ii. Breakthroughs: Key components of the research will target improved technology affordability through a variety of low-power and small-capacity technology approaches including the following:
   1. Development and evaluation of candidate home electrical architectures with both AC and DC-coupled configurations, including DC-only subzones where beneficial.
   2. Modeling of technology packages that combine solar PV, small-format batteries (<2 kWh), smart subpanels, optimized evaporative cooling, ceiling fans, heating pads, portable air filtration, and adequate ventilation to maintain occupant health and comfort using <400 watts.
   3. Simulation of thermal performance, demand flexibility, and resilience scenarios using advanced whole-building energy modeling tools.
   4. Inclusion of additional load-reducing strategies, such as solar thermal preheating, thermal storage, and graywater heat recovery.
   5. Evaluation of controls and communication strategies for demand response and Flex Alert participation.

   This research will prioritize modular system designs that can be implemented in factory-built housing or as retrofit kits for existing homes, supporting large-scale deployment and reduced installation costs.

iii. Outcomes: The potential innovation cool room, combining passive and low-power cooling solutions, if implemented at scale has the potential to reduce peak demand in individual homes by up to 70% during hot weather days and/or heat waves. Thus, this innovation enables more grid-friendly cooling and heat resilience and reduces the need for electricity grid peak generation investments. Additionally, for the end-users it will enable greater choices and operational affordability. The concept also provides a pathway to maintain minimum habitable indoor temperatures in rental or multifamily units, under consideration of the recent AB 209 (under consideration) and LA County ordinance (approved).

iv. Metrics: Cost of cool room implementation in new and existing homes; resilience benefits provided e.g. number of hours of safety during worst case heat waves and concurrent grid power loss; peak load reduction at the scale of single homes and then scaled up at the scale of neighborhoods, regions, and the state. For cost of implementation the cost of cool room implementation can be compared with whole home cooling in moderate, coastal settings that lack air conditioning units today.

v. References:
   1. A journal paper led by Jeetika Malik (under review) on cool rooms available by request. Key findings include (1) Cool room configuration with tiered cooling solutions (passive, low-power active and solar-powered active) can maintain thermal safety during heatwaves with concurrent power outage in homes located in moderate coastal regions. (2) Cool rooms also reduced peak electricity demand by 70% compared to a central HVAC baseline for scenarios with grid power. (3) Cool Room strategy can be an effective solution for enhancing indoor heat resilience, particularly for homes with limited or no access to cooling.
   2. Findings from a recent research report highlight that localised cooling (single-zone) with passive cooling measures is a crucial resilient cooling strategy for LA homes and recognizes gaps in adoption due to high initial cost and the need for incentives. (Park, Hye Min, Kelly Klima, Sophia Charan, and Javier Rojas Aguilera, Identifying Resilient, Sustainable Cooling Strategies for Los Angeles: How Might Landlords of Single-Family Homes Meet Indoor Temperature Thresholds? Santa Monica, CA: RAND Corporation, 2025. https://www.rand.org/pubs/research_reports/RRA3563-1.html

vi. Strategic Goal: Distributed Energy Resource Integration, Climate Adaptation

vii. Support for Goal: The California housing and energy landscape is being reshaped by multiple converging trends:
   1. Title 24 and state emissions policies are impacting consumer choice for electricity.

2. Extreme weather events are intensifying demand for resilient home energy systems, especially in communities that are more likely to face public safety power shutoffs (PSPS) and heat waves.
3. Distributed energy resources (DERs) such as solar, batteries, and smart panels are increasingly available, but remain cost-prohibitive for many households without targeted innovation and support.
4. Builders and manufacturers are exploring prefabricated and modular homes that can integrate advanced energy systems offsite for cost savings and code compliance.
5. The potential California market includes:
    a. Over 6 million single-family homes eligible for DER or resilience retrofits.
    b. More than 1.5 million households facing high energy burdens and heightened outage risks.
    c. Growing demand in the prefabricated housing sector, where integrated energy-resilience packages could become a core feature of next-generation home offerings.

By developing scalable, low-power, and affordable energy solutions tailored to the state's evolving needs, this research will directly support California's energy affordability and resilience objectives. This also addresses the strategic objective L - Reducing feeder/circuit peaks.

viii. Contributors to This Concept Include: Max Wei, Jeetika Malik, Kaiyu Sun, Daniel Gerber, Tianzhen Hong, Chao Ding

3. Innovative, Scalable, and more Affordable Approaches for Retrofitting Residential Buildings

i. Description: This concept would develop innovative, scalable, and more affordable approaches for retrofitting residential buildings in California to improve energy efficiency, optimize building energy mix, and drive greater resilience in the built environment to ensure public health and safety. This would be achieved by developing innovative strategies, modeling, and demonstrations.

Typical energy related programs are focused on new construction, major retrofits in existing homes, and/or they rely on voluntary home energy assessments and voluntary retrofits. These programs rely on energy rebates or discounts to incentivize participation by property owners. However, historical rates of participation are much lower than that required for the state to meet its goals. While new construction may not benefit from this, there are still many older residential buildings in the state that would benefit from energy efficiency retrofits and related upgrades to ensure resilience to growing extreme weather threats. Affordability is still a key concern for the first costs of electricity-powered heat pumps and operating costs especially with high and rising electricity rates in California. At the same time the frequency, duration, and severity of extreme weather events is increasing over time (heat, wildfires, storms, flooding) and there is the need for greater resilience in the built environment.

This research initiative seeks to lower the cost of home energy efficiency upgrades, reduce peak electricity demand, improve energy affordability, and improve resilience to extreme weather in the residential sector.

ii. Breakthroughs: Key components of the research could include the following:

1. A comprehensive strategy and development of low-cost technical approaches to perform home energy audits across the wide range of older homes in the state. This could incorporate AI/machine learning techniques that enable virtual home energy assessments based on some combination of survey data, a small set of home equipment pictures, green button utility data, and other data. Developing and demonstrating this capability would overcome the high cost of in-person energy audits and provide a larger set of granular data on the status of the residential building stock. Careful efforts would be made to protect the privacy and accessibility of this data set.
2. Block scale home retrofits and the development of templates for packages of measures enabled by virtual home energy audit or ML-abetted home audits that allow for scaling up of home retrofits and lower costs.
3. For example, developing innovative registries and block scale replacements of furnaces and air conditioning equipment nearing end of life. Today, every car on the road is registered with the state and is required to have smog checks. How would innovative voluntary data collection be collected and managed to enable more orderly and lower cost equipment replacements?
4. Explore the potential for selective retrofits or "right-sized" upgrades tailored to aging in place population. A whole home retrofit for Energy Efficiency could cost $30-40k while this market segment may only use 20-30% of the rooms in their home and in many cases may live in their homes for several more decades. This work would explore innovative

concepts to make retrofits more flexible, and/or more modular to enable right-sized and ultimately more affordable upgrades. Retrofits for the elderly may also prioritize thermal comfort and resilience. (Typically today, if a water heater or furnace stops operating, it is an emergency-type situation and the home owner would face a large bill for a whole home HVAC or water heating replacement including optionally a new heat pump or heat pump water heater).

5. Development of more integrated home energy assessments that include resilience to extreme heat and/or wildfires. These enable the development of packages of upgrades that address both efficiency and resilience.
6. Development of a decision support tool for residential resilience upgrades similar to the Home Energy Saver tool for energy efficiency. With such a tool, property owners would be able to answer questions such as how hot and unsafe would my home or property get with a worst case heat wave or a worst case heat wave experienced adjacent geographically to my home; how at risk is my property to wildfires, flooding, and other severe weather risks; what are the recommended sets of resilience measures (and related energy efficiency measures in some cases) to best protect my home from more frequent extreme weather conditions.

iii. Outcomes:

1. Virtual retrofits would sharply reduce the cost and transaction cost barriers to obtaining residential building audit data
2. Block retrofits would make home upgrades more affordable
3. Right sized, flexible retrofits would reduce equipment costs and operating costs, and would contribute lower peak loads.
4. Integrated energy efficiency & resilience retrofits and resilience decision support tools would provide vital information to the public to improve resilience to extreme weather events and public health and safety.

iv. Metrics:

1. Cost of home energy audit
2. Cost of home retrofits for individual measures and/or packages of measures
3. Home retrofits savings for right-sized retrofits vs whole home retrofits
4. Retrofit rates over a given period of time and by region or area could be evaluated after implementation of these types of programs.
5. The impact of resilience retrofits could be studied by M&V for IEQ metrics such as air quality, PM2.5, temperature and humidity, and/or

modeled based on thermal comfort metrics such as Heat Index, PMV, and SET.

v. References:

1. Wei et al 2023 and Earle et al. 2023 discuss benefits of more integrated retrofits. https://eta.lbl.gov/publications/final-project-report-building https://doi.org/10.1016/j.apenergy.2022.120256
2. Retrofits are consistent with existing low-income assistance programs and other existing programs such as HEERA in so far as they target efficient, appropriately-sized alternatives to existing equipment. However, residents who do not qualify for low income assistance programs are a gap and these programs may only indirectly address right-sizing.

vi. Strategic Goal: Building Decarbonization, Climate Adaptation

vii. Support for Goal: The California housing and energy landscape is being reshaped by multiple converging trends:
Title 24 and state emissions policies are impacting consumer choice for electricity.
Extreme weather events are intensifying demand for resilient home energy systems, especially in communities vulnerable to public safety power shutoffs (PSPS) and heat waves.
The potential California market includes:

a. Over 6 million single-family homes eligible for DER or resilience retrofits.
b. More than 1.5 million households facing high energy burdens and increasing housing costs.

By developing more innovative, scalable and affordable energy retrofit solutions tailored to the state's evolving needs, this research will directly support California's building sector energy goals (by increasing the rate of energy upgrades), energy affordability (by lowering the cost of home energy assessments and equipment), and resilience in the face of extreme weather events objectives (by bundling home energy and resilience assessments and upgrades).

viii. Contributors to This Concept Include: Max Wei, Jeetika Malik, Tianzhen Hong, Kaiyu Sun

4. Residential Fire Resilience

i. Description: Fire resilience is increasingly critical for both new and existing homes in California, as underscored by the catastrophic wildfires in Los

Angeles County in early 2025. Wildfire risk is growing with the state approaching a year-round fire season. Over 5 million homes in California are located within the Wildland-Urban Interface (WUI), an area where human development meets wildland vegetation and an area that is particularly vulnerable to wildfires. Retrofitting a home for wildfire resilience can cost as much as $100,000. These high costs pose a significant barrier to widespread retrofitting. Additionally, fire-resistant materials can be difficult to source, and many local contractors may lack the necessary knowledge to carry out such projects. Despite the establishment of programs like the California Wildfire Mitigation Program (CWMP), the pace of retrofitting remains slow, with only a small number of homes having been retrofitted so far.

The focus of this concept is to develop lower cost and easier to install fire resilient technologies, more fire-resilient new homes, and fire-resilient home retrofits and to aid in the dissemination of these technologies across the state. EPIC funds are needed since the pace of retrofitting remains slow, with only a small number of homes having been retrofitted so far.

ii. Breakthroughs:

These objectives will be accomplished through several key technical approaches:

1. Fire resilient design for new homes and retrofits, and the development of optimal packages that provide fire resilience and where possible, enhanced energy efficiency.
2. Affordable and more fire resilient modular housing and development and demonstration of lower cost, easier to install components such as exterior wall insulation panels that provide fire resistance and improve energy efficiency.
3. Development and characterization of fire-reflective window, wall, and roof materials that improve the fire resistance of buildings (detailed in a separate concept).
4. Techno economic analysis and total cost of ownership modeling of the technologies and packages above.
5. Stakeholder engagement with the following groups: residential and commercial builders and developers, electric utilities, state agencies (CPUC, CalOES), the state insurance office, local towns and governments such as LA County, tribal and territorial (SLTT) entities, other Federal agencies, local stakeholder organizations and non-profits,

and the public. There are several reasons to do this engagement: (1) identify barriers to scaling up retrofits; (2) collect approaches to overcoming these barriers; and (3) work to prioritize the most promising of these approaches. This prioritization could inform case studies and pilots.

6. Project dissemination will summarize key actionable information and best practices in the form of design guides, checklists, fact sheets, and links to suppliers and technologies for the audiences listed above.

iii. Outcomes: This project aims to benefit ratepayers by minimizing the risk of property loss and destruction due to future wildfires, as well as lowering insurance premiums, without adding extra burden to energy cost. By offering more affordable, fire-resistant, and energy-efficient housing—both new and existing—this concept supports the EPIC objective of improving safety and affordability.

Wildfires in California are estimated to have caused over $100 billion in property losses over the past 10 years. The January 2025 fires in Los Angeles alone resulted in property losses ranging from $30 billion to $50 billion. Therefore, a reduction of 5% to 10% in these damages over the last decade could have resulted in avoided losses between $5 billion and $10 billion.

iv. Metrics:

Quantitative:

a. Cost of retrofitting fire-resilient exterior panels, including parts, labor, and additional fire resilience upgrades.
b. Number of roof, wall, and window products measured for fire reflectance properties
c. Number of new or updated roof, wall, and window products developed in partnership with industry and/or included in fire reflectance ratings in partnership with the Cool Roof Rating Council and the National Fenestration Rating Council
d. Cost of new homes with fire resilience features that meet or exceed voluntary consensus standards such as the IBHS Wildfire Prepared Home™ standards
e. Residents’ energy cost before and after retrofit (should get lower or at least keep the same)

v. References:

1. Low rate of fire-resilience upgrades in California: https://calmatters.org/housing/2025/04/california-fire-home-hardening/
2. Fire reflectance of roof, wall, and window products: https://doi.org/10.1016/0378-7788(95)00921-J
3. Fire-resilient modular housing example: Build a Fire-Retardant Home with Steel Modular Design
4. IBHS Wildfire Prepared Technical Standard: https://wildfireprepared.org/wp-content/uploads/WFPH-Technical-Standard.pdf

vi. Strategic Goal: Climate Adaptation

vii. Support for Goal: The proposed concept would improve resilience efforts by developing lower cost, easier to install fire resilient new homes and existing home retrofits. These would increase the number of fire resilient homes across the state, resulting in less damages and destruction from future fires, lower insurance premiums, and improved public health and safety.

viii. Contributors to This Concept Include: Max Wei, Ronnen Levinson, Jingjing Zhang, Jeetika Malik, Luis Fernandez, Tianzhen Hong, Margaret Taylor

5. Modular Construction: A Catalyst for Efficient, Affordable, and Resilient Buildings

i. Description: Modular construction serves as a powerful catalyst and system integration platform, accelerating the development of more efficient, affordable, and resilient buildings. An RD&D program focusing on the off-site integration of more efficient and resilient technologies into modular building components, units, and systems can significantly advance this sector. The inherent benefits of modular construction—including high-quality factory precision, standardization, and significantly shorter construction times—can help lower overall system costs and improve quality and reliability for integrated energy & resilience technologies and measures.

Driven by increasing costs and the urgent need for resilience, the building industry is actively pursuing promising innovations across architecture, planning, policy, technology, construction, and financing. CEC has already invested in demonstrating several small-scale, modular home pilots during the last EPIC period. Recognizing the substantial advantages of the modular approach, the CEC could consider expanding its program to support rapid industry growth through market scaling initiatives and new R&D research areas to help address both housing and energy affordability and to meet state goals. This could include technical assistance for large-scale demonstration projects, increased data collection, case studies, targeted research & development, and/or design-build competitions.

The program could consider the following research areas:

1. Enhancing Housing Affordability and Grid Integration - A recent proposal for a $10 billion Affordable Housing Bond could fund over 35,000 new homes in the State. The CEC could play a crucial role in making these homes even more affordable while simultaneously leveraging them as grid resources, such as virtual power plants that provide load flexibility and could integrate a wide variety of end uses (HP water heaters, EVs) leveraging CalFlexHub. Modular construction offers an ideal, potentially more streamlined and standardized pathway to integrate efficient, resilient, and grid-interactive technologies, thereby reducing overall energy system integration costs by leveraging less on-site installation and decreased soft costs.
2. Enabling Infill Development and Distributed Energy Resource Integration - Pre-installing distributed energy technologies and energy efficiency measures in a factory setting can significantly reduce marketing and on-site labor costs through a modular approach. One study suggests this method could cut the total cost of some onsite generation technologies plus energy storage by nearly 30%. Further research is needed to identify appropriate use cases and manage the risks associated with transportation and on-site integration. Additionally, coupling the factory integration of distributed energy systems with small infill development could support the deployment of more affordably priced homes that meet the State's building goals.
3. Innovating Plug-and-Play Modular Retrofit Strategies - Several companies and research initiatives are currently developing "plug-and-play" modular facade systems that can integrate insulation, high-performance windows, and shading for rapid deployment in both residential and commercial buildings for lower potential cost, faster, more streamlined installation times, and increased potential for scaling up. Continued innovation is essential in these areas to enhance cost-effectiveness. Potential use cases include large-scale demonstration in multi-family housing, retrofitting and repurposing

empty office spaces for alternative uses, such as residential housing; and providing templates and lower cost conversions from single family homes to duplexes or tri-plexus in support of SB 9 (California Housing Opportunity and More Efficiency (HOME) Act).

4. Modular Resilience Hub - The modular resilience hub concept envisions a local facility, constructed using rapid off-site prefabrication, that integrates energy technologies like solar panels and battery storage. These hubs are designed to maintain critical services and provide safe refuge during emergencies such as power outages, extreme weather, and wildfire smoke events, ensuring communities have access to power, clean air, and essential resources when traditional infrastructure fails. Their modular nature allows for quick deployment, high quality, and cost-effective integration of essential resilience features either as new construction projects or to retrofit existing buildings such as public schools/ libraries, community centers, or other public facilities.
5. Database, Benchmarking, and Best Practices - A comprehensive strategy is needed to support market scaling of modular housing. This involves creating a standardized framework for gathering data on project costs, timelines, energy efficiency, and material usage from a wide range of modular projects. By systematically collecting this information, the industry can establish benchmarks and key performance indicators (KPIs) to measure efficiency, resilience, and the management of long term externalities against traditional construction methods. This data will not only highlight the proven benefits of modular building but also provide the foundation for developing and sharing best practices and detailed case studies.

ii. Breakthroughs: The concept accelerates state energy goals by enabling off-site, factory-precision integration of more efficient and resilient technologies. This directly overcomes market barriers like high upfront costs and complex on-site installation, reducing costs by up to 30% and shortening construction timelines by 50%. It makes energy efficiency and resilient technologies more economically viable and scalable and can reduce energy costs and improve public health and safety with the incorporation of advanced energy efficiency and resilience features.

iii. Outcomes: Reduced technology/ratepayer costs, significantly improved energy performance, enhanced value proposition for energy upgrades. Potential at Scale: Transform California's building stock, enabling rapid deployment of more affordable, highly efficient, grid-interactive housing and commercial spaces and better enable the state to meet its targets.

Ratepayer Benefits: Affordability (lower bills, reduced upfront costs), Reliability (grid stability via VPPs), Environmental goals (reduced emissions), Safety (factory QC), Accessibility and Resilience (affordable, resilient housing).

iv. Metrics:
   1. Quantitative:
      a. % reduction in system integration costs (e.g., DERs).
      b. % reduction in on-site construction/retrofit time.
      c. Building energy efficiency improvements (e.g., kWh/sq ft).
      d. Value of grid services provided (e.g., kW peak reduction).
      e. Emissions reductions.
      f. Number of modular projects/units delivered.
   2. Qualitative:
      a. Market adoption signals and industry interest.
      b. Occupant comfort and satisfaction.
      c. Workforce development opportunities.
      d. Replicability and scalability assessment.

v. References:

vi. Strategic Goal: Building Decarbonization, Climate Adaptation, Distributed Energy Resource Integration

vii. Support for Goal: The CEC's goals are supported in the following ways: accelerating the adoption of highly efficient modular design and deep energy retrofits, enhances building resilience to extreme weather through superior envelopes and provides on-site energy resilience (storage) during outages, and enabling cost-effective, factory-precision off-site integration of DERs, making buildings active participants in grid management.

viii. Contributors to This Concept Include: Jingjing Zhang, Max Wei

6. Attic and Crawlspace Solutions for Wildfire Resilience in New and Existing Homes

i. Description: Enabling attic and crawlspace solutions for wildfire resilient home construction and renovation of attic and crawlspaces: The concept is to develop design guides and demonstrate their energy and fire resistance efficacy for sealed and insulated attics in new and retrofit construction. The work would address the known issue that many home losses associated with wildfires occur due to ember intrusion into purposeful ventilation openings into attic spaces that are required by the building codes for moisture and thermal management. Sealing attics can eliminate the risk of embers entering an attic but careful design and implementation is needed to avoid potential moisture damage, especially in existing dwellings and those with complex geometries. The potential moisture risks need to be weighed against the potential protective benefits against wildfires, and the economics for justifying this work may be strongly impacted by potential energy savings, moisture impacts, and fire resilience. The efficacy of sealed attics must also be compared to other solutions, such as "fire protection vents" (see Ch7A of the California Building Code). EPIC funds are required because this area requires substantial R&D efforts in order to support amendments to building practices in the state.

ii. Breakthroughs: Attics and crawlspaces play a critical role in the thermal, moisture, IAQ and fire resilience of residential structures. Past work has demonstrated that many home losses associated with wildfires occur due to ember intrusion into purposeful ventilation openings that are required by the building codes for moisture and thermal management. These ventilated openings allow wildfire embers to enter the structure where it is unprotected and can initiate fire from within. Similarly, intentionally ventilated spaces permit smoke intrusion into dwellings, which ultimately can lead to increased exposure to harmful contaminants for occupants. Sealed and insulated attics are a potential solution that avoids placement of large ventilation openings on the outside of California homes. They have also been widely recognized for having important energy savings potential, especially when ducted HVAC equipment is located in the sealed space. But these solutions require careful design and implementation to avoid potential moisture damage, especially in existing dwellings and those with complex geometries. The potential moisture risks now need to be weighed against the potential protective benefits against wildfires, and the economics for justifying this work may be strongly impacted by potential energy savings, moisture impacts, and fire resilience. This area requires substantial investigation and work in order to support amendments to building practices in the state.

iii. Outcomes: This work will lead to home construction that is more energy efficient and more resilient to wildfires.

iv. Metrics: Occupant exposure to wildfire smoke. Reduced risk of fire spread from embers. Reduction in mold risk for building assemblies

v. References:

1. https://firesafemarin.org/harden-your-home/fire-resistant-vents
2. Walker, I.S. and Less, B.D. 2019. Measured Moisture Performance of Sealed and Insulated Attics with Permeable Insulation in California

homes. Proc. Thermal Performance of the Exterior Envelopes of Buildings XIV. Clearwater Beach, FL. ASHRAE, Atlanta, GA.

3. Less, B., Walker, I.S., and Levinson, R. (2016). A Literature Review of Sealed and Insulated Attics—Thermal, Moisture and Energy Performance. LBNL-1006493. Lawrence Berkeley National Lab: Berkeley, CA. https://doi.org/10.2172/1340304

vi. Strategic Goal: Building Decarbonization, Climate Adaptation

vii. Support for Goal: This concept would lead to reducing energy use by bringing thermal distribution systems inside the thermal boundary of the home (a concept that has been studied and developed in the past). The greatest current challenge to achieve this performance is risk around moisture considerations that are still not well-established in the industry. Similarly the reduction in ember intrusion is a recognized advantage for unvented attics - but the impact remains unquantified. Without this quantification it is not possible to make decisions around policy or building practices regarding the application of this technology to homes.

viii. Contributors to This Concept Include: Iain Walker & Brennan Less

7. Real-Time Monitoring of IAQ During Extreme Heat, Wildfires, and Storm Events

i. Description: Extreme weather events such as heatwaves, wildfires, and storms (among others), are increasingly compromising indoor air quality (IAQ), particularly affecting communities with poorly adapted residential buildings. While these events intensify pollutant infiltration and humidity fluctuations, current monitoring approaches often lack the resolution, responsiveness, and contextual understanding needed to characterize occupant exposure in real time including in energy efficiency. This concept aims to develop a scalable, data-driven framework that leverages machine learning (ML) to enhance IAQ monitoring during extreme weather emergencies.

The concept involves deploying a network of low-cost IAQ sensors across a variety of home types in California, including energy-efficient residences, strategically selected in regions vulnerable to extreme weather hazards. These sensors will continuously monitor key parameters (such as PM2.5, humidity, temperature, etc.) to capture real-time indoor environmental conditions during extreme weather events. To address sensor limitations, ML models will be trained to correct drift, detect anomalous spikes linked to specific weather events, and impute missing or low-quality data. To move beyond static zone-based assessments, we will integrate occupant activity data (e.g., room use patterns, door/window status) to train models that estimate real-time individual exposure levels with room-level resolution. By linking sensor data with environmental and behavioral inputs, this research fills critical gaps in understanding how extreme weather events interact with building performance, including energy efficient homes, and occupant behavior to shape acute exposure. The approach supports increased adoption of adaptive ventilation and filtration strategies, while informing resilience-oriented building practices and public health guidance. The anticipated beneficiaries include California ratepayers, public health agencies, housing providers, and utilities seeking to identify at-risk homes and populations. Ratepayer benefits stem from more targeted and cost-effective IAQ interventions, reducing health burdens without overinvestment in energy-intensive systems. Key metrics include exposure-adjusted IAQ indices, sensor-data reliability, ML model accuracy, and disparities in exposure across groups based on deployed resilience measures. Ultimately, this project advances indoor environmental quality resilience.

ii. Breakthroughs: The proposed concept advances technological innovation by addressing key barriers to adoption, including the lack of real-time, high-resolution IAQ data during weather emergencies. It leverages low-cost sensors and machine learning to improve data accuracy, predict occupant-specific acute exposure, and guide adaptive ventilation strategies. This fills critical gaps in understanding how extreme events interact with building systems and behavior (including energy efficient buildings), supporting targeted, low-cost interventions. In addition, the concept aims to help assess how extreme events impact on acute exposure risks for occupants. Beneficiaries include public health agencies, utilities, and housing providers seeking data-driven tools to reduce exposure differences and support energy-efficient, resilient buildings

iii. Outcomes: If successful, this research will deliver a scalable, low-cost IAQ monitoring and analytics system that enables real-time exposure assessment during extreme weather events. By improving the accuracy and usability of low-cost sensors through machine learning, the project reduces reliance on costly mitigation measures and supports targeted, energy-efficient interventions. At scale, it will help utilities and agencies identify vulnerable homes, optimize ventilation strategies, and avoid overinvestment in HVAC systems. This innovation supports EPIC's guiding principles by enhancing safety (through health risk reduction), reliability (via adaptive IAQ management), affordability (by lowering technology and intervention costs), environmental goals (through efficient energy use), and accessibility(by prioritizing low-income and high-risk communities).

iv. Metrics: The impacts of the proposed research will be evaluated using a combination of quantitative and qualitative metrics. Key quantitative indicators include potential energy savings from IAQ-based ventilation controls, exposure-adjusted IAQ indices (such as time-weighted PM2.5, etc), sensor data accuracy and completeness compared to reference-grade monitors, and machine learning model performance metrics. Additional evaluation will assess disparities in IAQ exposure across market segments and measure the cost-effectiveness of targeted interventions compared to conventional upgrades. Qualitative metrics will include user feedback on sensor usability, installation, and perceived value. Together, these measures will assess the technical effectiveness, user acceptance, and accessibility impacts of the proposed innovation.

v. References: The following references provide background information:

1. Ivey, Cesunica, and Jennifer Ofodile. 2025. “LowCost Sensors for Healthier Indoor Air Quality in Impacted Communities.” California Air Resources Board.
2. Less, B., Walker, I., Lorenzetti, D., Mills, E., Rapp, V., Dutton, S., Sohn, M., Li, X., Clark, J. and Sherman, M. 2020. Smart Ventilation for Advanced California Homes. LBNL-2001342. https://doi.org/10.2172/1635274
3. Walker, Iain, Woody Delp, and Brett Singer. 2019. “Are Low-Cost Sensors Good Enough for IAQ Controls?” RHEVA Journal 56 (1): 7.

vi. Strategic Goal: Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Climate Adaptation

vii. Support for Goal: This research supports CEC’s goals by enabling more precise data-informed ventilation and filtration strategies that maintain IAQ without defaulting to energy-intensive HVAC use, especially critical as buildings become more airtight through efficiency retrofits. By improving real-time IAQ monitoring and acute exposure assessment, the project helps identify when and where ventilation is truly needed, reducing unnecessary energy consumption while maintaining occupant health.

For resilience, the system provides real-time insights into how extreme heat, wildfire smoke, and storms affect indoor environments. This allows households, building managers, and public agencies to respond quickly to environmental hazards, protecting the public and improving building resilience under extreme weather events.

The concept also supports CEC’s goals by promoting smarter, more targeted use of existing building systems, and enabling optimization of energy sources for air conditioning and filtration. The scalable, low-cost nature of the solution ensures that resilience and other benefits are accessible, accelerating adoption of innovative technologies and adaptive building practices across all income levels. It leverages low-cost sensors and machine learning to improve data accuracy, predict occupant-specific exposure, and guide adaptive ventilation strategies. This fills critical gaps in understanding how extreme events interact with building systems and behavior, supporting targeted, low-cost interventions. Beneficiaries include public health agencies, utilities, and housing providers seeking data-driven tools to reduce exposure differences and support energy-efficient, resilient buildings

viii. Contributors to This Concept Include: Núria Casquero, Iain Walker, Brett Singer, Max Wei

8. Integrated Passive Cooling for Residential Resilience

   i. Description: This concept develops a suite of nature-inspired, energy efficient design strategies—innovative emerging radiative cooling materials and technologies (e.g. sky cooling materials); emerging thermal storage materials (e.g., phase change materials); natural and night ventilation (including biomimetic windcatchers and yakhchal-inspired subterranean vents); evaporative cooling elements; and smart, minimal-power controls—that together maintain safe indoor temperatures (≤82°F) during extreme heat waves and power outages. The purpose is to create a passive cooling toolkit for both new construction and retrofit of California homes, especially benefiting populations such as seniors and low-income residents. By optimizing passive elements in combination—rather than in isolation—and validating them across representative climates (coastal, Central Valley, desert), we will generate performance-tested design packages, control algorithms, and guidance for builders and policymakers. EPIC investment is critical because this integrated approach spans multiple disciplines—thermal-fluid experiments, advanced materials testing, high-fidelity building simulations, and field prototyping—that exceed the capacity of typical municipal or utility R&D budgets. Key R&D gaps remain unfilled: there is no publicly available, location-tailored validation of combined passive strategies; durable, low-cost radiative materials have not been demonstrated in real-world California settings; and fully integrated, sensor-driven control systems that coordinate multiple passive cooling strategies in residential settings remain largely undeveloped and untested. EPIC funds will underwrite: (1) lab and outdoor testing of PCMs and radiative coatings; (2) CFD and energy modeling across a wide range of weather patterns; (3) development of autonomous sensor-driven controls; and (4) real-world demonstration in pilot homes. Without EPIC support, the rigorous, cross-disciplinary development and validation needed to transition from individual passive measures to a reliable, integrated residential system would be infeasible.

ii. Breakthroughs: This concept addresses key technical and market barriers that currently stall passive cooling in California's hot climates. Today, builders and homeowners lack rigorous, region-specific guidance on how combined passive strategies—such as phase change materials (PCMs), radiative sky-cooling panels, and natural ventilation—perform during extreme heat events or grid outages. Without such data, they default to energy-intensive air conditioning. Our research fills this gap by quantifying: (a) peak indoor temperature reductions of 3–5 °C using integrated PCM and radiative panels; (b) airflow rates and cooling capacity from biomimetic stack-effect systems—drawing on case studies like Harare's Eastgate Centre and modern "solar chimneys"—and demonstrating their applicability in retrofit and new-build residential and small commercial settings; and (c) evaporative cooling performance in arid zones. These benchmarks will directly inform energy policy updates and financial incentives for passive design adoption.

From a market standpoint, the absence of validated, end-to-end passive cooling systems has stymied mass adoption and economies of scale. Our project will deliver a comprehensive Passive Cooling Toolkit—including detailed materials specifications, modular control algorithms, and step-by-step installation guides—that can be tailored to multiple audiences: DIY homeowners, architects seeking design precedents, contractors and installers requiring technical blueprints, and developers evaluating cost-benefit analyses. Each stakeholder will find dedicated modules—e.g., simplified "quick-start" sheets for enthusiasts, in-depth CFD-backed design guides for professionals, and procurement checklists for builders—ensuring broad usability and confidence in deploying passive solutions. We will target performance thresholds to drive market acceptance: a 50% reduction in peak cooling energy demand, and 12-hour off-grid thermal comfort (≤82°F) during heat waves. While the core system is passive, we will also demonstrate optional coupling with rooftop PV and battery storage to extend autonomy during multi-day heat events. Achieving these metrics will unlock new market pathways for cool-roof incentives, PCM rebates, and passive-cooling labels, accelerating building innovation across California's residential sector.

iii. Outcomes: If successful, our research will deliver validated passive-cooling system packages that reduce or eliminate active air-conditioning during extreme heat, cutting residential cooling energy use and peak demand by up to 50%. For ratepayers, this translates to $100–150 million/year savings statewide (assuming $300 million annual residential cooling spend). Vulnerable households will see lower utility bills and improved health outcomes during heat events. By minimizing peak loads, the innovation also reduces the frequency and severity of grid stress and PSPS events, enhancing reliability and reducing grid investment costs for peak-power plants.

At scale, the toolkit's rapid simulation enables cities to retrofit millions of homes cost-effectively, maximizing public health benefits (fewer heat-related ER visits), reducing household energy bills, cutting emissions from peak cooling demand, and ensuring accessibility by deploying interventions where they may be most beneficial. Our integrated approach ensures that investments in resilience deliver high leverage across multiple EPIC principles. Moreover, by packaging passive-cooling systems into modular "plug-and-play" kits—complete with sensor-driven controls and digital twins—municipalities and utilities can integrate them into broader DER microgrids, demand-response programs, and smart-city platforms. For example, neighborhoods could use aggregated temperature and ventilation data to orchestrate community-wide night-ventilation schedules, while other housing types such as complexes, could pair passive cooling with rooftop solar and battery storage to maintain critical services during outages.

iv. Metrics:
1. Quantitative:
   a. Indoor Peak Reduction: Average drop in maximum indoor temperature (°C) during heat waves versus baseline (target ≥3 °C).
   b. Cooling Energy Savings: Percent reduction in air-conditioning load (target ≥50%).
   c. Grid Load Impact: Reduction in peak residential electricity demand at household level during summer peaks (target ≥10%).
2. Qualitative:
   a. User Satisfaction: Surveyed comfort levels and ease-of-use scores from residents, particularly seniors.

b. Design Adoption: Number of builders and municipalities integrating toolkit guidelines into building practices and/or incentive programs.
c. Health Impacts: Changes in heat-related emergency visits in pilot communities; tracking of prioritization metrics.

v. References: Passive cooling strategies in hot climates like California have been shown to deliver substantial thermal comfort and energy savings. Meta-analyses from peer-reviewed studies reveal average indoor temperature reductions of around 2.2°C and cooling load decreases of about 31%, leading to approximately 29% annual energy savings across residential buildings (Mohammadi et al., 2023). PCM-enhanced insulation retrofits in California homes achieved cooling reductions ranging from 10% to 41%, along with peak demand reductions up to 81% when combined with improved air sealing and nighttime ventilation (Pistochini et al., 2024). Radiative cooling techniques—such as high-emissivity panels or cool roof coatings—have demonstrated passive surface temperature drops of 10°C below ambient and yielded estimated energy savings of up to 15% in California studies (Chen et al., 2022; Rosado et al., 2014). These results support the feasibility and scale of our integrated passive cooling concept.

1. Mohammadi, M., Tahsildoost, M., & Barbhuiya, S. (2023). The effects of passive design on indoor thermal comfort and energy savings for residential buildings in hot climates: A systematic review. Urban Climate, 49, 101466. https://doi.org/10.1016/j.uclim.2023.101466
2. Pistochini, T., Feng, J. D., Aboud, A., Mitra, D., & Outcault, S. (2024). Phase-change material-enhanced insulation for residential exterior wall retrofits. California Energy Commission Report CEC-500-2024-086. Retrieved from https://www.energy.ca.gov/publications/2024/phase-change-material-enhanced-insulation-residential-exterior-wall-retrofits
3. Chen, L., Zhang, K., Song, G., & Li, F. (2022). Study on the cooling performance of a radiative cooling-based ventilated roof for its application in buildings. Building Simulation, SAGE Publications. https://doi.org/10.1177/01436244221106342

vi. Strategic Goal: Climate Adaptation, Distributed Energy Resource Integration, Building Decarbonization

vii. Support for Goal:
1. The concept directly enhances local resilience by maintaining safe indoor temperatures during extreme heat and power disruptions.

2. By reducing cooling loads and peak demand, the toolkit facilitates more reliable DER operation (solar + storage) and lowers grid stress during heat waves.
3. The passive solutions reduce or eliminate active cooling, accelerating building electrification and slashing emissions from residential HVAC systems.

viii. Contributors to This Concept Include: Chao Ding, Nihar Shah, Max Wei

9. Health Risks of Overheating in Energy-Efficient Envelope Retrofits

i. Description: Building envelope retrofits aimed at improving energy efficiency, such as increased insulation and airtightness, can inadvertently elevate the risk of indoor overheating, with growing evidence linking such conditions to adverse health outcomes. This project synthesizes empirical research on the thermal and health implications of energy-efficient envelope retrofits, with a focus on naturally ventilated residential buildings. Although measures such as increased insulation and airtightness reduce winter heating demand, they often contribute to elevated indoor temperatures and extended periods of thermal discomfort during summer months (specially during heatwaves), particularly on upper floors, in multifamily dwellings, and in homes lacking active cooling systems. These overheating conditions frequently surpass established thermal comfort thresholds (e.g., Passivhaus, CIBSE, EN 15251), raising concerns about occupant health, especially among populations most susceptible to harm from heat exposure. Underestimating overheating risks can render homes uninhabitable in extreme heat, while overestimating may prompt unnecessary installation of energy-intensive cooling systems. EPIC funds are needed because this is currently a subject that is not fully recognized by industry practitioners and there is currently no information or analyses available to avoid these overheating problems in energy efficient buildings.

ii. Breakthroughs: The proposed concept addresses a critical but underrecognized barrier to California's goals: the risk of indoor overheating from energy-efficient envelope retrofits and new construction. Common strategies, such as increased insulation and airtightness, reduce winter energy demand but can elevate indoor temperatures in summer. This performance gap threatens occupant health, undermines resilience, and drives unnecessary adoption of energy-intensive air conditioning, increasing emissions and grid stress. This concept would advance technological innovation by synthesizing empirical evidence from building science and public health to quantify overheating risks, identify affected building types, and define performance thresholds (e.g., discomfort hours, CIBSE/EN 15251 thermal comfort limits). It fills key data and modeling gaps by addressing co-factors such as behavioral adaptation, IAQ, and passive cooling potential (often overlooked in current rating systems and retrofit programs). The results will inform appropriate retrofit strategies, improve voluntary consensus standards around building performance, and support the integration of passive and smart ventilation technologies. By enabling resilient, efficient retrofits that protect occupant health and comfort, this work supports California's energy goals by increasing consumer trust and acceptance of energy upgrades for resilience. Policymakers, utilities, designers, and energy modelers will directly benefit from these findings

iii. Outcomes: If successful, this research will enable safer, more resilient, and cost-effective energy retrofits by preventing overheating-related health risks and reducing reliance on energy-intensive cooling. It will improve retrofit performance, guide integration of passive and smart ventilation technologies, and enhance energy rating systems. At scale, it supports widespread adoption of appropriate, efficient retrofits that lower utility costs, reduce emissions, and protect building occupants from the harm of heat exposure. By improving indoor environmental quality while maintaining affordability and reducing grid impacts, the innovation aligns with EPIC's goals for California ratepayers.

iv. Metrics: The proposed research will use both quantitative and qualitative metrics to evaluate impacts.

1. Quantitative metrics include indoor temperature data such as hours above thermal comfort thresholds from CIBSE/EN 15251, frequency and duration of overheating events, reduction in projected cooling energy demand, modeled and/or measured impacts on peak load and energy costs, and estimated health risk reduction including heat-related symptoms to acute exposure and exposure metrics, including economic savings to the health care system.
2. Qualitative metrics include occupant-reported thermal comfort and adaptive behaviors, stakeholder feedback on the usability of retrofit guidance, and improvements in building performance evaluation tools such as integration of passive cooling criteria.

v. References: The following references provide background information:

1. Lozinsky, C. H., Casquero-Modrego, N., & Walker, I. S. (2025). The health and indoor environmental quality impacts of residential building

envelope retrofits: A literature review. Building and Environment, 112568.
2. S. Sharifi, W. Saman, A. Alemu, Identification of overheating in the top floors of energy-efficient multilevel dwellings, Energy Build. 204 (Dec. 2019) 109452, https://doi.org/10.1016/j.enbuild.2019.109452
3. Chvatal, K. M. S., & Corvacho, H. (2009). The impact of increasing the building envelope insulation upon the risk of overheating in summer and an increased energy consumption. Journal of Building Performance Simulation, 2(4), 267-282.
4. Less, B.D.,Casquero-Modrego, N., Walker, I.S. (2022). Home Energy Upgrades as a Pathway to Home Decarbonization in the US: A Literature Review. Energies 2022, 15, 5590. https://doi.org/10.3390/en15155590

vi. Strategic Goal: Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Climate Adaptation

vii. Support for Goal: The proposed concept supports the state’s goals in the following ways: by promoting retrofit strategies that reduce heating demand while minimizing the need for energy-intensive cooling, through the integration of passive and smart ventilation solutions; by enhancing resilience by identifying and mitigating overheating risks, especially during extreme heat events, improving the resilience and habitability of buildings; by informing voluntary consensus standards and tools to enable -appropriate, efficient retrofits that protect occupant health, reduce emissions, and support accessibility.

viii. Contributors to This Concept Include: Núria Casquero, Iain Walker, Max Wei

10. Low Peak Power Homes

i. Description: Low Peak Power Homes: Low peak power (or Power Efficient) homes have the equipment and controls needed to minimize their peak power. Advancing this concept will remove or reduce the need for costly new infrastructure in individual homes and for the electric grid. This is fundamentally different from current energy efficiency approaches that aim to reduce energy use, and not peak power. It should be noted, incidentally, that energy efficient approaches can also contribute to lower peak power. The concept addresses two key points. The first is that it addresses a key cost barrier to the state's energy goals. The second is that it addresses the limited remaining peak capacity in the electric grid that is already becoming a limit on added electric loads. The objectives are to better understand the current status of electric infrastructure for California's homes and to develop and demonstrate low peak power approaches to the point where they are considered to be low risk, proven to have lower costs, and are accepted in the building and construction community as well as in energy-related programs. For example, rather than subsidize home electric panel and service replacement with higher capacity equipment, we could subsidize lower-cost approaches that avoid the panel and service replacements. EPIC funds are needed because this is a new innovative concept that is not broadly known about or understood by the buildings and electric power industry. Furthermore, many innovators in this area are small businesses that lack the funds to invest in the required R&D and documented demonstrations. There is also little or no incentive for contractors to pursue low peak power strategies due to the risk of novelty and the reduction in individual project revenues that will result from successful low peak power deployment.

ii. Breakthroughs: California's energy future is fundamentally constrained by the limited capacity of its residential electrical infrastructure. If the state continues with a business-as-usual (BAU) approach, the new electric loads from homes and electric vehicles, and adding Solar PV and battery systems will overwhelm existing electrical equipment in homes and across the grid. This path necessitates widespread, costly, and time-consuming upgrades to service panels and utility infrastructure, which would in turn increase construction costs, create project delays, and ultimately raise electricity rates for all Californians. The strategic solution is to establish power efficiency and low-power design as standard practice in both new home construction and the retrofitting of existing homes, an approach intended to reduce costs and enable consumer choice. A significant research opportunity exists to develop the data and technologies that support this strategy. For new construction, there is a critical need for analyses and demonstration projects to prove that all-electric homes can be built using standard 200A panels, avoiding 400A BAU approaches. Research is needed to develop new metrics and concepts suitable for compliant integration into building practices. Similarly, for existing homes, case studies are needed to validate low peak load strategies using efficient equipment and controls, and inform the creation of new utility programs that support peak load management. Previous studies have shown that the cost savings for individual homes are typically in the range of $3,000 to $30,000, with similar potential costs for utilities (that are then passed on to ratepayers in future rate increases). These cost savings can make individual projects more affordable for more households (leading to greater adoption at scale), can be used to offset the use of higher performance/efficiency equipment (leading to less energy use), energy program funds can cover more homes, and reduce future increases in already very high electric rates in CA.

iii. Outcomes: These strategies will enable more use of on-site generation and batteries (strategic goal #2) without overstressing home or grid infrastructure - avoiding the associated costs and time delays. These strategies will reduce ratepayer costs when adding loads to their homes, future ratepayer costs associated with paying for new utility infrastructure, particularly for homes optimizing their energy mix (strategic goal #3 (and maybe goal #4)). The data gathered will enable better utility resource planning as we develop a better understanding of how many homes will need new panels/service and what the added grid peaks are - even if we don't replace panels or service). These strategies will allow a lot more integration of EVs into home electric infrastructure without costly service or panel replacements and minimizing peak load impacts. In response to strategic goal #1, developing technologies and approaches that minimize grid impacts due to home charging (which is where most people charge their EVs) is needed. To affordably meet strategic goal #4 and to get to scale, we need to limit infrastructure costs and delays, which necessitates taking into consideration barriers under BAU scenarios such as: low likelihood of getting enough transformers and low likelihood of getting enough power plants built to meet the demand.

iv. Metrics: Reductions in new construction and existing home remodeling costs and time delays. Reductions in future electric rates. Increase in grid reliability and resiliency.

v. References: The following references provide background information relating to costs and installed infrastructure:

1. Less, B.D.,Casquero-Modrego, N., Walker, I.S. (2022). Home Energy Upgrades as a Pathway to Home Decarbonization in the US: A Literature Review. Energies 2022, 15, 5590. https://doi.org/10.3390/en15155590

2. Less, B. and Walker, I. 2024. HVAC Heat Pump Upgrades and their Impact on Household Maximum Power Demand. Proc ACEEE Summer Study 2024. ACEEE, Washington, DC.

3. Less, B., Walker, I., Murphy, S. and Fournier, E. 2024. Electrical Service Panel Capacity in California Households with Insights for

Equitable Building Electrification. Proc ACEEE Summer Study 2024. ACEEE, Washington, DC.

4. Casquero, N., Venkatraman, M and Walker, I. 2024. The Costs of Decarbonizing Multifamily Buildings in DACs and Rural Areas. Proc ACEEE Summer Study 2024. ACEEE, Washington, DC. doi.org/10.20357/B7DP43

vi. Strategic Goal: Transportation Electrification, Distributed Energy Resource Integration, Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: Integrating the new EV loads for transportation into homes without introducing high infrastructure costs is essential. Similarly, current infrastructure and BAU will not support widespread DER. This concept aims to reduce the infrastructure barriers to DER. New electric loads for heating, hot water, clothes drying, etc. currently require costly new home and grid infrastructure - and those costs are a significant barrier to rising residential electrical demand. This work plans to reduce or eliminate the need for all this new infrastructure, saving billions of dollars and many years of time in meeting the state's energy goals.

viii. Contributors to This Concept Include: Iain Walker and Brennan Less

11. California-Specific Electricity Demand Forecasting Platform

i. Description: The rapid uptake of electric equipment (e.g., heat pump water heating and space conditioning, induction cooking), electric vehicles, and network-connected equipment will lead to residential electricity demand that will diverge from previous historical trends and will vary by region within California. We propose the use of EPIC funds for investigating the development of a bottom-up, forecasting platform that integrates equipment-stock turnover, economic modeling of equipment purchasing decisions, technology-diffusion models, and high-resolution end-use load shapes to project future electricity demand at a highly granular, neighborhood or feeder level. Such forecasts can provide detailed snapshots of anticipated load growth by end use at regional scales over the next 10-15 years (the typical lifetime of many large, energy-intensive equipment items) in different scenarios. By integrating projections with feeder locations, the assessment will enable utilities to identify emerging capacity constraints, effectively plan for growing grid capacity, and identify opportunities to promote cost saving equipment upgrades in regions with slower adoption of energy-efficient technologies. EPIC funding is essential in developing this California-specific forecasting platform, providing utilities with clearer predictability in preparing for future residential load growth and providing benefits to ratepayers.

ii. Breakthroughs: This concept represents a significant technological advancement by combining multiple, disparate data sources into a unified, California-specific forecasting platform that produces the detailed load projections by end use that utilities and decision makers need to meet the State's energy goals. This tool directly overcomes the critical barrier of grid planning uncertainty in an era of rapidly changing energy landscape. By producing feeder-level forecasts, the tool will identify electric-load growth from heat pumps, EVs, and other emerging end-uses by region, and how each end use affects peak demand and capacity requirements. These forecasts will lower the risk of over- or under-investing in grid infrastructure, ensuring that limited resources are allocated efficiently and proactively. Regional forecasts will also identify neighborhoods with aging, inefficient equipment, enabling utilities to target efficiency incentives that will provide consumer savings and load reduction on the grid. Beneficiaries of this concept include (1) state agencies that will have access to improved projections of adoption by end use (2) utilities that will be able to forecast necessary grid capacity at the feeder-level, and (3) California ratepayers that will benefit from targeted efficiency incentive programs that will reduce homeowner electricity bills.

iii. Outcomes: At scale, the forecasts from the platform will identify how much each end-use contributes to feeder-level peaks and it will identify neighborhoods that offer the greatest opportunity to replace aging equipment with high-efficiency alternatives. These granular results will allow utilities to right-size future investments, avoiding stranded or undersized assets, while region-specific peak forecasts enhance grid reliability. The platform will help promote incentives to communities with aging equipment, enabling accessible adoption of high-efficiency technologies and delivering a more reliable grid for all Californians.

iv. Metrics: The impacts of the proposed research will be evaluated using both quantitative and qualitative metrics.

Quantitatively, the platform can be used to project various scenarios using different assumptions for end use load growth to calculate the economic and environmental benefits (e.g., avoided infrastructure costs and emissions reductions) relative to a business as usual case. A primary indicator of success will be the accuracy of our feeder-level forecasts compared against current/historical data from utilities. Additionally, tracking uptake of incentives geographically will provide a quantitative metric of performance for the incentives offered.

Qualitatively, the platform's value could be assessed through stakeholder feedback from utility grid planners and state agencies on its perceived value in their infrastructure planning and investment decision-making processes.

v. References:

1. CEC 2022 Integrated Energy Policy Report (IEPR): The 2022 CEC IEPR highlights that projected electricity demand in California is highly sensitive to the rate of building and transportation electrification, and that "current forecasting methods lack sufficient spatial and temporal resolution to inform distribution system planning and targeted decarbonization efforts." https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report-iepr/2022-integrated-energy-policy-report

2. Love, J. et al., The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial. Applied Energy. 204 (2017) 332-342: This peer-reviewed article models grid impacts from heat pump adoption using load profiles derived from field-metering data. Demonstrates the ability to estimate grid impacts using a bottom-up approach. https://discovery.ucl.ac.uk/id/eprint/1566603/1/heat%20pump%20load%20profiles%20paper.pdf

3. 2019 Residential Appliance Saturation Survey (RASS): The 2019 RASS is a detailed survey of California household appliance stock that serves as the starting point for understanding regional differences in end uses. https://www.energy.ca.gov/data-reports/surveys/2019-residential-appliance-saturation-study

vi. Strategic Goal: Building Decarbonization, Climate Adaptation, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: Focusing consumer incentives on the basis of equipment age and efficiency will facilitate the adoption of technologies supporting California's building-sector emission reductions goals. End-use forecasts will allow for increased predictability of loads at regional scales and will provide the ability to model peak loads under extreme conditions (e.g., extended heat waves), directly supporting weather and grid resilience efforts. Tracking regional adoption rates will provide much needed granular information on whether CA's goals are being achieved evenly across the State and the end uses to target for future emission reductions efforts. This also addresses the strategic objective D - Reducing cost of whole-home electrification.

viii. Contributors to This Concept Include: Mo Ganeshalingam, Tom Burke, Sanaee Iyama, Colleen Kantner, Scott Young

E. Innovative Approaches for Difficult-to-Decarbonize Sectors

1. Energy, Environmental, and Economic Pathways for the California Maritime Sector

   i. Description: -California's maritime sector faces overlapping challenges in its efforts to reduce emissions: high upfront capital costs for maritime vessel energy technologies and shore power infrastructure, fragmented industry structures that complicate coordination across ports, utilities, and vessel operators, and sunk costs associated with long-lived, conventionally powered ships that are expensive to retrofit. The proposed research concept aims to address the long-term energy, environmental, and economic challenges facing California's maritime sector. The study will evaluate the impacts of emerging technological options—including advanced fuels, electric and hybrid vessels—on emissions, energy use, and costs. Building on LBNL's Maritime Battery Electrification Simulator (MariBES), we will expand the tool's capabilities to assess a broader range of technologies. This will involve integrating ship-level geocoded Automatic Identification System (AIS) data with vessel engineering specifications to track emissions and operational profiles across different vessel types.

      One key focus is to support California's goal to reduce emissions from ocean-going vessels while they are docked at California ports. Technical barriers to reduce emissions are compounded by uncertainty around future shore power (Cold Ironing or Alternative Maritime Power (AMP)) demand, making it difficult for ports and utilities to plan investments efficiently. Without accurate shore power demand forecasting, infrastructure may be over- or under-built, leading to stranded assets, higher costs to ratepayers, and missed emission reduction opportunities. The proposed research will include forecasting AMP demand, which allows vessels to plug into onshore electricity sources while docked, significantly reducing emissions and fuel consumption. As regulatory pressures and operator interest in AMP grow internationally, ports face increasing difficulty in reliably planning infrastructure to meet future demand. This research will provide insights to help California reduce emissions from shipping and ports, while identifying new economic and business opportunities in upgrading the maritime fleet. This modeling and lifecycle analysis will inform follow-on phases focused on the design, development, and demonstration of low emission vessels, in collaboration with industry, academia, and public-sector partners.

ii. Breakthroughs: This research addresses key technical and market barriers preventing widespread adoption of maritime technologies with enhanced energy and environmental quality performance features. Specifically:

   a. Lack of granular, vessel-specific emissions data across a variety of ship classes and routes hinders accurate planning of infrastructure like shore power (AMP).
   b. Insufficient modeling tools to evaluate performance tradeoffs between emerging technologies (e.g., hybrid-electric systems, advanced fuels) hinders technology investments.
   c. Limited forecasting capacity for AMP demand, especially under future policy and operational scenarios, hinders investment in appropriate landside infrastructure and leads to unnecessary emissions and higher costs for ratepayers. Port authorities face uncertainty in prioritizing infrastructure investments, particularly AMP systems, without predictive insights into vessel behavior and energy demand. Vessel operators are hesitant to invest in advanced technologies without reliable cost-benefit data under real-world operational conditions. By expanding LBNL's simulation tool, MariBES, to integrate geocoded AIS data and including additional non-battery technologies and engineering parameters, this research will enable accurate tracking of emissions, fuel use, and shore power potential by vessel type, fill data and modeling gaps critical to shore power investment decisions and long-term energy mix optimization strategies, and support achievement of California's goals by helping reduce port and maritime emissions.

iii. Outcomes: This project will help reduce ratepayer and infrastructure costs by enabling more accurate sizing of shore power infrastructure, avoiding stranded assets and minimizing overbuild, improve system performance by identifying optimal technology mixes (e.g., hybrid vs. battery-electric) tailored to vessel profiles, accelerate advanced technology adoption in ports and vessels by clarifying long-term benefits, operational feasibility, and emissions reduction, and enhance planning and coordination across port, utility, and policy stakeholders through shared data and scenarios. Air pollutant emission reduction will improve local air quality, leading to improved regional health outcomes and ultimately resulting in improved quality of life for nearby residents. The tools and methods will be designed to be replicated across California's major ports, and eventually inform national and international maritime stakeholders.

   If the research leads to a pilot project of electric push boats and electric barges for inland waterway shipping along routes connecting Oakland, Sacramento, and Stockton, these vessels could reduce traffic on key corridors such as I-5, I-580, and Highway 99 by shifting bulk freight to inland waterways, while delivering quieter and safer logistics through communities disproportionately affected by air pollution and heavy truck traffic.

iv. Metrics: Quantitative metrics include number of vessels, vessel types and operational profiles modeled; estimated energy demand by technology and ship types; emission and pollutant reductions; predicted AMP load (MW) by port and time period, required/avoided infrastructure costs (e.g., cost per kW of AMP capacity), life cycle costs comparing conventional and advanced technology cases. These results could be validated through a pilot project. Additional indicators will assess how well the research informs decision-making for infrastructure planning, and technology and policy development.

v. References:

a. Hee Seung Moon, Won Young Park, Thomas P Hendrickson, Amol A Phadke, Natalie Popovich. 2024. Exploring the cost and emissions impacts, feasibility and scalability of battery electric ships. Nature Energy, volume 10, pages41–54 (2025). https://www.nature.com/articles/s41560-024-01655-y

b. David Wooley, Elizabeth Larsen, and Michihiro Horakawa. 2024. Policy Options to Decarbonize Ocean-Going Vessels. https://gspp.berkeley.edu/assets/uploads/page/Policy_Options_to_Decarbonize_Ocean-Going_Vessels_REPORT_Final.pdf

c. U.S. Department of Energy. Port Electrification Handbook. Prepared by Pacific Northwest National Laboratory. https://www.pnnl.gov/sites/default/files/media/file/Port_Electrification_Handbook_FINAL.pdf

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Transportation Electrification

vii. Support for Goal: This concept supports two of the Strategic Goals. By improving forecasting accuracy for AMP demand and providing comprehensive data on performance tradeoffs of alternative technologies for individual vessels, this project will reduce investment risk in electric marine transport. Similarly, more accurate assessments of shore power demand resulting from this project will help ports and other stakeholders invest in infrastructure needed to support both maritime vessels that deploy the related advanced technologies and the associated port-side equipment they would use.

viii. Contributors to This Concept Include: Won Young Park, Natalie Popovich

2. Enhanced Indoor Air Quality and Energy Management
   i. Description: Actively controlling CO2 levels in indoor environments through direct air capture (DAC) modules retrofitted with building HVAC systems offer dual benefits of energy savings and carbon management. By scrubbing CO2 from indoor air–where CO2 concentrations typically range between 600-1000 ppm–rather than ambient air at around 420 ppm, building-integrated DAC has shown to reduce HVAC energy demand by 30-60% while benefiting from thermodynamic advantage, and existing air circulation infrastructure such as fans and ducts that standalone DAC units lack. Realizing these benefits also need to consider other safety requirements such as airborne pathogens that could considerably increase HVAC-related energy demand. Germicidal UV lights (GUV) have been demonstrated to effectively inactivate airborne pathogens, including viruses, bacteria, and fungi, while using up to 90% less energy than equivalent ventilation-based strategies, yet this UV-based strategy may result in accumulating CO2, possibly beyond safety limits, if ventilation is limited.

      Thus, we propose that CEC invest in developing integrated DAC and GUV solutions as well as a testbed to accelerate its development and demonstration. The proposed solution can be retrofitted with existing building HVAC systems to take advantage of triple benefits of affordable carbon management, reduced energy demand, and improved public health. This integrated solution would feature 1) compact, fully electrified DAC and GUV modules designed for seamless integration into air handling units, 2) AI-optimized advanced control system, and 3) a testbed to evaluate the developed system in multiple realistic scenarios. Multiple combinations of DAC technologies–based on material types and regeneration configurations–and GUV systems can be investigated for their performance and compatibility with indoor air control systems. The AI-optimized control system can dynamically balance air circulation, CO2 capture, and pathogen disinfection to meet multiple energy targets with limited user interventions. The testbed can leverage state-of-the-art capabilities such as FLEXLAB® or DAC modules in LBNL to help assess a multitude of building operation scenarios as well as technology configurations.

      The outcome will include a technology solution that can be retrofitted with existing buildings and public infrastructure in California–such as offices, gyms, and Bart stations–as well as a testbed to evaluate its performance in realistic conditions. This research can accelerate California's progress towards its energy goals.

ii. Breakthroughs: The proposed program will develop a breakthrough distributed carbon capture retrofit solution for existing infrastructure that delivers dual benefits of energy savings and public health improvements. This program aims to efficiently promote the development of this concept by supporting synergistic hardware integration of two emerging technologies, advancing AI-driven control systems that can adapt autonomously to California's varied indoor environments, and developing a testbed to de-risk the development and provide a robust evaluation platform.

    This program will unlock the untapped carbon capture potentials in existing infrastructure while simultaneously reducing energy and improving public health. While key technologies are separately demonstrated at small-scales, this integrated approach requires support at all levels to move forward. A formal program led by California will send a strong market signal, reduce investment uncertainty and ambiguity. Establishment of a testbed can help reduce complexity of the system and provide a reliable assessment baseline to de-risk technology. Delivering these breakthroughs requires coordinated collaboration amongst parties from disparate expertise and motivations, and a well-defined framework to guide the efforts.

iii. Outcomes: If successful, this program will deliver substantial benefits that accelerate California's progress toward its goals. This program will generate a new retrofit-ready technology platform that supports California's priorities. This technology will be designed to be adaptable to California's widespread building types, indoor environment, and operation needs. The modular hardware can scale across a wide range of air-treatment volumes, while AI-driven controls autonomously optimize energy use, CO_2 removal, and air-quality targets with minimal operator intervention and robust system reliability. A dedicated testbed—leveraging facilities like FLEXLAB and LBNL's DAC rigs—will validate performance under realistic scenarios, de-risking commercial deployment by proving energy savings, carbon capture efficiency, and public-health outcomes.

iv. Metrics: Impacts of this proposed concept can be evaluated using both quantitative and qualitative metrics. Quantitative metrics can include net energy savings in buildings compared to conventional HVAC and their potential ranges considering varied weather pattern scenarios. Environmental impacts can be quantified based on tonnes of CO_2 captured in buildings on an annual basis as well as lifecycle emissions reductions. For public health, log-scale reductions in aerosolized pathogens or decrease in occupant sick-leave days can be estimated. The economics of this strategy can be measured based on payback period and net present value, accounting for both CAPEX and OPEX. The efficiency of the AI-optimized control algorithm can be evaluated against state-of-the-art HVAC control strategies, based on net improvements the new algorithm can yield in terms of energy savings, carbon capture, and improvements in public health. These metrics can be estimated at varying scales-by building types, or at city or county levels, or across California.

v. References:

a. https://doi.org/10.1038/s44296-025-00056-w
b. https://www.energy.gov/sites/default/files/2023-05/bto-peer-2023-32106-guv-disinfection-pnnl-arnold.pdf#:~:text=•%20Using%20increased%20ventilation%20to,Measures%20to%20reduce%20airborne%20disease
c. https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2024.1443974/full
d. https://www.pnnl.gov/publications/pnnl-researchers-advance-germicidal-ultraviolet-technologies#:~:text=Their%20goal%20is%20to%20characterize,of%20disease%20in%20their%20facilities

vi. Strategic Goal: Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Climate Adaptation

vii. Support for Goal: Supporting California's ambitious climate targets require exploring innovative solutions that can expand affordable technology portfolios. Innovative approaches of integrating DAC and GUV with existing HVAC systems through AI-optimized control algorithms have shown great potential and key technologies have been already demonstrated. But proofing this concept and scaling requires a coordinated program. Successful implementation of this project will provide additional technology options that California can adapt today that are closely aligned with its energy and climate goals. The captured CO_2 can directly support building decarbonization and help California achieve net zero climate targets.

viii. Contributors to This Concept Include: Tae Hwan Lim, Donghun Kim

3. Strategic Energy Management Practices to Achieve Sustained Improvements in Energy Performance
    i. Description: Strategic Energy Management (SEM) is a proven business practice used by commercial and industrial sites to achieve sustained improvements in energy performance. The U.S. Department of Energy's 50001 Ready program provides a no-cost SEM framework based on the ISO 50001 standard, helping organizations establish a long-term pipeline of capital and operational energy improvements. Manufacturing sites that implement ISO 50001 have been shown to achieve nearly four times the average first-year energy savings and sustain more than 3% reductions in energy consumption annually over a decade with simple payback of less than two years. In California, investor-owned utilities and Marin Clean Energy have successfully deployed SEM programs with strong results—PG&E's program earned a CPUC-verified Total Resource Cost of 5.03. However, these efforts have not yet been fully leveraged to support facility-level emissions reduction planning. More than half of participants in DOE's national commercial and industrial 50001 Ready training already use the framework to support emissions reduction. EPIC funds are needed to develop California-specific 50001 Ready guidance and training materials that reflect state policy goals, targets, and compliance pathways. This would enable businesses to use the SEM foundation to identify actionable emissions reduction pathways, define implementation steps, and maintain progress over time. By aligning with ISO 50001, this approach supports scalable, voluntary consensus standards-based emissions reductions across sectors and regions. It empowers California businesses to meet the state's energy goals while maintaining economic competitiveness.
    ii. Breakthroughs: The proposed concept addresses a key barrier to meeting California's goals: the lack of standardized, facility-level emissions reduction planning tools tailored to state policies. By developing California-specific 50001 Ready-based guidance and training, this effort helps commercial and industrial sites identify actionable emissions reduction pathways and sustain progress over time. It translates energy and emissions data into structured plans that support technology adoption, compliance, and financing. End users—including facility managers and consultants—gain tools to align operations with California's energy goals. Building on existing SEM success, this approach enables scalable, cost-effective emissions reduction across sectors with demonstrated energy savings and ROI.

iii. Outcomes: This concept will enable California businesses to develop standardized, actionable emissions reduction plans while improving operational efficiency. Facilities using the 50001 Ready-based framework are expected to achieve sustained annual energy savings of over 3%, reducing technology and implementation costs through better project planning and integration. At scale, this approach supports broad adoption of advanced energy technologies by aligning emissions reduction with business processes and state energy goals. The framework supports access to emissions reduction tools for small businesses across the state which are typically not eligible for ratepayer SEM programs.

iv. Metrics: Impacts of the proposed research concept will be evaluated using both quantitative and qualitative metrics, including uptake and use of the developed guidance and training materials, number and variety of stakeholders engaged, and the success of pilot implementations. Additional indicators may include the level of emissions reduction planning achieved by participating companies, the extent to which participants report increased ability to pursue emissions reduction actions, and integration of the materials into existing technical assistance or compliance pathways. Qualitative feedback from industry stakeholders regarding usability, relevance, and perceived value will also be collected to assess broader impacts on accessibility, scalability, and market adoption.

v. References:

a. https://eta-publications.lbl.gov/sites/default/files/strategic_energy_management_program_persistence_and_cost_effectiveness_p_therkelsen_0.pdf

b. https://pda.energydataweb.com/api/view/2572/GroupD-D11.03-SEM%202018-19%20Impact%20Evaluation.pdf

c. https://www.sciencedirect.com/science/article/pii/S2213138823002734

d. https://www.mdpi.com/1996-1073/16/14/5441

vi. Strategic Goal: Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: This project supports the CEC's goals by enabling California businesses to develop actionable, facility-level emissions reduction plans aligned with state policy. Using the proven 50001 Ready framework, it will deliver California-specific guidance and training that help companies identify emissions reduction pathways across multiple modalities. Pilot implementations will demonstrate replicable models across sectors. The project also promotes accessibility by equipping small businesses with low-cost planning tools. By increasing organizational readiness and aligning actions with policy goals, this effort supports scalable emissions reductions, energy investment, and long-term contributions to state goals.

viii. Contributors to This Concept Include: Peter Therkelsen, Rory Schmick

4. Achieving Best-in-Class Grid Responsive Commercial Building Performance

   i. Description: Despite ongoing investments in building upgrades, California's commercial sector continues to face a persistent gap between expected and realized energy savings, often due to inconsistent operational practices, outdated controls, and a lack of actionable performance data. An aggregated annual energy savings of 29% is estimated in the commercial sector alone through the implementation of efficiency measures using current state-of-the-art sensors and controls to retune buildings. Existing Building Commissioning (EBCx) and Monitoring-Based Commissioning (MBCx) are proven processes for systematically improving building operations, especially through the adoption of Energy Management and Information Systems (EMIS) data analytics tools. Certain advanced analytics platforms can even self-correct operational faults, accelerating the realization of benefits. EBCx alone can save between 6 percent, and EMIS users report median annual cost savings of $0.19/sqft, or about 9 percent, with savings increasing over time. Yet, the full benefits of these approaches are often limited by unclear performance targets, challenges integrating with legacy systems, and a workforce that is not fully equipped to implement or sustain high-performance strategies. Further, building performance analytics tools (e.g., Fault Detection & Diagnostic software) have been proven effective but are still limited in their ability to diagnose root cause for all fault types, requiring manual effort to investigate and resolve faults which can be overwhelming when a building's HVAC system can experience 245 operational faults per month.

      In parallel with performance improvement processes such as EBCx and MBCx, ASHRAE Guideline 36 (G36) sets a new standard for high-efficiency control sequences, providing a clear operational benchmark for HVAC systems. Field demonstrations have shown that updating to optimized, G36-based control sequences can yield 11–35 percent electricity savings, with simple paybacks ranging from 2 to 8 years depending on whether it's a software-based retrofit or a full upgrade of the controls. However, adoption of advanced control strategies like G36 remains slow, hampered by uncertainties around implementation, integration with existing systems, and workforce readiness. Field demonstrations are valuable but difficult to scale, and practical guidance for applying G36 in a wide variety of building contexts is lacking. Beyond energy savings, these advanced control strategies also unlock significant demand response (DR) potential, enabling buildings to dynamically reduce or shift loads during grid stress events. In fact, recent studies suggest that G36 sequences can achieve higher peak load reductions than traditional controls—about 3 W/m^2 during pre-cooled shed events.

California was a leader in establishing EBCx processes and utility program approaches in the early 2000s, with the Energy Commission at the heart of these efforts, but achieving widescale adoption has stalled over the past decade due to both market and technical barriers. Maturity of EMIS analytical tools and the emergence of G36 can provide a robust foundation from which to reorient efforts in a way that is compelling and scalable. The Energy Commission has funded prior work in support of G36 adoption, and the outcomes of that work identified a number of follow up recommendations that align with this concept proposal. While Guideline 36 will be part of 2026 Title 24, a multi-faceted effort is needed to translate those benefits to the billions of square feet of existing commercial building stock.

We propose that EPIC invest in a comprehensive initiative to close the commercial building performance gap by integrating best-in-class commissioning processes (EBCx/MBCx), modern EMIS tools, and high-performance operational targets such as G36. This initiative will embrace an “outcome-based commissioning” approach, in which traditional EBCx/MBCx processes retain their proven steps but are oriented toward achieving specific, measurable performance outcomes rather than simply improving on a building’s baseline. In practice, this means setting and sustaining targets—such as maintaining an EUI below a defined threshold, so that performance is both verifiable and persistent.

This project will develop actionable guidance, readiness assessment tools, and training resources to help building owners, operators, and service providers implement advanced control sequences, optimize existing systems, and sustain high performance over time. Activities will include targeted field pilots, simulation studies, stakeholder engagement, and the creation of practical toolkits and case studies tailored to both new and existing buildings.

By generating independent validation, practical implementation resources, and scalable frameworks for performance persistence, this initiative will accelerate market adoption, reduce operational risk, and maximize the long-term value of energy investments across California's commercial building stock. EPIC funding is essential to provide the applied research, demonstration, and workforce development needed to bridge persistent gaps between technology, operations, and outcomes—ensuring that all commercial buildings can reliably achieve and sustain best-in-class performance, and be responsive to grid constraints.

ii. Breakthroughs: This initiative will accelerate adoption of advanced commercial building operations by integrating EBCx/MBCx, EMIS, and high-efficiency control sequences (e.g., ASHRAE G36). These elements will close the persistent gap between expected and realized savings.

a. Barriers Addressed
    1. Unclear operational benchmarks - Provide G36-based targets and toolkits for new and legacy systems.
    2. Integration challenges with legacy BAS/BMS - Develop readiness assessments, integration guides, and case studies.
    3. Limited workforce capacity - Deliver training and hands-on field modules for operators and service providers.

b. Technological Advancement
    1. Closed-loop EMIS + G36: Enables persistent energy savings through automated diagnostics and optimization.
    2. Scalable commissioning framework: Standardized targets and workflows reduce the cost and complexity of ongoing MBCx.
    3. Generate real-world benchmarks and integration guidance to de-risk adoption.
    4. Benefits owners, operators, utilities, and stakeholders by unlocking persistent, verifiable savings that support SB 96.

EPIC support is essential to bridge the gap between available technologies and commercial development, enabling California's existing commercial buildings to reliably achieve and sustain high-performance operation.

iii. Outcomes: If successful, this initiative will transform commercial building operations in California by making high-performance, low-cost energy savings scalable and persistent.

a. Cost and Performance Gains
    1. Demonstrate a replicable pathway for commercial buildings across the state to adopt advanced control sequences and ongoing MBCx practices, with the potential to achieve 11-35% HVAC energy savings in pilot buildings with 2-8-year simple paybacks, reducing ratepayer energy costs.
    2. Enable long-term savings persistence through EMIS-enabled monitoring and G36-based automated diagnostics, minimizing costly re-commissioning cycles.
    3. Reduce capital costs by optimizing existing BAS/BMS infrastructure rather than requiring full system replacement.
    4. Market and Technology Potential at Scale
    5. Equip the California workforce with new skills in EMIS, G36 controls, and data-driven commissioning, addressing a critical market bottleneck to broad adoption.
    6. Create toolkits, benchmarks, and case studies that utilities and service providers can directly integrate into incentive and emissions reduction programs.

b. Ratepayer and Societal Benefits
    1. Affordability: Reduce operating costs for all commercial customers, including medium-sized commercial properties, Class B commercial offices, etc.
    2. Reliability and Safety: Provide visibility into building performance, identify operational faults that can prevent outages or equipment failures, and incorporate demand flexibility control sequence enhancements into core EBCx/MBCx practices.
    3. Accessibility: Focus outreach and training on smaller portfolio owners and service providers, when needed. Therefore improving access to high-performance solutions across all communities.

c. Broader Market Transformation
    1. Establish a data-driven foundation for statewide adoption of advanced operational targets, accelerating emissions reduction in buildings without waiting for full capital retrofits.
    2. Position California's commercial building sector as a national model for integrating EMIS, commissioning, and high-efficiency sequences into mainstream practice.

iv. Metrics:

a. Number of utility incentive programs incorporating EBCx/MBCx or G36 design elements, and number of buildings enrolled in those programs.

b. Number of success stories published, as examples of outcome-based commissioning.
c. Stakeholder engagement metrics, e.g., enrollees in related training, number of downloads of published guidance documents, etc.
d. Estimates of market penetration and overall market potential for commissioned buildings meeting G36 criteria

v. References:

a. EBCx alone can save ~6 percent in some cases, with EMIS users reporting median annual cost savings of $0.19/sqft, or about 9 percent, with savings increasing over time.
"Building analytics and monitoring-based commissioning: industry practice, costs, and savings"
https://betterbuildingssolutioncenter.energy.gov/sites/default/files/building_analytics_-_kramer.pdf
https://eta-publications.lbl.gov/sites/default/files/crowe_-_building_commissioning_costs_and_savings_.pdf
b. G36-based control sequences can yield 11–35 percent electricity savings, with simple paybacks ranging from 2 to 8 years depending on whether it's a software-based retrofit or a full controls upgrade
"Demonstrating Scalable Operational Efficiency Through Optimized Controls Sequences and Plug-and-Play Solutions" CEC Study
Average building experiences 245 faults per month
"Empirical Analysis of the Prevalence of HVAC Faults in Commercial Buildings":
https://eta-publications.lbl.gov/sites/default/files/empirical_analysis_of_the_prevalence_.pdf
c. G36 sequences can achieve higher peak load reductions than traditional controls—about 3 W/m²
Analyzing The Impact Of Energy Efficient ASHRAE Guideline 36 Control Sequences On Demand Flexibility Potential Of Commercial Buildings: A Multi-Region Analysis:
https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160817328_e1f8c12a-8395-4cb6-8db5-aeaf48749caa.pdf

vi. Strategic Goal: Building Decarbonization

vii. Support for Goal: This initiative supports CEC's building decarbonization goals by closing the persistent commercial building performance gap and enabling outcome-based commissioning that delivers verifiable energy and peak demand savings. By integrating EBCx/MBCx processes with EMIS analytics and G36 high-performance control sequences, the project will unlock persistent efficiency, enable flexible load management, and reduce coincident peak demand across California's commercial building stock. In addition to these direct emissions reduction outcomes, optimized building operations magnifies the impact of other decarbonization efforts, for example: [1] it enables electrification retrofits to be right-sized based on data-driven analytics (as opposed to replacing over-sized existing equipment with over-sized electrified equipment); [2] Data-driven analytics ensures that any electrification retrofits are performing as intended and that performance is maintained long term; [3] The monitoring underpinning EBCx/MBCx allows for better integration of distributed energy resources to maximize their benefits. Additionally, with respect to CEC objectives, the following benefits are expected:

a. Smart Systemwide Planning Tools for New Load: Field-validated performance and load shape data from outcome-based commissioning will improve forecasting of commercial building load flexibility, supporting utility capital planning and reducing the need for costly grid upgrades.
b. Providing Data Input into a Value of DER Framework: By producing actionable guidance, practical toolkits, and replicable demonstration results, this project will accelerate cost-effective, scalable decarbonization and flexible load adoption in the commercial sector, directly supporting EPIC-5 goals to lower grid costs, reduce emissions, and maximize ratepayer benefits.

viii. Contributors to This Concept Include: Eliot Crowe and Jessica Granderson

5. Statewide Initiative to Assess Plant-level Electricity Utilization Potential Across a Variety of Manufacturing Facilities

i. Description: In the West Census region's manufacturing sector, including California, nearly 40% of final energy demand is estimated to go toward process heat. The ability to shift towards utilization of electricity in this sector presents a transformative opportunity: electric heating technologies such as electric arc and resistance heating, electromagnetic heating (e.g., induction, radiofrequency, microwave, infrared), high-temperature heat pumps, and hydrogen can more than double process efficiency by delivering heat precisely where and when needed, minimizing energy losses. These technologies can significantly reduce energy demand, increase production speed, lower operating costs, and enable the production of goods, enhancing the competitiveness of both the California and the broader U.S. manufacturing base.

Despite this potential, industrial utilization of electricity for heating applications remains quite low. A key barrier is the limited understanding of how specific technologies apply at the unit operation level and which are best suited for different industrial contexts. To address this, we propose that the CEC, through the EPIC program, fund a statewide initiative to assess plant-level electricity utilization potential across a variety of manufacturing facilities. At least one facility from each major hard-to-abate industrial subsector in California should be surveyed. These assessments should be paired with evaluations of onsite generation feasibility, such as solar PV, solar thermal, and energy storage, to enable electricity utilization pathways.

The initiative would also include techno-economic analyses of electric heating technologies for each facility, evaluating performance, cost-competitiveness, infrastructure compatibility, environmental quality, and adoption barriers. This work will also leverage a lab-funded effort that maps energy and thermodynamic requirements for energy-intensive processes at the unit operation level, critical for aligning technologies with actual process needs. EPIC support is essential to guide technology development, accelerate market deployment, and inform strategic grid planning, especially given rising electric demand from sectors such as data centers and EVs.

ii. Breakthroughs: The proposed initiative directly addresses the technical and market barriers hindering industrial end-users from selecting electricity as a fuel source, unlocking critical opportunities to meet California's goals. Nationally, about 50% of manufacturing energy goes to process heating, yet only 5% of that heat comes from electricity. In the Western region, including California, industrial process heat accounts for roughly 40% of final energy use.

High electricity prices, averaging approximately six times the cost of natural gas in California, have historically made electric heating uneconomical. The proposed concept seeks to overcome that challenge by identifying where high efficiency electric heating can offset these cost disparities. By mapping process specific needs, it will highlight where electric or hybrid technologies (e.g., including hydrogen) can deliver required performance at competitive lifecycle costs, and explore cost levels necessary for achieving broader adoption.

Additionally, many industrial processes require high temperatures or specialized heat profiles, with few viable electric alternatives historically available. The variety of unit operations (e.g., drying, melting, distillation) adds complexity, as each demands tailored solutions. A major barrier is the lack of awareness and trusted data, and many plant managers are uncertain which electric technologies exist or how they would integrate with their processes. The proposed work fills that gap through unit operation level assessments to determine the best fit electrical technologies, such as induction, microwave, and high temperature heat pumps, for each application. By surveying representative facilities across hard-to-abate sectors (food processing, refining, pulp and paper), the project will develop case studies and best practices covering feasible electrical energy options, performance metrics (e.g., temperature, COP, production rate), and retrofit requirements.

Moreover, infrastructure limitations, such as inadequate electrical capacity at older plants or long grid upgrade timelines, also pose barriers. The project will quantify expected facility-level load increases and assess self generation potential, providing utilities and decision makers with the data needed for timely infrastructure planning and addressing the perception of limited electricity supply.

Ultimately, this initiative provides critical data, tools, and roadmaps that break the technical status quo and empower industry to optimize its energy mix. It offers actionable insights to guide technology development and deployment, enabling electrical end uses without compromising performance.

iii. Outcomes: If this research concept succeeds, even partially, it will generate valuable outcomes that enhance the value proposition of electric heating technologies and deliver broad benefits to ratepayers. Expected outcomes include lower energy costs, improved efficiency and performance, emissions reductions, environmental and health benefits, and economic development.

By demonstrating process specific electrical solutions, some of which can more than double energy efficiency, the project enables significant industrial cost savings. Technologies like resistive or induction heaters offer near 100% thermal efficiency and precise control, allowing manufacturers to use less energy to produce the same output. These efficiency gains directly reduce utility bills and help ratepayers by avoiding unnecessary energy generation and costly grid upgrades.

Electricity also provides flexibility for load management. In general, electric process heating systems can be rapidly ramped up or down, allowing facilities to shift energy use to periods of low electricity prices. This not only reduces operating costs but also supports grid reliability, as factories can act as flexible loads or rely on stored heat during peak demand.

As these technologies mature and costs fall, the benefits to ratepayers expand further through lower rates from reduced energy consumption and avoided emissions costs. Ensuring performance parity among heating fuel sources is a key project outcome. Many electric technologies offer faster response times, finer control, and improved product quality. Documenting these gains through real-world assessments will shift industry perception, positioning electricity as a productivity and economic upgrade rather than a risk.

Shorter heat up times, more uniform heating, and reduced defect rates can lead to increased profitability. Electric systems also enhance safety and reliability by eliminating combustion related hazards such as open flames or gas leaks, reducing downtime and creating safer working conditions, supporting EPIC's guiding principles of safety and reliability.

Moreover, California's industrial sector contributes roughly 20% of statewide emissions. The proposed assessments and resulting technology deployments could chart a path toward eliminating a significant share of these emissions by 2050 and beyond. Additionally, ratepayers benefit from improved air quality and public health, especially in communities near industrial facilities. Electrical processes can exhibit lower onsite emission compared to other energy sources, aligning with EPIC's focus on environmental quality and access.

Over time, scaling up electric industrial heating technologies, such as heat pumps and advanced electric furnaces, can drive down costs through economies of scale and learning by doing, much like solar PV and batteries. This innovation supports EPIC's core goals of affordability through efficiency improvements and cost reductions, reliability via flexible demand and on site resources, safety by eliminating combustion risks, major emissions reductions, and by improving air quality and supporting job creation.

iv. Metrics: To rigorously evaluate the impacts of the proposed research, we will define both quantitative metrics and qualitative indicators of success. These will track progress throughout the project and measure outcomes against our objectives across three main categories: 1) energy and emissions, 2) economic, and 3) adoption and market indicators.

For each surveyed facility and sector, we will quantify potential energy savings and emissions reductions from electrical solutions to end uses. A key metric is the reduction in energy use (in joules) from adopting recommended electric technologies, along with the associated emissions reductions. Aggregating across all case studies will provide an estimate of total emissions reduction potential.

Economic viability will be assessed through the Levelized Cost of Heat (LCOH), measured in dollars per joule of useful heat, comparing electrified systems to incumbent technologies. A successful outcome is demonstrated when electric technologies achieve an equal or lower LCOH in multiple scenarios. Performance metrics include the system's efficiency (COP or thermal efficiency), its impact on production throughput (e.g., tonnes per hour), and, when available, product quality metrics such as yield. These indicators ensure that electrified systems maintain or improve operational and economic performance.

Since this is a research and assessment concept, a critical measure of success is how findings drive real-world action. Qualitative indicators include stakeholder engagement and intent to adopt. For example, the number of facilities moving forward with pilot projects or seeking funding reflects the project's influence. We will also track industry interest (e.g. requests for case study results) and policy uptake (e.g. references in CEC or utility plans and documents). Coverage of industrial subsectors is another key indicator. We aim to survey at least one representative facility in each major hard-to-abate subsector relevant for California, providing a broad and actionable dataset.

As the project also addresses on-site generation and grid planning, we will quantify DER integration potential. Metrics include the share of electric load that could be met by onsite generation and the change in peak demand before and after applying load management strategies.

Together, these metrics will provide a comprehensive evaluation of the project's success in terms of energy savings, cost effectiveness, emissions reductions, and progress toward California's energy goals. Regular reporting on these indicators will help ensure the research delivers practical, high impact results for ratepayers.

v. References: This research concept builds on and is supported by existing studies and data that highlight the potential of industrial electrification, cost targets, and barriers to overcome. The following literature was consulted to identify gaps, develop the concept, and outline success metrics:

a. Beyond Zero Emissions (2018). "Zero carbon industry plan: Electrifying industry." https://www.bze.org.au/research/report/electrifying-industry
b. McMillan, C. A. (2018). Electrification of Industry: Summary of Electrification Futures Study Industrial Sector Analysis (No. NREL/PR-6A20-72311). National Renewable Energy Lab (NREL), Golden, CO. https://www.osti.gov/servlets/purl/1474033
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In summary, these references provide a strong foundation for our research concept. They validate the need for targeted industrial assessments highlighting the ability to optimize energy mix among end uses, confirm the feasibility and efficiency gains of electric technologies, illuminate cost and performance benchmarks, and highlight broad stakeholder support for such innovations. We have integrated these insights into our concept to ensure it is grounded in current research and designed for high impact.

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: Our proposed concept is fundamentally aligned with California's goals related to emissions with a focus on the challenging industrial sector and the need for a coordinated approach related to incumbent practices. Reaching such goals is not possible without tackling industrial emissions, which make up a significant share of the state's most difficult to abate sectors. This project offers a clear, actionable pathway to eliminate those emissions.

By identifying opportunities across major industrial subsectors and pairing them with goal-aligned energy technologies, we envision a future where factories operate without producing significant on-site emissions. This strategy includes replacing or upgrading boilers, heaters, and production lines with systems and technologies that achieve an optimal energy mix. Our emphasis on energy efficiency, delivering the same heat with significantly less energy, helps reduce total demand, easing the load on California's energy supply and grid.

This approach directly supports the state's Scoping Plan, which prioritizes fuel mix optimization for hard-to-abate applications. By conducting detailed technical and economic analyses at a representative set of industrial facilities, we are effectively creating a roadmap for full industrial deployment of these technologies as the primary strategy to achieve the state's energy goals.

The concept also evaluates when and where industrial gas demand may persist due to technical needs, potentially served by advanced alternatives like hydrogen or other fuels which help achieve the state's environmental quality goals. Through facility-level assessments, we will identify specific sites or processes that could benefit from electrical energy and those that may require gaseous fuels in the near term.

This information is critical for system planning. New industrial loads represent increases in electricity demand, which, if uncoordinated, could strain the grid. Our analysis addresses this through load management, energy efficiency, and on-site generation strategies that align electric load growth with broader systemic considerations.

Importantly, achieving the state's goals must be achieved without displacing pollution. Our approach ensures reductions in emissions that support EPIC goals around environmental quality, air quality, and public health.

In summary, this comprehensive approach accelerates California's path to achieving its goals while supporting an integrated treatment of the wider utility sector. It directly responds to the state's call for innovative, cross-sector research to address hard-to-abate industries and aligns with the broader vision for a safe, resilient, and affordable energy future.

viii. Contributors to This Concept Include: Jibran Zuberi, Prakash Rao, Nick Karki, Hanna Breunig

6. Digital Twin Platform for Energy-Intensive Industrial Sector

i. Description: We propose developing and integrating a digital twin platform and control system, coupled with existing full-scale experimental test facilities, to accelerate the development and deployment of low-emission technologies in energy-intensive industrial sectors. This innovative approach will help lower emissions in difficult sectors by enabling industries to test, validate, and optimize solutions in a risk-free, data-driven environment, bridging the gap between laboratory operation and real-world performance. The testbed will also serve as a critical resource for identifying and demonstrating an array of potential low-emission technologies—such as alternative fuels, high-temperature thermal storage, and fuel optimized process solutions—that could replace or augment traditional combustion processes. By providing a flexible and collaborative platform for evaluating these innovations, this initiative will inform investment and adoption decisions across the industrial landscape. EPIC funding is essential to ensure broad access, foster cross-sector collaboration, and drive meaningful progress toward California's energy and emissions reduction targets.

ii. Breakthroughs: The proposed concept will accelerate emissions reductions and optimize energy mixes of energy-intensive industries by providing a flexible platform to develop, test, validate, and optimize low-emission technologies, including alternative fuels and electrically enabled processes. By reducing technical and market barriers, this approach will provide the option for broader adoption of low-emission solutions.

iii. Outcomes: If successful, this research will significantly lower the cost and risk of deploying advanced low-emission and electric technologies in energy-intensive industries, leading to reduced emissions and improved air quality. By enabling faster, more cost-effective validation and optimization of new solutions, the platform can help shorten time-to-market and lower technology adoption costs, ultimately resulting in reduced operational expenses for industry and potential cost savings for ratepayers. At scale, this innovation could transform California's industrial sector, contributing to statewide emissions reductions and improved grid reliability. The open-access nature of the testbed will promote accessibility by making cutting-edge resources available to a wide range of stakeholders, while supporting EPIC's core principles.

iv. Metrics: Impacts of the proposed research concept will be evaluated using both quantitative and qualitative metrics, including reductions in emissions, improvements in system efficiency, achieving digital twin simulation accuracy, and conducting industry-led test scenarios to demonstrate the integrated digital-twin and experimental system. Additional indicators may include cost reductions achieved for participating industries, payback periods for implemented solutions, number and variety of industry partners engaged, and the extent of knowledge transfer facilitated by the platform. Qualitative feedback from industry stakeholders regarding usability, accessibility, and perceived value will also be collected to assess broader impacts on accessibility and market adoption.

v. References: Need for better industrial combustion controls to adapt to advanced systems: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Climate Adaptation

vii. Support for Goal: This proposed digital twin-enabled experimental testbed directly advances the CEC's goals by accelerating the identification, validation, and adoption of low-emission and electric technologies in California's most energy-intensive industrial sectors. By offering a flexible, high-fidelity data-driven platform to test and optimize industrial control systems for combustion processes that could leverage alternative fuels, high-temperature thermal storage, or other fuel source alternatives, this integrated system will enable industry to transition toward emerging technologies while maintaining operational reliability and performance. The digital twin's advanced simulation capabilities will inform optimal integration of emerging technologies, minimize technical and economic risks, and support system-level emission reduction and energy efficiency building strategies that align with California's evolving grid and gas system. This approach also facilitates the coordinated evolution of the gas system by enabling demonstration and assessment of fuel blending and hybrid solutions that leverage both gas and electricity to enhance grid flexibility, resilience, and emissions reductions. Furthermore, by supporting the deployment of adaptive, low-emission technologies, the platform equips industries to better respond to operational challenges—such as extreme heat, air quality events, and water constraints—thereby enhancing resilience and long-term success in California's industrial landscape.

viii. Contributors to This Concept Include: Vi Rapp, Doug Black, Christoph Gehbauer

7. AI and Robotics to Sense, Monitor, and Improve Operations of Commercial Buildings and Facilities

i. Description: This concept proposes to test and apply robotics to sense, monitor and improve operations of commercial buildings and facilities. Embedded with different and powerful sensors and imagery capabilities, the robots move around a building and collect indoor conditions, energy system operational parameters, occupancy, etc. The embedded AI engine integrates and analyzes the data sources to provide analytics and actionable insights into the building conditions and energy performance as well as alerts of operational issues and faults. EPIC funds are needed to help complete the prototype robot development (DOE funds the robotics concept development) and more importantly test its performance in actual commercial buildings and facilities. Improving California commercial building operations at scale with low-cost solutions (robots can be rented) can be essential to help the state meet energy goals.

ii. Breakthroughs: Although much more data has been generated from sensors, meters, and BAS systems in commercial buildings, their integration and analysis is very limited to unlock the operational issues or opportunities for improvements. One-off building level project has been done but with high costs and required expertise lacking feasibility to scale up. The proposed robotics technology will automate the process and provide insights at scale for commercial buildings. This includes using robots to detect and fix leakage of next generation refrigerants that can be high pressure, toxic and flammable that pose health and dangers for humans.

iii. Outcomes: It is estimated commercial buildings can achieve 10% to 30% energy and utility bill savings with the robotic technology. The robotic technology can provide a foundation for programs such as demand response, emergency planning for wildfire, extreme heat and power outages etc.
iv. Metrics: Costs and benefits. Ranges of energy, emission, and energy costs savings for commercial buildings. Technology costs based on business models (own, lease or subscription of robots).
v. References: A review article on robotics for the building and HVAC industry is coming.
vi. Strategic Goal: Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas
vii. Support for Goal: AI-embedded robots provide low-cost sensing, monitoring, and analytics to reveal commercial building operation and energy use patterns and changes. It provides actionable insights for building managers, operators to fix or improve operational strategies to reduce energy use, emissions, utility costs, and improve resilience.
viii. Contributors to This Concept Include: Tianzhen Hong, Han Li

8. Assessment of Electric Preconditioned Air Units Using Heat Pump Technology for Airports
   i. Description: At many airports, preconditioned air (PCA) systems still rely on aircraft auxiliary power units (APUs) or inefficient electric PCA units that don't use advanced refrigerants. In contrast, advanced PCA units employing heat pump technology and advanced refrigerants can significantly reduce both energy use and emissions.
   This research aims to develop an energy and emissions analysis model specifically tailored to PCA systems, incorporating detailed data on local weather conditions and usage patterns at California airports. By quantifying the performance of advanced PCA technologies, the study will assess their potential to reduce emissions, improve energy efficiency, and lower operational costs. In addition to environmental quality, the project is expected to yield several co-benefits, including enhanced domestic energy security, improved air quality, and expanded economic opportunities in deployment of advanced technology. The findings will offer critical insights to support the adoption of robust aircraft heating and cooling practices at airports across the state.

ii. Breakthroughs: Key technical and market barriers include the limited availability of detailed performance data for advanced PCA units under different climatic and operational conditions; the absence of robust modeling tools to quantify energy use and emissions reductions from replacing APUs and inefficient electric PCA systems; and a lack of data on the operational reliability, cost-effectiveness, and environmental quality performance of heat pump-based PCA technologies. Additionally, concerns about system performance during extreme temperatures or peak-load conditions further hinder adoption.

    The proposed research addresses these challenges by developing a robust, region-specific modeling framework tailored to PCA systems at California airports. It will quantify the cost and emissions benefits of advanced PCA units using advanced refrigerants and heat pump technology, while filling critical data gaps by providing validated performance data, lifecycle cost estimates, and emissions reduction potential for various PCA configurations. Heat pumps are estimated to reduce emissions by 90% or greater, compared to traditional APU-based systems.

iii. Outcomes: The proposed research will help reduce technology and operational costs by identifying cost-effective PCA design improvements that optimize energy use. It will support the adoption of advanced PCA systems by providing robust, site-specific performance data and emissions impact estimates. By quantifying co-benefits—such as improved air quality near terminals and reduced emissions—the study will also inform stakeholders across relevant agencies and constituencies.

    Additionally, the research will enhance affordability and reliability through better-informed procurement and planning decisions, potentially lowering electricity demand peaks at airports and avoiding costly infrastructure upgrades. The modeling framework and findings will be applicable across all commercial airports in California and adaptable to local conditions in regions nationwide. This work also supports the broader transportation infrastructure ecosystem, including integration with electrical ground support equipment and airport energy resilience planning.

iv. Metrics: Quantitative metrics include energy use reduction (kWh/year) per PCA system and airport; emissions and pollutant reductions; system performance across temperature ranges and humidity levels; lifecycle costs and payback periods compared to baseline systems.

v. References:

a. Achatz Antonelli, Pietro. A Framework for Monitoring, Modeling, and Management of Airport Ground Power Systems During Aircraft Turnaround Operations. Diss. UC Berkeley, 2023. https://escholarship.org/uc/item/0dw9171k#:~:text=In%20this%20dissertation%2C%20a%20method%20is%20developed%20that,method%20was%20applied%20to%20SFO%20as%20a%20case-study.

b. National Academies of Sciences, Engineering, and Medicine. 2019. Optimizing the Use of Electric Preconditioned Air (PCA) and Ground Power Systems for Airports. Washington, DC: The National Academies Press. https://doi.org/10.17226/25623.

c. ACRP, Transportation Research Board, & National Academies of Sciences Engineering Medicine. (2012). Handbook for Evaluating Emissions and Costs of APUs and Alternative Systems (AERO Systems Engineering, Inc., & Synergy Consultants, Inc., Wyle, Inc.) The National Academies Press https://doi.org/10.17226/22797

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Transportation Electrification

vii. Support for Goal: This concept supports two of the Strategic Goals, (a) and (d), by providing a comprehensive analysis of the performance tradeoffs of heat pump technologies as alternatives to APU-based systems, this project will support informed investment decisions aimed at reducing emissions from aircraft at airports. In addition, more accurate assessments of heating and cooling demand generated through this research will enable airports and other stakeholders to plan and invest in the infrastructure needed to support air transport and ground-side equipment.

viii. Contributors to This Concept Include: Won Young Park

9. Advancing the State of the Art in Distributed Pumping Control Logic

i. Description: Commercial buildings use large pumps pressurizing a hydronic distribution loop combined with balancing and control valve to provide hot water to air handlers for space heating and cooling purposes. These systems have three major downsides: 1) the design requires high pressure distribution systems, increasing pump energy requirements, 2) improperly balanced systems provide inadequate flow to air handling units, leading to poor temperature control, and 3) incorrect flow through the air handling units leads to poor control of temperature returning to the central plant, decreasing efficiency of the heating and cooling chillers and boilers. Recent reductions in variable speed pump prices have enabled replacing the system's balancing and control valves with distributed variable speed pumping, avoiding the need for a high pressure system and ensuring the right amount of flow across each air handling unit. Preliminary field studies have shown 50-74% reductions in pump energy, and 15-28% improved temperature change across chillers.

This concept will advance the state of the art in distributed pumping control logic, and support industry adoption of the technology by addressing two key challenges. The first challenge is that the distributed variable speed pumps all use independent feedback control with no communication, leading to wasted energy on balancing flows. The concept will develop integrated control logic for all pumps to support precise system operation, further reducing electricity costs. The second challenge is that this is a new, unknown, and unsupported industry technology. This project will perform field studies demonstrating the energy cost savings and comfort benefits of distributed pumping, leading to publicly available datasets showing the impacts. These outcomes will support training programs teaching industry participants about the concept, and transfer data sets to the utilities about these emerging technologies, for use in supporting both incentive programs and building practices.

ii. Breakthroughs: This project will reduce the emissions and energy costs driven by commercial building heating, ventilation, and air conditioning processes in two key ways. First, reducing the amount of energy consumed by pumping and wasted by poor HVAC control will cause direct emissions reductions. Reducing the energy wasted by overheating buildings or reduced boiler efficiency will reduce natural gas combustion. Reducing the electricity consumed by distribution pumps and by poor control leading to low COP chiller operation will reduce the electricity that the grid needs to provide, reducing the need for new deployment of energy sources. Secondly, reducing the amount of energy required through heating, through better control and avoiding energy waste, will reduce the heating capacity required to serve a building. The reduced heating loads enable replacing existing boilers with lower capacity heat pumps, reducing the retrofit cost for improving efficiency and reducing emissions in existing commercial building heating systems and supporting building owner adoption of these systems.

iii. Outcomes: Distributed pumping has shown the ability to reduce commercial building HVAC pumping costs by 50-74%, indicating substantial energy cost reductions. Further improving the pumping control to avoid overpumping and bypass flows would likely increase the pumping cost savings to 55-79%. Simultaneously, it improves control of outlet temperature from air handling units avoiding overheating/cooling spaces. Since academic studies have found that ~30% of commercial building heating energy is wasted by poor control, this represents another opportunity for substantial energy cost savings.

Since distributed pumping is already a technology showing great benefits, the key value in this project will focus on market transformation efforts. The field demonstrations, reports, presentations, and available data sets will support the programs and practices of many related stakeholders. These programs will lead to increased awareness of the technology, as well as potentially representation in California's building energy practices.

iv. Metrics:
    a. Quantitative:
        1. Reduced pumping energy costs
        2. Reduced heating/cooling energy consumption
        3. Improved indoor air temperature costs, measured in terms of difference from the set temperature
        4. Impacts on system first costs compared to traditional pumping system designs
        5. Attendees at presentations and downloads of reports indicating industry attention to the topic
    b. Qualitative:
        1. Occupant satisfaction surveys
        2. Utility company indication of support for inclusion in training, incentive, and other programs

v. References:

    a. Sam Kwok Ho Lam, Koathari Akil, Yin Chun Leong. (2020) Distributed Pumping System (DPS) - A Practical & Energy Efficient Method of Chilled Water Pumping. ASHRAE
    b. Sam K. H. Lam, Chris Tham, Sunil Saseedharan, Liong Yin Chun, Adrian Wang. (2017) Distributed Pumping chilled Water Hydronic System for Air-conditioning Systems

vi. Strategic Goal: Building Decarbonization

vii. Support for Goal: This project will improve control of commercial building HVAC systems, thus avoiding wasted energy consumption through overheating spaces. Doing so will reduce the heating power required by commercial buildings, reducing the size of equipment needed to provide heating. Reduced capacity heat pumps are less expensive and less likely to require electrical service upgrades, thus significantly reducing the cost of emissions reduction in buildings. With these reduced costs building owners will be more likely to swap to efficient heating systems.

viii. Contributors to This Concept Include: Peter Grant & Anand Prakash

10. Leveraging Waste Heat Concept

i. Description: Achieving CEC's emissions goals requires strategic deployment of emissions management technologies such as direct air capture (DAC). However, scaling such strategies increases demand for electricity, placing new burdens on the grid. These challenges can be mitigated by integrating these technologies with waste heat. This underutilized resource is prevalent across multiple sectors in California, and it's only expected to increase as the demand for data centers scales up.

Recent studies show that costs for capturing and sequestering some pollutants from the air can be reduced by up to 22% when they leverage the energy in waste heat. Critical questions remain about real-world feasibility and scale: How do hourly and seasonal heat fluctuations affect output? Which facilities have suitable temperature and flow rates? What transport infrastructure is needed to convey the material being captured and sequestered? How many plants in California may qualify for such retrofits? What would the state-wide benefits be?

To bridge these fundamental knowledge gaps we propose that CEC fund a comprehensive, California-wide feasibility study of waste heat focusing on applications where it can benefit other pollution abatement activities. We further suggest an accompanying assessment toolkit grounded in process modeling, techno-economic and lifecycle analysis. By blending top-down (sector-wide surveys) and bottom-up (detailed process simulations and expert interviews) approaches, this effort develops a data source that quantifies each heat stream's temperature, mass flow, temporal availability, and geographic location. Such information would create tremendous value for a broad range of stakeholders including technology developers, industry, utilities, policy makers and others with a commercial interest in identifying and developing related projects. Equipped with these insights, policymakers and project developers can work in concert to identify high-impact "hotspots," tailor thermal-storage solutions, and design incentives that unlock the full value of waste-heat-driven technologies at scale to meet California's energy goals.

ii. Breakthroughs: The proposed concept bridges critical knowledge gaps in California's waste-heat database and will create a physics-based feasibility toolkit. This effort will establish the state's first comprehensive, high-resolution waste-heat atlas, highlighting both spatial and sectoral opportunities across every major industry, including data centers and natural-gas facilities. By pairing this atlas with rigorous process models—grounded in techno-economic and lifecycle assessments—we can pinpoint cost-effective hotspots for deploying waste-heat–driven technologies.

    From a market perspective, the project addresses several stakeholder pain points: the grid strain caused by electrical demands, wasted thermal energy from unutilized heat streams, and investment uncertainty that deters private funding. By revealing which facilities combine the right temperature and flow characteristics with stable waste-heat profiles—and by quantifying requirements for thermal storage and the transport of materials or pollutants captured in the process—this toolkit will inform policymakers, utilities, industrial operators, and technology providers exactly where and how much opportunity exists. These end users can leverage these insights for site selection, incentive design, interconnection planning, and decision making. By bridging knowledge gaps and delivering a robust assessment tool, this program will accelerate California's achievement of its energy policy goals.

iii. Outcomes: If successful, this effort will create California's first high-resolution waste-heat atlas and physics-based feasibility toolkit. These new capabilities can identify the lowest-cost pathways for scaling energy intensive pollution abatement activities by leveraging industrial heat streams. By identifying hotspot facilities that offer the greatest energy and emissions benefits, this database can map a pathway to deploy additional efforts that would otherwise be impossible due to practical constraints. For grid operators, such an integrated approach will alleviate increasing burdens on providing additional infrastructure to meet the demand for power. Finally, the developed waste heat data set will provide detailed information– disaggregated by technology, processes, geospatial locations, and site-specific constraints–and it will become a foundation for further research, uncovering new opportunities and driving innovation.

iv. Metrics: A combination of quantitative and qualitative metrics can be used to evaluate the success of this program. Examples include the quantified quality (e.g. temperature) and quantity (e.g. flow rates) of waste heat in a location, disaggregated by unit processes or by type of waste heat sources. The proposed data set will consolidate such data at city, county, and up to a state-level which can provide granular details of available waste heat streams, both in spatial and non-spatial terms. For each identified waste heat source, the cost and quantity impact on related pollution abatement activities can be estimated, enabling assessment of techno-economic feasibility and other net benefits. Based on this, hotspot facilities that offer the greatest energy and emissions benefits can be identified.

v. References:
   a. doi:10.2172/1185773
   b. doi:10.17226/25259
   (pre-print will become available soon) Lim et al. Optimization-based feasibility framework for industrial waste heat utilization: a case study in direct air capture (2025)

vi. Strategic Goal: Climate Adaptation, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: This proposed program will directly support California's goal of reaching 100% net zero emissions and improving climate adaptation. Not all sectors currently have affordable technologies to meet California's emissions goals. Waste heat utilization provides an additional technology pathway that can overcome some of the difficult barriers to their achievement.

However, fundamental knowledge gaps and a lack of quantitative tools prevent the identification of viable waste heat opportunities. A comprehensive waste heat database and assessment toolkit developed through this program will bridge this gap. In particular, the waste-heat pathway proposed here has proved efficient when paired with industrial natural-gas boilers—facilities that are expected to play a critical role in California's energy landscape. By mapping heat quality, flow rates, and temporal availability, and by modeling integration with related pollution management and capture technologies, this effort will enable informed deployment strategies that maximize stakeholder benefits.

viii. Contributors to This Concept Include: Taei Hwan Lim, Prakash Lao, Arman Shehabi

11. California Energy Technologies Incubation Program: Leveraging National Lab Assets for Commercialization

    i. Description: We propose that EPIC 5 supports an energy technologies incubation program modeled after the highly successful Cyclotron Road, IMPEL and Cradle to Commerce initiatives at Lawrence Berkeley National Laboratory. These lab-embedded entrepreneurship support programs offer a unique value proposition by embedding a market-driven innovation accelerator within the rigorous, impartial environment of a national lab. This distinct positioning fosters a unique public-private collaboration, where energy startups gain priority access to world-class technical expertise, cutting-edge research facilities, and a deep network of industry and investment mentors. Unlike traditional accelerators, such programs de-risk nascent technologies through validation from technical subject matter experts, and accelerate progress through executive pitch coaching and early entrepreneur-oriented training modules to help bridge the critical "valley of death" that often stalls promising innovations from reaching commercial viability.

       Unlike traditional accelerators, this CEC- incubator program would:

       a. Leverage multiple California-based National Lab assets (from LBNL, SLAC, Sandia) to:
          1. Provide access to curated intellectual property across labs
             i. A vast pool of scientific and deep tech experts who can conduct rigorous technical vetting of technologies
             ii. Enable expert matchmaking of teams and access to scientific and entrepreneurial talent
          1. Provide access to world-class technical infrastructure, including test beds, fabrication, and prototyping facilities to support long-term technical de-risking aligned with California's energy priorities
          2. Accelerate commercialization via executive pitch coaching, scientific and business mentoring, and early-stage entrepreneurial training

       This unique blend of scientific rigor from the National Labs, entrepreneurial support through coaching, mentoring, and networking, and real public and private sector pitching opportunities can ensure that publicly funded R&D directly translates into tangible market solutions.

For California and the CEC, this CEC- incubator could present a powerful mechanism to accelerate the state's ambitious energy, security, and affordability goals. It provides wraparound support for lab-to-market innovation, supported by a synergistic science and business infrastructure designed to drive energy innovations that directly benefit California ratepayers. By nurturing a robust pipeline of innovative energy startups, it directly supports the CEC's priorities in different energy domains such as grid modernization, nuclear, energy efficiency and fuels, and buildings. The program would stimulate job creation and economic growth within California's energy sector, ensuring that innovative energy solutions are accessible to all Californians.

EPIC funds are needed to support this concept by targeting technologies most relevant to California residents and addressing the state's unique energy challenges. This public interest funding is vital for endeavors that lay the groundwork for cost-effective and reliable deployment, allowing California to continue demonstrating leadership in transforming public research into impactful, real-world solutions applicable nationwide.

ii. Breakthroughs: This state-funded incubator would build on LBNL's nationally recognized leadership in energy innovation, bridging early-stage technologies with real-world deployment through a research-driven approach that is uniquely suited to overcoming entrenched technical, economic, and market barriers in the built environment and energy system. This work directly supports California's strategic goals by enabling technological breakthroughs that accelerate the development, commercialization, and adoption of energy solutions.

Adoption of these types of technologies continues to face several persistent barriers. A recurring challenge identified through past studies and regular participant surveys is uncertainty around real-world performance, particularly across California's many building types and unique weather patterns. Innovators often lack access to the testing infrastructure and data needed to validate their technologies at scale. In addition, many emerging solutions struggle to meet the cost and performance thresholds necessary for market acceptance, limiting interest from builders, investors, and policymakers. The innovation ecosystem itself also remains fragmented, making it difficult for startups to connect with the technical, compliance, and financial resources needed to scale. Finally, the absence of decision-grade data and impact assessment tools hampers both product development and policy alignment, slowing the broader implementation of energy solutions.

This incubator directly addresses these barriers by leveraging LBNL's unique research capabilities and proven ecosystem engagement models, like IMPEL and C2C. Through research-grade field validation and techno-economic analysis, such an incubator can help startups rigorously demonstrate reliability and quantify cost-performance benefits, enabling them to meet critical market thresholds. Building on the success of these programs, the incubator will provide structured access to technical expertise, demonstration opportunities, policy guidance, and funding pathways. This approach embeds scientific rigor into every stage of the commercialization process, accelerating both development and deployment.

Technologies supported through IMPEL and C2C already demonstrate the impact of this approach. For example, a San Francisco-based AI startup that participated in IMPEL benefited greatly from the unique combination of technical expertise and practical entrepreneurial guidance received during their program experience. This supportive environment allowed the team to rigorously test their assumptions, refine their value proposition, and ultimately lay the groundwork for building partnerships with over 60 cities throughout California.

iii. Outcomes:

a. A rigorously vetted technology pipeline with volume and velocity: Technology innovators may not have the staffing resources, proposal development experience, connection to larger institutions such as the National Labs, or awareness of funding mechanisms to apply for GFOs and other EPIC funding alone. Meanwhile, state funding opportunities can take a long time - often years - from proposal to demonstration, sometimes rendering the technology outdated or requiring updates by project end. The cohort incubator model we are proposing will create a pipeline that delivers the latest and most relevant technologies to Californians. It will also enable a greater number of innovations to participate in CEC demonstration opportunities through proven partnering/IP agreement mechanisms that LBNL has established with other startups in our C2C program.
b. Mitigated investment and ratepayer risk: This program will serve as a critical filter for technologies by conducting rigorous technical vetting

and feasibility studies throughout startups' participation, from program application, acceptance, technical feedback and mentoring, and tailored learning modules - a positive outcome for both innovators and ratepayers. Innovators will save significant time and capital by receiving early guidance, allowing them to pivot or refine their technology before making major investments. Meanwhile, ratepayers will face reduced risk of the state or utilities investing in technologies that fail to deliver, are unsafe, unreliable, or overly expensive.

c. Synergistic collaboration between the National Labs and California: An integrated partnership between LBNL and CEC, with the technical support of other National Labs (both in CA and beyond), can maximize the chances of success for innovators and by extension, all California ratepayers. Co-created learning modules led by LBNL will provide technical feedback and business foundations, while the CEC provides the policy context and a real-world stage for demonstration. The result is a suite of promising, validated technology solutions that can be deployed effectively within California's policy framework.

iv. Metrics: A state-funded, national lab-embedded advanced energy entrepreneurial support incubator could accelerate the chances of commercialization of new and promising technologies. Our program presents an opportunity for CEC to identify and have access to innovative, disruptive technologies that enable a safe, affordable, and resilient energy future.

a. Quantitative metrics include:

1. Total number of startups supported, by tracking the total number of startups or technologies vetted and supported by our program. To date, our team has supported over 300 energy technology startups at the National Labs through the IMPEL and C2C programs at LBNL.
2. Economic benefits to California, by tracking the number of FTEs created by participating startups, new manufacturing facilities, and expenditures within California. This may be measured through the program's operating costs, and other direct spending within California. As a record of our success in this area, our startups have gone on to create 250 jobs across the country, built seven manufacturing facilities, and successfully launched 50+ commercial products.
3. Funding raised by startups, by tracking funding rounds publicly announced or reported by startups. After participating in our

programs, our startups have gone on to raise $200M+ in publicly announced capital.

4. Energy Affordability, by measuring reductions in household energy costs offset by new technologies, or reduced operational and capital costs through the development of new smart grid components or monitoring tech that reduces wear on existing infrastructure
5. Ratepayer benefits, by measuring cost savings to households, utilizing CPUC's existing affordability metrics.

b. Qualitative metrics include:
   1. Scientifically vetted innovation ecosystem: The program will foster a pipeline of innovative technologies that have undergone rigorous validation. This will create a high-trust environment for multiple stakeholders. Tracking the adoption rate of technologies emerging from the program, partnership, or investment activity with utilities or government agencies would be a way for quantification.
   2. M&V via National Labs: Leveraging the expertise of national labs allows the team to conduct trusted M&V studies, supporting claims of performance and other impact metrics. This could be quantified by counting the number of technologies that undergo formal M&V, and the influence of those results on commercialization.
   3. Early identification of solutions: Through CEC-identified pilot and demonstration opportunities, startups can collect and share real-time technology performance data to inform decisions on refinement and scalability.
   4. Other economic benefits to California: This may be measured through indirect job creation in supplier industries and economic output to the state's GSP for tech that emerges from the program and is commercialized.
   5. Stakeholder Feedback: Structured interviews and surveys from participating innovators, public agencies, and partners, focusing on satisfaction with support received, increased capacity, and confidence in technology performance.
   6. Ecosystem Development: Case studies illustrating how the incubator facilitated connections between startups and critical resources (technical expertise, demonstration partners, market acceptance).

v. References:

a. Singh, R., Jain, Y., Wong, L., Weigel, M., & Ryan, N. (2024). From IMPEL to Impact: Lessons Learned in Accelerating Innovative Building

Technologies. Lawrence Berkeley National Laboratory. http://dx.doi.org/10.20357/B7XC7S Retrieved from https://escholarship.org/uc/item/7vt5d79f

vi. Strategic Goal: Transportation Electrification, Distributed Energy Resource Integration, Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Climate Adaptation

vii. Support for Goal: An innovation pipeline will cross-cut all of the CEC's EPIC strategic goals.

viii. Contributors to This Concept Include: Reshma Singh, Laura Wong, Yashima Jain, Vidhi Bhatia

F. Community-Scale Decarbonization

1. Thermal Energy Networks for Campuses and Dense Developments

   i. Description: We propose that EPIC investigates how Thermal Energy Networks (TENs) for campuses and dense developments can help reduce peak electrical demand, integrate utility-scale energy storage (e.g., through borefield thermal energy storage), improve energy efficiency, and increase resilience to heat waves, all while offering a cost-effective path to electrical heating. Recent findings at Joint Base Andrews, a military site, indicate that a geothermal-coupled district energy system, when compared to gas heating and air-source chillers, achieved a 45% reduction in peak electricity use and a 70% reduction in overall energy consumption, with a 20% increase in life cycle costs.

      Techno-economic feasibility studies for various climates and load profiles in California would investigate how this system solution can support California's objectives to enhance distributed energy resource integration and adapt buildings to extreme weather events. This approach would also create opportunities for energy service providers and utilities to offer grid-scale load balancing through distributed thermal and electrical storage. EPIC funding is essential for these techno-economic analyses across different climate regions and load distributions, as they require systematic, technology-neutral analysis, optimization, and derisking—steps that are pre-competitive and crucial for the cost-effective, reliable deployment of this technology.

   ii. Breakthroughs: This concept proposes to investigate the application of innovative approaches to providing efficient and reliable heating and cooling to communities through thermal energy networks in California contexts. Community scale thermal energy networks are able to utilize intermittent sources of heating/cooling (such as geothermal or lake/ocean), waste heat or energy recovery from buildings and/or industrial processes, community storage, or other co-generation processes to minimize the amount of energy or fuel needed to meet demand. Such resources can also be used to provide electric load flexibility at a large scale. Innovative thermal energy network designs circulate mild temperature water to sites that use water-source heat pumps to meet individual heating and cooling loads.

      While TENs have advantages, they are capital-intensive and complex systems to design, install, and operate. Techno-economic performance should include community perspectives as well as impact on parallel energy systems, such as the electric grid and gas network, in addition to performance for individual homes and businesses. Therefore, techno-economic feasibility studies and related tools and workflows are needed to determine suitability in California contexts. This research concept would provide more information and fill gaps about the feasibility of these systems in California, as well as lay the groundwork for potential design and installation of such systems.

Policy makers would benefit from these results to understand whether further investment or promotion is warranted. Engineers and designers would benefit from results to understand the technical potential and challenges for such systems to be designed for CA. Municipalities, planners, and other community or campus development officials would benefit from results to understand their options for new or retrofit heating and cooling system options. Electric and gas utilities would benefit from understanding the potential impacts on and co-benefits to their systems, such as avoided infrastructure costs stemming from capacity expansion requests and savings that accrue from moderating peak demand.

iii. Outcomes: The anticipated outcomes include techno-economic feasibility study reports, system design and operation considerations, computational tools and workflows to aid in future studies and projects, including for feasibility studies and detailed engineering analysis, and a network of potential owners and designers interested in pursuing both pilot demonstrations and commercial deployments.

The research would improve the value proposition of thermal energy networks by analyzing their economic and energy-related performance in the California context, and tailoring design and installation approaches accordingly. Thermal energy networks would reduce ratepayer costs by reducing the overall energy needed to provide heating and cooling to individual buildings as well as alleviate system capacity upgrade requirements for electric utilities due to lower peak demand.

Successful thermal energy networks provide efficient and reliable heating and cooling to communities of homes and businesses. Thermal energy network designs can be adapted based on heating and cooling load profiles, availability of natural sources of heating and cooling, and local conditions and performance requirements. However, design tools and workflows are still needed to streamline the feasibility studies, design, and installation processes for specific sites, which this research would help address.

Thermal energy networks take advantage of the multitude of available energy sources as well as heat recovery to leverage systemic benefits at community scale. This approach incorporates environmental quality and affordability. By reducing peak demand and using heating and cooling sources not dependent on air temperature, TENs can improve resilience.

iv. Metrics: For different system configuration options, local weather patterns, load profiles, energy prices, or other scenario-specific inputs/requirements, consider the system-wide and individual network entity (i.e. building owners, heat/cool/storage providers) capital cost, annual and annualized lifetime operating costs, peak electrical demand (MW), equipment efficiency (SCOP), a network economic indicator called Linear Heating Power Demand Density (LHPDD - the ratio of network capacity to length in kW/m).

v. References:

a. Behnaz Rezaie and Marc A. Rosen (2012). “District heating and cooling: Review of technology and potential enhancements.” Applied Energy, 93, 2-10.

b. Henrik Lund, Poul Alberg Østergaard, Miguel Chang, Sven Werner, Svend Svendsen, Peter Sorknæs, Jan Eric Thorsen, Frede Hvelplund, Bent Ole Gram Mortensen, Brian Vad Mathiesen, Carsten Bojesen, Neven Duic, Xiliang Zhang, and Bernd Möller (2018). “The status of 4th generation district heating: Research and results.” Energy, 164, 147-159.

c. Simone Buffa, Marco Cozzini, Matteo D’Antoni, Marco Baratieri, and Roberto Fedrizzi (2019). “5th generation district heating and cooling systems: A review of existing cases in Europe.” Renewable and Sustainable Energy Reviews, 104, 504-522.

d. Michael Wetter, Jianjun Hu (2019). “Quayside Energy System Analysis.” LBNL-2001197.

e. Tobias Sommer, Matthias Sulzer, Michael Wetter, Artem Sotnikov, Stefan Mennel and Christoph Stettler (2020). “The reservoir network: A new network topology for district heating and cooling.” Energy, 199.

f. Ettore Zanetti, David Blum, and Michael Wetter (2023). “Control development and sizing analysis for a 5th generation district heating

and cooling network using Modelica." In Proc. of the 15th International Modelica Conference, Oct 9-11, Aachen, Germany.

g. Matthias Sulzer, Michael Wetter, Robin Mutschler and Alberto Sangiovanni-Vincentelli (2023). "Platform-based design for energy systems." Applied Energy, 352.

h. Michael Wetter (2025). "Thermal reservoir networks for modularly expandable thermal microgrids." SERDP & ESTCP Webinar Series (#214), Feb 13, 2025.

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Climate Adaptation

vii. Support for Goal: DER Integration: Thermal energy networks, particularly so-called ambient loop configurations, enable the integration of community-scale DER like storage (geothermal, large bodies of water, community tanks), heat recovery (industrial process waste heat, simultaneous heating and cooling loads), and co-generation (thermal/electrical or waste heat from other fuel production). Additional DERs such as local storage for load shifting or on-site heat recovery at individual sites can be utilized for the benefit of the whole network. These DERs, especially storage, can be used to shift electricity use by heat pumps and network pumps in coordination with the needs of the electric grid.

Building Decarbonization: Thermal energy networks offer the opportunity to increase the efficiency of heat pumps at individual sites since water-sourced heat pumps can utilize mild temperatures from the network, which in turn can be moderated and controlled by DERs like geothermal, rather than air-source heat pumps which are less efficient at high and low ambient air temperatures. Water-source heat pumps used with a thermal energy network can lower the energy costs for consumers as compared to air-sourced heat pumps. Thermal energy networks also offer the opportunity for community scale heat recovery and waste heat utilization, further lowering overall energy use to provide heat and cooling at the scale of the network. Together, more efficient heating and cooling can lower peak demand on the electric grid, freeing capacity for other systems or uses.

Achieving 100% Net Zero Emissions and the Coordinated Role of Gas: Thermal energy networks offer an opportunity to utilize waste heat from co-generation of fuel (e.g. electricity, hydrogen, biomass) at community scales, thereby enabling coordination between fuel distribution systems and achieving higher overall energy resource utilization efficiencies.

Climate Adaptation: Water-source heat pumps drawing from a thermal energy network with community-scale storage and DERs can enable greater resilience. Air-source heat pumps suffer a loss of efficiency and in some cases face operational failure when compressor lifts are too high because ambient temperatures are outside the equipment's operating range. Since they don't use ambient air as a source, water-source heat pumps drawing from a TEN can be more efficient and operate in a wider range of ambient temperatures as compared to their air-source counterparts.

viii. Contributors to This Concept Include: Michael Wetter, David Blum

G. Impacts research for new generation and storage

1. Solar-MAR

   i. Description: The co-development of solar PV + storage along with Managed Aquifer Recharge (Solar-MAR) infrastructure and water treatment offers some unique enabling techno-economic benefits that can increase the development of both. Additionally, there are operational synergies that can allow for the maintenance of the MAR assets along with the solar PV and storage systems. There are now four (4) "Solar-MAR" installations operating at California water agencies showing commercial viability. We believe the core concept has much broader applicability to be discovered through research.

   ii. Breakthroughs: The energy usage required to operate some Managed Aquifer Recharge and post treatment technologies can be ideally met through co-development of solar PV and battery energy storage systems. In California, energy to convey and treat water is projected to increase by 21-40% by 2035. Co-locating solar PV can help address this rising energy demand stemming from water management. There are several co-benefits which if proven would increase the economic value of the Solar-MAR approach. One example centers on the viability of establishing native and possibly native pollinator plantings under the array area but in the recharge basin. Establishing plantings would increase solar energy production, maintain basin percolation rates, reduce maintenance costs and provide pollinator habitat. This research would include but not be limited to investigating inclusion of water treatment, additional sectors (ag, municipal governments), utility scale projects and may have strong ties to combining these assets with agricultural activities (agro-voltaic-MAR) and possible use of native plants to increase water percolation along with ecological benefits. While Proposition 4 will fund significant water infrastructure projects, there is a need for viable commercial models that can enable broad adoption - development, financing, constructing and operating these combined energy/water assets.

   iii. Outcomes: Increase the co-development of solar, MAR and water treatment infrastructure thereby mitigating the economic impact and energy intensiveness of water treatment. This co-location strategy can also deliver significant resilience to the water treatment portion during extended power outages. Vital water supplies can be maintained during emergencies making both communities and crops more resilient.

iv. Metrics: Use onsite generation to reduce the energy intensity and cost of stored, pumped and treated water relative to the base case of fully grid-supplied power. Energy and water resilience metrics such as system average interruption duration and frequency (SAIDI & SAIFI).

v. References:
   a. https://www.conservation.ca.gov/dlrp/grant-programs/Pages/Multibenefit-Land-Repurposing-Program.aspx.
   b. https://floodmar.org/
   c. https://www.sciencedirect.com/science/article/abs/pii/S0011916425006642

vi. Strategic Goal: Distributed Energy Resource Integration, Climate Adaptation, Building Decarbonization

vii. Support for Goal: Reduced energy costs for water treatment and asset maintenance by co-development with solar and storage enable DERs for reduced peak load and flexibility for the grid.

viii. Contributors to This Concept Include: Craig Ulrich, Peter Fiske, and Gerald Robinson

2. Co-generation Product Pathways

i. Description: Significant innovation in above and belowground distributed long duration energy storage (LDES) technologies is possible with adequate investment and customer matching. Meeting the unique needs of under-resourced and critical infrastructure customers with storage discharging needs ranging from 10 to 100 hours requires systematic classification of LDES and coupling with storage technologies. For example, the LDES of cold climate customers are not the same as the LDES needs of a port trying to reduce power surges stemming from infrequent cruise ships, nor the needs of an agriculture center with seasonal fluctuations in both power needs, consumables, and resources. The proposed concept is to identify technical, social, and economic performance metrics of LDES applications and benchmark the top 10% of electrochemical, chemical, mechanical and thermal technology innovations against these targets for various time scales. While conventional metrics including system cost ($/kW), depth of discharge, cycleability, and self-discharging will be included, metrics critical to California industries and ratepayers will also be captured, including flexible revenue options for local economy development. Examples include non-ammonia fertilizer co-production, and transport-stable energy-storage forms for export at the ports . The proposed dataset and methods of LDES matching and evaluation with specific end uses of LDES is highly timely, as a number of novel datasets, models, and emerging companies have led to the generation of LDES technology simulations and trials in different market sectors. Specifically, a broader portfolio of LDES beyond electrochemical systems are available, ranging from boreholes, to thermal energy storage, to formate-bicarbonate batteries, while social acceptance and review of BESS such as the Tesla PowerWall has risen. This work should interface with ongoing activities that include stakeholder engagement, such as the ARCHES Hydrogen Hub, which includes POAK, POLB, POLA, and POSD.

California possesses vast generation resources that can be utilized in strategic production of profitable and safe alternative fuels, feedstocks, which could be exported or used instate. Deployment in California requires a unique scaling as well as a coupling of both new and emerging technologies, particularly ones with grid co-benefits such as LDES. For example, ports have strict rules around the storage and transport of hazardous chemicals such as ammonia. Furthermore, the conversion of electricity to alternative products that can be stored and transported at meaningful scales comes with technical considerations ranging from the added cost and complexity of continuous versus batch operation, use of critical materials, water, and feedstocks including petroleum derived products, and of course, the implication for batteries and power demand to ensure products meet emissions targets for export or internal use.

ii. Breakthroughs: California is comprised of highly heterogeneous types of LDES end users, yet the systematic development of prototypical characteristics would enable the alignment of LDES technology design, prototyping, customer engagement, and scaleup to meet the urgent GW scale requirements for storage in the timeframes projected.

iii. Outcomes: (1) Define and map LDES end user needs, operation cycles, typical land footprints and resources, climate regions, and characteristics and translate into requirements for LDES. Use the map to downselect the most promising LDES innovations and technologies for each end user. (2) Identify production pathways for critical products used within California that could be generated flexibly from electricity, methane, and hydrogen in the process of serving storage capacity requirements. (3) Characterize unique aspects of LDES technologies including life-cycle cost and impacts, supply chain vulnerabilities and scaling risks, safety and permitting hurdles, social acceptance, and co-benefits with utility systems. (4) Identify LDES that could alternatively provide feedstocks or heat for critical products that could be used in local economies or exported from California that align with port capacity, mandates, and safety concerns. Notably, clarifying the cost and alignment of non-ammonia fertilizers that can be derived using LDES materials would fill a key knowledge gap for California.

iv. Metrics: Technical considerations include depth of discharge, energy density, cyclability, cold climate suitability, response time, ease of automation, round trip efficiency and emissions intensity of co-products. Economic and financial considerations including system cost, minimum sale price, levelized cost, payback period, construction period, maintenance requirements, energy payback period, RTE, ROI, financing challenges. Business considerations include resource needs such as new infrastructure or the ability to leverage existing infrastructure, water, gas, and power capacity, land leasing, and permitting processes. Social considerations include air quality benefits, safety for workers and customers during maintenance, job type and development, opportunities for tribal communities, and social acceptance.

v. References: The proposed work stems from a rich library of chemical, electrochemical, mechanical, and thermal LDES technology operation cycles and process models from 0 to 100 hours of discharge and from 0 to 1 GW scale power. Outreach with companies in the space is made possible through the depth of network established by LBNL and DOE programs on LDES that will allow for collection of data, as well as a strong advisory board. Partnership with local energy hubs such as ARCHES in California and MITI in Minnesota will enable further collection of data on cold climate and unique LDES market needs, where hydrogen is actively compared with BESS for LDES.

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: While Lithium-based batteries could achieve great reduction in levelized cost in the next 10 years, DOE estimated in 2024 that the required financial investment is estimated to be more than $1 billion. Investments in LDES that truly serve the needs of under-resourced customers, spanning rural to mountain regions, and critical infrastructure customers require a sophisticated matching of LDES capabilities that employ metrics of resilience and local economy development.

viii. Contributors to This Concept Include: Hanna Breunig

3. Domestically Sourced Electrodes
    i. Description: Current rechargeable battery systems (such as Li-ion) rely heavily on expensive materials mined outside the US. To lower costs and improve US energy security, it is essential to develop and manufacture rechargeable batteries using inexpensive, domestically mined materials such as manganese. To practically use Mn-based electrode materials for rechargeable batteries, this concept proposes the development and optimization of Mn-based electrodes from the material level to the cell level, ensuring good cycling stability, fast charging, and improved safety. The results will directly support California's energy goals by lowering battery cost, expanding life time, and enabling fast charging, which benefits not only electric vehicles but also grids.
    ii. Breakthroughs: This concept can lower the cost of rechargeable battery manufacturing and its implementation for EVs and other infrastructure. It will make batteries more affordable and efficient to store energy.
    iii. Outcomes: This concept would make batteries (energy storage systems) more affordable.
    iv. Metrics: To evaluate the impact, the following metrics need to be considered: manufacturing and lifetime costs.
    v. References:
        a. Importance of Mn-based rechargeable battery systems and their current status:
            1. https://doi.org/10.1002/adma.202502766
            2. https://doi.org/10.3390/batteries9050246
    vi. Strategic Goal: Transportation Electrification, Building Decarbonization
    vii. Support for Goal: The results will directly support California's energy goals by lowering battery cost, expanding life time, and enabling fast charging, which benefits not only electric vehicles but also grids.
    viii. Contributors to This Concept Include: Haegyum Kim

4. Unlocking Hydrogen’s Potential for California
    i. Description: We propose that EPIC investigate the performance and durability of promising hydrogen technologies that can directly address the EPIC 5 strategic goals as well as California’s wider energy policy goals. Several hydrogen technologies are currently in the planning stages of being deployed in transportation (e.g. polymer electrolyte membrane fuel cells), hydrogen generation from electricity (e.g. various electrolyzers) and in buildings (e.g. solid oxide fuel cell) through public-private partnerships.

Specifically, we propose developing sensing technologies to instrument fuel cells and electrolyzers operating in the field to collect performance data as a function of the operating environment. We also propose utilizing these data sets to advance the understanding of these cutting-edge electrochemical systems as well as developing models to improve their lifetime performance.

ii. Breakthroughs: While both electrolysis and fuel cell technologies have shown great promise in meeting the state's energy goals, their cost performance and durability need improvements to spur widespread commercial adoption. Developing robust performance and durability models that are validated with data has the potential to significantly enhance commercial adoption. For both electrolysis and fuel cells simultaneously meeting the DOE's performance/cost/durability targets is a significant challenge which the availability of robust models validated with experimental data can resolve. For example, electrolysis systems operating dynamically when coupled to variable generation show higher degradation rates. The deployment of these systems in California provides a unique opportunity for EPIC to fund Industry/National Laboratory/Academia collaborations that can lead to the development of improved fuel cell and electrolysis technologies.

iii. Outcomes: Improve lifetime performance of electrolyzers and fuel cells through performance and durability models that are validated with data.

iv. Metrics: The metrics utilized to evaluate the research concept include: i) the amount of available fuel cell and electrolysis performance data, ii) increased durability of fuel cell and electrolysis systems , and iii) publicly available performance and durability models

v. References:
   a. Fuel cell and electrolysis cost targets: https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-multi-year-program-plan
   b. Cost and performance of current generating technologies: https://www.eia.gov/outlooks/aeo/assumptions/pdf/elec_cost_perf.pdf

vi. Strategic Goal: Transportation Electrification, Distributed Energy Resource Integration, Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: Transportation goals: Increase fuel cell vehicle deployment. Building Goals: Increased fuel cell deployment in combined heat and power applications. Emissions reductions goals: Producing

Hydrogen from electricity and utilizing it in fuel cells as dispatchable power or in transportation or home applications. DER goals: Producing Hydrogen from electricity and utilizing it in fuel cells as dispatchable power.

viii. Contributors to This Concept Include: Rangachary Mukundan

5. Innovation at the Foundation of the Offshore Energy System

i. Description: As California accelerates toward its energy goals, floating offshore wind will be a cornerstone of the state's energy portfolio—offering multi-gigawatt-scale potential in deep waters beyond the reach of fixed-bottom foundations. While recent EPIC investments have advanced wind resource characterization, grid integration, and environmental monitoring, major innovation gaps remain in infrastructure durability, constructability, and lifecycle cost management—particularly for floating platforms designed to withstand harsh Pacific conditions over 25+ years. Future offshore wind success will depend not only on turbine technology or permitting, but on the development of robust, intelligent, and field-adaptable substructures that lower cost, reduce maintenance, and ensure safety. Emerging approaches that combine resilient materials, circular design principles, and embedded sensing can help close these gaps—particularly when deployed through modular, scalable construction methods that are compatible with California's constrained port and manufacturing infrastructure.

Targeted RD&D in this space would support California's leadership in offshore wind, unlock local energy job creation, and de-risk early deployments in the Humboldt and Morro Bay lease areas. Such work aligns with EPIC's strategic goals by accelerating infrastructure innovation, improving reliability and affordability, and fostering resilience through innovation at the foundation of the offshore energy system.

ii. Breakthroughs: The proposed concept targets key technical and market barriers to scaling floating offshore wind in California, including high lifecycle costs, structural durability in harsh marine conditions, and limited port infrastructure for large-scale construction. By advancing resilient materials, embedded sensing for real-time structural health monitoring, and modular construction compatible with California's ports, this work aims to reduce capital and O&M costs by 10–20% and extend platform lifespans beyond 25 years. It also addresses data gaps in platform performance under Pacific conditions, benefiting developers, designers, and other key stakeholders by enabling risk-informed permitting, predictive maintenance, and lower insurance costs. These innovations are critical to achieving the state's stated goals by unlocking multi-GW offshore wind potential.

iii. Outcomes: If successful, this research will enable the development of durable, intelligent, and cost-effective floating offshore wind platforms tailored to California's deep-water conditions and infrastructure constraints. Anticipated outcomes include a 10–20% reduction in capital and O&M costs, increased structural reliability through embedded sensing, and improved constructability via modular design. At scale, these innovations will lower the levelized cost of offshore wind energy, accelerate deployment in Humboldt and Morro Bay, and enhance safety through real-time monitoring. Ratepayer benefits include more affordable electricity, increased grid reliability from diversified energy sources, reduced environmental impact via circular design, and expanded access to high-quality jobs.

iv. Metrics: The impacts of the proposed research will be evaluated using the following metrics:
   a. Cost Reduction: Percentage reduction in capital expenditures and O&M costs ($/kW and $/MW/year)
   b. Performance Improvement: Increase in projected platform lifespan (targeting >25 years) and reduction in unplanned maintenance events
   c. Constructability: Time and cost metrics for modular assembly and deployment using California port infrastructure
   d. Sensing Efficacy: Accuracy and reliability of embedded sensing systems in detecting structural degradation (e.g., >90% anomaly detection rate)
   e. Technology Readiness: Advancement of key components (materials, sensing systems, construction methods) by at least 2 TRLs
   f. Workforce development: Number of local jobs supported or created in manufacturing, assembly, and monitoring
   g. Adoption Potential: Uptake of innovations by developers or incorporation into design guidelines and permitting frameworks

v. References: The proposed concept is supported by a strong body of literature highlighting both the critical need and transformative potential of innovation in floating offshore wind. The DOE's previous Floating Offshore Wind Shot set a significant cost target of 75% reduction by 2035 to unlock over 2,000 GW of deep-water wind capacity, much of it off the U.S. West Coast (DOE, 2022; NREL, 2023). Key market barriers include high lifecycle costs, limited port infrastructure, and uncertainty in platform durability and maintenance (IEA, 2019; NREL, 2023). Studies emphasize the need for advances in corrosion-resistant materials, modular construction, and embedded sensing for structural health monitoring (DOE O&M Roadmap, 2023). Circular design and recycling strategies further improve long-term sustainability (DOE WETO, 2021). Workforce assessments project tens of thousands of new jobs annually if supply chains and training programs are strengthened.

These references demonstrate that targeted RD&D in floating platform technologies aligns with both state and national energy goals.

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: The proposed concept directly supports California's goals by enabling large-scale deployment of floating offshore wind—one of the most promising and necessary energy sources for the state's deep coastal waters. By advancing durable, intelligent, and cost-effective floating platform technologies, the concept helps unlock multi-gigawatt offshore wind capacity in the Humboldt and Morro Bay lease areas.

viii. Contributors to This Concept Include: Yuxin Wu

6. Natural and Stimulated Geologic Hydrogen in California

i. Description: To unlock the full value of geologic hydrogen, a series of research breakthroughs are needed to de-risk and scale the use of natural and stimulated hydrogen in California, including:

a. Development of understanding and associated tools to assess the currently unexplored subsurface for its potential for natural hydrogen in California. This will require an integrated workflow that combines surface gas collection and analysis, isotope geochemistry, and surface and/or subsurface geophysics, all combined with reactive flow and transport physics-based and AI modeling to assess the feasibility of finding and extracting natural hydrogen resources from the subsurface. The integrated workflow will enable substantial improvements in our ability to target subsurface natural hydrogen resources by identifying promising exploration sites.

b. Assessment of currently unexplored resources for seismic-safe stimulation of geologic hydrogen in ultramafic and mafic rocks in California, with quantitative predictions of expected hydrogen generation and extraction rates achievable from the depths, temperatures, and pressures of interest in the subsurface. These analyses would factor in laboratory-determined data on reaction rates and pathways as well as changes to rock physical properties as a function of temperature, pressure, and chemistry, and would quantify the water required for hydrogen generation and extraction. The workflow here would include field-scale characterization and prediction of permeability (especially fracture-controlled permeability) as it affects the ability to introduce the water needed to stimulate and extract hydrogen. Note that ultimately the workflow may involve the development of new and novel sensors for characterization of the subsurface.

There are two possible areas where the TRL level for geologic hydrogen may be higher, and this can be carefully investigated in California: (1) Orphan wells across the state, some of which may show geologic hydrogen levels of interest; (2) Co-production with geothermal and other geo-resources, where the production infrastructure already exists. Either of these could substantially raise the TRL for Geo H2 if proven.

Why EPIC 5?
Initial funding for some of this came from DOE ARPA-E, however the focus was not on exploration, field-scale exploration and also it was not focused on California. This concept will leverage the work done to develop CA-centric geologic hydrogen and co-production with geothermal and other geo-resources.

ii. Breakthroughs: This concept supports California's energy goals by addressing key barriers to the development of economically feasible natural and stimulated geologic hydrogen. The objective is to develop strategies and associated workflows that will take the field of geologic hydrogen beyond "seat of the pants" exploration. The integrated toolset will include a combination of subsurface and surface geochemistry and geophysics to provide a much-improved basis for making exploration decisions, especially as it reduces the uncertainty associated with costly (and potentially unsuccessful) drilling.
    a. Key Barriers Addressed:
        1. Exploration Risk: The project will integrate physics-based modeling and geoscientific data to provide training for the latest generation of AI tools that can be used to create refined and high-resolution resource maps and/or volumes for geologic hydrogen, thus de-risking exploration by lowering early-stage geologic hydrogen exploration costs and reducing uncertainty.

2. Mitigation of Risks and Monitoring: Coupled process modeling combined with high-resolution geochemical, geological, and geophysical imaging will reduce the risks associated with subsurface investigations for both natural and stimulated hydrogen, thus providing for safer project design and permitting.
3. Siting Challenges: Resource mapping will guide planning of the co-location of stimulated and natural hydrogen sites with local energy users.

iii. Outcomes: Targets and Benefits:
   a. Reduce the need for drilling by 75% via an integrated workflow that reduces uncertainty; Identify specific targets for both natural and stimulated geologic hydrogen.
   b. Data Gaps & End Users: Identifies the key data gaps in terms of favorable rock types, permeability, and the optimal depth, pressure, and temperature conditions for successful and cost-effective exploration for natural hydrogen; Identifies favorable formations and depth (temperature + stress) windows for geologic hydrogen stimulation.
   c. Innovation at Scale: If the workflow for either natural hydrogen or stimulated hydrogen is demonstrated in California with its abundant ultramafic rocks, then this offers a huge potential for the entire state.
   d. Fills Gaps: Integrated subsurface resource assessments, seismic risk analysis, and infrastructure alignment.
   e. Beneficiaries: State agencies—in terms of infrastructure and resource planning; Developers—for de-risking the siting of projects; Utilities—leveraging reliable, dispatchable energy and grid planning; and local communities— leveraging local development of resources, with use of the local labor force.

iv. Metrics: The metrics for natural and stimulated hydrogen would consider exploration costs, including drilling and personnel, versus the value of potential exploitable resources. More specifically, the achievable flux of geologic hydrogen (e.g., kg H_2/s) to the surface multiplied by its value would be compared directly to the exploration and transportation costs.

v. References: The potential economic benefits here are vast, and of considerable interest to the State of California. So this turns primarily on establishing the viability of 1) exploration via drilling, and 2) subsurface stimulation of hydrogen. Until viability is established, cost targets and market barriers are premature. The technical potential, however, has recently been demonstrated in the laboratory at Berkeley Lab, where hydrogen was produced by circulating hot water through ultramafic rock collected in California.

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Distributed Energy Resource Integration

vii. Support for Goal: This is largely described above. The integrated workflow would lower the cost of exploration by reducing the need for drilling, and by improving the success rate of such drilling. And by aiding in the design of subsurface stimulation campaigns, it would go a long way toward demonstrating the feasibility of the technology.

viii. Contributors to This Concept Include: Carl Steefel, Mengsu Hu, Ben Gilbert, David Alumbaugh, Adam Weber

7. Comprehensive “Geo-oriented” Energy Resource Analysis

i. Description: This concept proposes a comprehensive analysis of California’s co-located geothermal, storage and geothermal hydrogen and raw material resources to identify high-potential zones for integrated energy development and up-scaling recent technology developments at optimized costs. It addresses the current gaps in California’s resource assessment that misses recent technological breakthroughs such as Enhanced Geothermal Systems (EGS), industrial heat storage and hydrogen. The study would combine both existing and new geological, geophysical, and geochemical data, and apply machine learning approaches to map subsurface characteristics and assess the integrated production from geothermal systems. Multi-scale coupled processes modeling will provide evaluation of economic potential and mitigation of seismic risks. Assessment will also be integrated with locations of existing infrastructure. The purpose is to de-risk early-stage exploration and inform infrastructure planning for future energy hubs. EPIC funding is critical to support this cross-cutting, pre-commercial research that private industry is unlikely to fund due to high uncertainty and limited near-term returns. The results would directly support California’s energy goals by advancing innovative, place-based strategies for secure energy, hydrogen and critical materials.

ii. Breakthroughs: This concept supports California’s energy goals by addressing key barriers to the deployment of geothermal energy, geothermal hydrogen, subsurface storage, and critical materials recovery. These resources remain underutilized due to high exploration risk, data gaps, and lack of integrated planning tools.

a. Key Barriers Addressed:

1. Exploration Risk: The project uses AI and integrated geoscientific data to create resource maps, reducing uncertainty and lowering early-stage geothermal and hydrogen exploration costs.
2. Lack of Integrated Resource Assessment: It introduces a co-optimization framework to evaluate geothermal energy, hydrogen production, and critical material extraction together, improving project economics.
3. Mitigation of Risks: Coupled process modeling will assess subsurface flow behavior and associated risks and, enabling safer project design and permitting.
4. Siting Challenges: Infrastructure and resource mapping will guide planning of energy hubs that align with existing transmission and water infrastructure.

b. Targets and Benefits:
  1. Improve geothermal resource prediction accuracy by 50%.
  2. Identify zones for geothermal hydrogen production.
  3. Increase project IRRs through co-development strategies.

c. Data Gaps & End Users:
  1. Fills Gaps: Integrated subsurface resource assessments, seismic risk analysis, and infrastructure alignment.

d. Beneficiaries:
  1. State agencies (CEC, CPUC): Infrastructure and resource planning
  2. Developers: De-risked project siting
  3. Utilities: Reliable, dispatchable energy planning
  4. Communities: Informed local development

This research is essential for advancing place-based, integrated energy systems and de-risking early-stage energy investments—work that is unlikely to be funded by the private sector alone.

iii. Outcomes: Anticipated Outcomes and Ratepayer Benefits

If successful, this research concept would significantly advance California's ability to develop integrated geothermal energy hubs, combining geothermal power, energy storage, geothermal/natural hydrogen production, and critical mineral recovery. The anticipated outcomes align strongly with EPIC's guiding principles and would contribute to ratepayer benefits in the following ways:

a. Reduction in Technology and Ratepayer Costs
  1. Improved resource targeting through advanced geoscientific analysis and machine learning will reduce exploration risk and cost, a major barrier to geothermal and co-located resource development.

2. By identifying high-potential zones for multi-resource integration, the research supports cost-sharing across technologies (e.g., using combined geothermal, critical material and hydrogen production), reducing overall development and operational costs.
3. This de-risking can shorten permitting and development timelines, lowering costs passed on to ratepayers in future projects.

b. Increased Performance and Value Proposition
    1. Multi-scale coupled process modeling will optimize production strategies, helping to increase the efficiency of energy, hydrogen, and material recovery.
    2. Co-location and infrastructure alignment (e.g., proximity to transmission or industrial loads) will maximize the return on investment for public and private infrastructure.
    3. This integrated approach improves energy system resilience and reliability by diversifying generation and storage at a single site.

c. Potential at Scale
    1. Once high-potential zones are identified and validated, the framework can be replicated statewide or even nationally, enabling the strategic development of other energy hubs.
    2. The research would position California as a leader in integrated subsurface resource utilization, attracting further investment and enabling scalable deployment of advanced energy technologies.

d. Alignment with EPIC Guiding Principles
    1. Safety: Improved understanding of subsurface systems and seismic risk modeling will reduce hazards related to geothermal and hydrogen operations.
    2. Reliability: Co-located systems can provide firm, dispatchable power, supporting grid reliability and enabling greater penetration of DERs.
    3. Affordability: Lower exploration and integration costs will translate to more cost-effective energy solutions for ratepayers.
    4. Environmental Quality: The concept promotes the efficient use of subsurface resources, reducing land use and emissions through co-located technologies.
    5. Ratepayer value: Prioritizing infrastructure alignment and place-based strategies particularly in the Imperial Valley and other resource-rich but economically challenged areas.

    This research would generate critical pre-commercial knowledge to unlock the potential of integrated geothermal-based energy hubs in California. It will lay the groundwork for future public and private investment, accelerate progress toward California's decarbonization goals, and deliver long-term benefits to ratepayers through lower costs, improved reliability, and enhanced environmental and social outcomes.

iv. Metrics: To comprehensively assess the outcomes and value of this research, a combination of quantitative and qualitative metrics should be used. These metrics are aligned with the goals of the EPIC program and the broader objectives of advancing integrated geothermal-based energy.

a. Quantitative Metrics

1. Number of High-Potential Zones Identified
2. Count of geologically and infrastructurally viable sites identified for integrated geothermal, hydrogen, storage, and critical material development.
3. Benchmark: ≥5 zones with detailed characterization.
4. Reduction in Exploration Uncertainty
5. Measured through improvements in subsurface characterization accuracy (e.g., depth to reservoir, temperature gradient, permeability estimates).
6. Comparison of pre- and post-analysis uncertainty ranges.
7. Modeled Resource Potential
8. Estimated megawatts of geothermal energy, kilograms/day of hydrogen, and tons/year of recoverable critical materials at identified sites.
9. Economic potential based on techno-economic modeling results.
10. Seismic Risk Assessment Outputs
11. Quantitative reduction in modeled seismic hazard under optimized development scenarios.
12. Number of scenarios evaluated and mitigation strategies proposed.
13. Cost Projections for Integrated Development
14. Estimated cost per MW or kg of hydrogen for integrated systems versus stand-alone development.
15. Potential cost savings from co-location and shared infrastructure.
16. Alignment with Existing Infrastructure
17. Number or percentage of identified zones located within a defined distance of key infrastructure (e.g., transmission, water, road access).

18. Geospatial analysis outputs demonstrating development readiness.

b. Qualitative Metrics

1. Stakeholder and Industry Engagement
2. Number of stakeholder interviews or workshops conducted.
3. Qualitative feedback from developers, utilities, and local communities on the usability of the results.
4. Value of Decision-Support Tools and Maps Produced
5. User feedback from policymakers and planners on the usefulness of deliverables (e.g., geospatial data layers, site prioritization tools).
6. Replicability and Scalability
7. Assessment of the framework's applicability to other regions in California or the western U.S.
8. Documentation of methodology that supports replication.
9. Academic and Technical Dissemination
10. Number of publications, conference presentations, or publicly available datasets resulting from the research.

c. By applying a blend of quantitative indicators (e.g., resource potential, cost estimates, seismic risk modeling) and qualitative assessments (e.g., stakeholder feedback), the project will deliver measurable outcomes that demonstrate its value, scalability, and alignment with California's energy goals.

v. References:

a. https://docs.nrel.gov/docs/fy23osti/85033.pdf

b. https://www.osti.gov/servlets/purl/897111

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Distributed Energy Resource Integration

vii. Support for Goal: This concept contributes to EPIC goals in two fundamental and complementary ways.

First, by conducting a comprehensive assessment of California's co-located geothermal, storage, hydrogen, and critical mineral resources, this project supports the identification of high-potential zones for integrated, multi-resource energy development. By incorporating recent technological breakthroughs—such as Enhanced Geothermal Systems (EGS), industrial-scale heat storage, and geothermal hydrogen production—the project addresses critical gaps in current state-level resource assessments, which often overlook the synergies enabled by these innovations. These integrated systems can provide baseload-capable, dispatchable energy, which is essential for reaching the most challenging stage of California's decarbonization pathway: the "last 10%" of grid emissions. As solar and wind reach higher levels of penetration, firm, location-specific energy capacity will be crucial to maintaining grid reliability, flexibility, and year-round decarbonized energy supply. This effort directly aligns with EPIC's mission to accelerate the development and deployment of pre-commercial, transformative technologies that enhance California's energy system.

Second, by mapping and evaluating the co-production potential of critical raw materials—including lithium, rare earth elements, and materials for long-duration storage—the project directly supports the state's broader climate resilience and technology supply chain goals. These minerals are fundamental to the manufacture of batteries, hydrogen systems, and other low-emissions infrastructure, and securing a domestic source reduces both economic and geopolitical risks. The integration of machine learning techniques with multi-scale coupled modeling will enable robust analysis of subsurface characteristics, mitigate seismic risks, and provide reliable forecasts of technical and economic feasibility. By overlapping this resource assessment with existing infrastructure, the project also informs the siting and planning of future energy hubs, where energy production, storage, and materials recovery can be co-located to maximize efficiency and minimize cost.

Together, these efforts—leveraging California's vast subsurface potential—address several key EPIC priorities: grid decarbonization, critical minerals independence, and technology innovation. Importantly, the focus on early-stage exploration and infrastructure-informed planning will de-risk future development and expand energy access to local communities, especially in geologically promising but historically overlooked regions. The project will not only accelerate progress toward the state's goals, but also provide a scalable model for integrated, place-based energy systems that can be replicated across California and other energy frontiers.

viii. Contributors to This Concept Include: Eva Schill, Mengsu Hu

8. Extended Assessment of the Lithium Valley Subsurface

i. Description: This concept on the Lithium Valley proposes an extended assessment of the Lithium Valley subsurface to identify hidden critical mineral resources co-located with geothermal systems, expanding the scope beyond the well-characterized Salton Sea geothermal field. Special attention will be given to the areas surrounding the Salton Sea, with the goal of uncovering new opportunities for integrated resource development that can benefit California broadly, and local stakeholders in the area in particular.

The project will integrate existing and newly collected geological, geochemical, and geophysical data with advanced machine learning techniques and multi-scale coupled process modeling to characterize the subsurface and evaluate the technical and economic potential of integrated geothermal and mineral recovery systems.

By de-risking early-stage exploration and enhancing subsurface visibility, the study will inform strategic investment decisions and infrastructure planning for future development of geothermal energy and critical materials in southern California.

EPIC funding is essential to support this pre-commercial, cross-cutting research, which carries high uncertainty and limited near-term returns, making it unlikely to be funded by the private sector. The outcomes of this work will directly advance California's energy goals by supporting the secure, and affordable development of domestic energy and mineral resources, strengthening grid resilience, supply chain security, and economic opportunity for ratepayers and communities alike.

ii. Breakthroughs: This concept supports California's energy goals by addressing key barriers to an increase in deployment of geothermal energy and critical materials recovery.
   a. Key Barriers Addressed:
      1. Exploration Risk: The project uses AI and integrated geoscientific data to identify hidden resources, reducing uncertainty and lowering early-stage geothermal and critical material exploration costs.
      2. Mitigation of Exploitation Risks: Coupled process modeling will assess subsurface flow behavior and associated risks, enabling safer project design and permitting.
      3. Targets and Benefits: Identify zones for geothermal and critical minerals production.
      4. Data Gaps & End Users: Integrated subsurface resource assessments
      5. Beneficiaries: State agencies (CEC, CPUC): Infrastructure and resource planning; Developers: De-risked project siting; Utilities:

Reliable, dispatchable energy planning; Communities: Informed local development

b. This research is essential for advancing place-based, integrated energy systems and de-risking early-stage energy investments—work that is unlikely to be funded by the private sector alone.

iii. Outcomes: Anticipated Outcomes and Ratepayer Benefits

If successful this research concept would significantly advance southern California's ability to develop integrated geothermal energy and critical mineral extraction. The anticipated outcomes align strongly with EPIC's guiding principles and would contribute to ratepayer benefits in the following ways:

a. Reduction in Technology and Ratepayer Costs
    1. Improved resource targeting through advanced geoscientific analysis and machine learning will reduce exploration risk and cost, a major barrier to geothermal and co-located resource development.
    2. By identifying hidden zones for multi-resource integration, the research supports cost-sharing across technologies such as combined geothermal and critical material production, reducing overall development and operational costs.
    3. This de-risking can shorten permitting and development timelines, lowering costs passed on to ratepayers in future projects.
b. Increased Performance and Value Proposition
    1. Multi-scale coupled process modeling will optimize production strategies, helping to increase the efficiency of energy and material recovery.
    2. Co-location and infrastructure alignment (e.g., proximity to transmission or industrial loads) will maximize the return on investment for public and private infrastructure.
c. Potential at Scale
    1. Besides the leadership in geothermal production, the research would position California as a leader in critical mineral extraction from geothermal brine, attracting further investment and enabling scalable deployment of advanced energy technologies.
d. Alignment with EPIC Guiding Principles
    1. Reliability: Co-located systems can provide firm, dispatchable power, supporting grid reliability and enabling greater penetration of DERs.
    2. Affordability: Lower exploration and integration costs will translate to more cost-effective energy solutions for ratepayers.

3. Environmental Quality: The concept promotes the efficient use of subsurface resources, reducing land use
4. This research would generate critical pre-commercial knowledge to unlock the geothermal potential in southern California. It will lay the groundwork for future public and private investment, accelerate progress toward California's energy goals, and deliver long-term benefits to ratepayers through lower costs and improved reliability

iv. Metrics: Metrics to Evaluate the Impacts of the Proposed Research Concept - To comprehensively assess the outcomes and value of this research, quantitative metrics will be used. These metrics are aligned with the goals of the EPIC program and the broader objectives of advancing integrated geothermal-based energy development.
   a. Number of Hidden Zones Identified
      1. Benchmark: ≥5 zones with detailed characterization.
   b. Reduction in Exploration Uncertainty
      1. Measured through improvements in subsurface characterization accuracy (e.g., depth to reservoir, temperature gradient, permeability estimates).
      2. Comparison of pre- and post-analysis uncertainty ranges.
   c. Modeled Resource Potential
      1. Estimated megawatts of geothermal energy and tons/year of recoverable critical materials at identified sites.
      2. Economic potential based on techno-economic modeling results.
   d. Cost Projections
      1. Estimated cost per MW and kg of critical materials.
      By applying a blend of quantitative indicators , the project will deliver measurable outcomes that demonstrate its value, scalability, and alignment with California's secure energy goals.

v. References: https://docs.nrel.gov/docs/fy23osti/85033.pdf https://www.osti.gov/servlets/purl/897111

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: First, by targeting hidden and underexplored geothermal resources in Southern California—particularly those co-located with critical mineral systems—this project supports the expansion of baseload-capable, dispatchable electricity. Such resources are essential for addressing the most challenging phase of California's decarbonization strategy: the "last 10%" of the electricity sector's transition to lower emissions operations. As intermittent sources like solar and wind approach saturation, additional firm capacity becomes increasingly vital to ensure grid reliability, stability, and year-round energy supply. Geothermal energy offers a uniquely suited solution, and unlocking new geothermal potential directly supports EPIC's mandate to advance innovative, pre-commercial technologies that enhance energy system resilience.

Second, the co-production of critical materials—such as lithium, manganese, and rare earth elements—has far-reaching implications for achieving statewide climate and energy goals. These materials are essential for large-scale energy storage systems, electric vehicles, and other low-emissions technologies. By identifying and characterizing new subsurface mineral resources, this project addresses known supply chain vulnerabilities and aligns with California's efforts to secure a domestic, responsible, and supply of energy-relevant minerals. In doing so, it enables the deployment of the storage technologies necessary to integrate DERs and improve the grid resilience.

Together, these efforts—expanding geothermal energy and sourcing critical minerals domestically—directly address multiple EPIC priorities, including grid decarbonization, technology innovation, economic development, and energy access, especially for all populations in the Salton Sea region. The outcomes will not only support the state's goals but also create a blueprint for integrated energy and resource systems that can be replicated across the state and beyond.

viii. Contributors to This Concept Include: Eva Schill, Peter Nico

9. Stakeholder-responsive Lifecycle Assessment (LCA) for Emerging Generation and Storage Technologies

i. Description: This concept proposes the development of a novel, stakehonde-responsive lifecycle assessment (LCA) methodology tailored to emerging generation and storage technologies, piloted using a distributed pumped storage hydro (D-PSH) system developed by the University of Utah and collaborators. D-PSH is a modular, closed-loop system designed for deployment near underutilized hydropower infrastructure, capable of delivering long-duration energy storage while reducing environmental and siting constraints. The purpose of this project is to design transparent, replicable LCA workflows that align with local stakeholder and information needs by integrating rigorous scientific modeling with participatory, stakeholder-informed processes.

The project responds directly to CEC Strategic Objective (G) by advancing impact research that is co-created with communities and addresses economic, land, air, water, net energy, health, and safety impacts. Unlike conventional LCA approaches, which often lack contextual sensitivity or public transparency, this effort will explore how LCA methods can be reshaped to incorporate stakeholder engagement, cumulative impacts, and geographically specific risks and benefits.

EPIC funds are needed to support this effort because traditional market forces and federal R&D funding mechanisms do not prioritize stakeholder-led analysis of emerging energy infrastructure. Without dedicated support, communities lack tools and resources to evaluate technologies like D-PSH in ways that reflect their localized priorities, values, and risks. This project addresses that gap while strengthening the methodological foundations for broader impact research across the EPIC portfolio.

ii. Breakthroughs: This concept addresses several technical and market barriers that currently limit the adoption of long-duration energy storage systems like D-PSH. These include:

   a. Insufficient publicly validated, project-specific lifecycle data on environmental, economic, and health-related impacts
   b. A lack of stakeholder-informed frameworks for interpreting the tradeoffs and benefits of emerging storage technologies
   c. Gaps in stakeholder trust and capacity to engage in project evaluation processes.

By integrating localized environmental and socioeconomic indicators—such as land use, water availability, air quality, and infrastructure proximity—this research fills key data and process gaps in both lifecycle impact assessment and public engagement. The methods developed will benefit state energy planners, local governments, developers, and local stakeholder organizations by offering a replicable, participatory framework for evaluating emerging storage projects in the context of siting, permitting, and planning decisions. These tools help overcome barriers related to transparency, siting opposition, and procedural trust, ultimately supporting accelerated, lower-risk deployment of long-duration storage across California.

iii. Outcomes: If successful, this project will:

a. Deliver a complete lifecycle inventory and impact assessment of the D-PSH technology, co-developed with stakeholder input and focused on relevant indicators (e.g., emissions, land use, water consumption, visual/aesthetic impacts).
b. Produce a flexible, stakeholder-responsive LCA methodology, with templates and guidance materials for replication in other contexts or technologies.
c. Demonstrate measurable improvements in stakeholder understanding and trust regarding D-PSH and related infrastructure, evaluated through surveys and engagement feedback.
d. Create public-facing, plain-language summaries of lifecycle results (e.g., fact sheets, infographics, short videos) for use in outreach and permitting discussions.
e. Provide actionable recommendations for integrating stakeholder-centered LCA into CEC and CPUC planning and siting processes.

These outcomes will improve technology readiness and reduce deployment risk, helping ensure that long-duration storage options like D-PSH are both technically viable and socially acceptable.

iv. Metrics:
a. Number of stakeholder groups engaged and level of satisfaction with participatory LCA processes.
b. Completion of a lifecycle assessment using stakeholder-informed indicators and weighting schemes.
c. Incorporation of LCA results into communications for D-PSH siting or permitting activities.
d. Replication of the methodology in at least one other EPIC or publicly funded project.
e. Inclusion of plain-language materials and stakeholder-facing impact summaries in the final project outputs.
f. Policy uptake: Integration of stakeholder-responsive LCA findings into agency decision-support tools.

v. References: D-PSH technology has been proposed to address California's need for scalable, long-duration storage to balance variable renewable generation and enable decarbonization of the grid (University of Utah technical proposal, 2024). The CEC's Long-Duration Energy Storage Midterm Gap Analysis (2022) notes the need for site-flexible, modular storage technologies with minimal environmental impacts and local acceptance risks. Previous siting controversies (e.g., with large-scale renewables or conventional PSH) demonstrate the importance of transparent, participatory impact assessment in achieving successful deployments. Literature on public engagement underscores the gap in tools for stakeholder-centered evaluation of infrastructure projects (e.g., Williams et al. 2020, Carley et al. 2021).

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: This concept directly advances Strategic Objective Impacts Research for new generation and storage and supports multiple EPIC 5 goals by: (1) Providing a replicable framework for transparent impact assessment of new storage technologies; (2) Reducing procedural barriers and trust deficits that slow adoption of energy projects in among local stakeholders; (3) Supporting resilience by improving siting and deployment pathways for long-duration storage that balances variable generation sources. (4) Enabling smarter co-design of energy infrastructure to align with goals while reducing opposition and unintentional harms. (5) Improving distributed energy deployment by validating technologies like D-PSH that can be sited more flexibly and operated with lower environmental footprint.

viii. Contributors to This Concept Include: Margaret Taylor, Jenn Stokes-Draut (not yet confirmed, but involved in previous effort with Sonoma Water), Peter Benoliel, Sydny Fujita

10. M/L Accelerated Development of Next-gen Batteries

i. Description: CEC should fund an effort that uses advances in machine learning that lead to life prediction of energy storage technologies as a function of use, where a few representative samples are required as many of the newly proposed systems are expensive to build and test. This is presently not being supported and is fairly new with the advent of new machine learning techniques. This would be a first step for CEC in deciding to further invest in a particular technology and to determine how well any investment is advancing toward its technical goals.

ii. Breakthroughs: New technologies are needed to meet the stringent targets set by CEC to meet its objectives. CEC will not know how to decide which technology to adopt without some assurance that the technology will meet its technical targets. This is a way to provide accurate estimates of expected performance over the lifetime of its use.

iii. Outcomes: This capability will allow CEC the ability to properly test technologies or give OEMs the tools to properly test technologies such that it can make wise decisions in its selection of technologies to put on the grid that will be cost competitive without wasting millions of taxpayer dollars betting on an unsuccessful technology.

iv. Metrics: The results of this testing methodology will provide the average life of a battery under various cycling and temperature scenarios and more importantly the distribution of the life of batteries that will highlight the expense of technologies that have a wide spread of early failures, saving the state millions of dollars in selecting a technology with an unacceptable early failure rate.

v. References: Alghalayini, Maher B; Collins-Wildman, Daniel; Higa, Kenneth; Guevara, Armina; Battaglia, Vincent; Noack, Marcus M; Harris, Stephen J

vi. "Machine-learning-based efficient parameter space exploration for energy storage systems" https://doi.org/10.1016/j.xcrp.2025.102543

vii. Strategic Goal: Achieving 100% Net-Zero, DER Integration, transportation electrification

viii. Support for Strategic Goal: There is an urgent need for novel and next-generation battery technologies that are not vulnerable to supply chain challenges or based on materials that are abundant. Testing these batteries for ensuring their reliability, safety and performance in a cost-effective way will accelerate the scale-up, adoption and deployment of next-gen batteries for behind the meter storage as well as stationary storage on the grid for better DER integration, resilience and grid reliability.

ix. Contributors to This Concept Include: Vince Battaglia

11. Bridging Expensive Commercial Platforms and Basic Controls in Distributed Battery Storage

   i. Description: California's distributed battery storage sector faces a critical problem: over 80% of smaller installations operate with basic controls that ignore battery health, significantly underperforming their potential. Advanced optimization platforms cost over $100,000 annually, creating a barrier that prevents municipal utilities, rural cooperatives, and local stakeholders from accessing better technology. This gap is particularly significant as the global BESS optimization software market grows from $25-32B in 2024-2025 to $114-172B by 2030-2032.

      OpenBESS solves this through a low-cost optimization platform that uses machine learning to track battery health and maximize performance. The system focuses on Lithium Iron Phosphate (LFP) batteries, which capture 87% of market share, and runs on standard computers while providing transparent, auditable decision-making that meets regulatory requirements.

      EPIC funds are essential to develop this accessible solution that bridges expensive commercial platforms and basic controls. This would accelerate California's battery storage deployment, improve DER integration, and ensure all communities can access advanced optimization technology, directly supporting the state's energy goals while reducing costs for ratepayers.

      a. Breakthroughs: OpenBESS addresses critical barriers preventing achievement of SB 96's goals by making sophisticated battery optimization affordable for all operators.
         1. Market Breakthrough: Current optimization platforms costing $100,000+ annually create a two-tier market where most distributed storage systems operate poorly. OpenBESS bridges this gap through machine learning that automatically learns battery aging patterns from real operational data, solving the challenge of applying laboratory battery research to real-world systems with thousands of individual battery cells.
         2. Performance Targets: The platform targets under $10,000 annual costs—a 90% reduction from current solutions—while delivering 15-25% revenue improvements and completing optimization calculations in under 10 seconds on standard computers. This

        makes advanced optimization accessible to municipal utilities, rural cooperatives, and mid-sized developers previously shut out of the market.
    3. Data Gaps Addressed: OpenBESS tackles the critical shortage of real-world battery performance data through validated testing methods. Municipal utilities gain affordable optimization tools; rural cooperatives access battery health-aware operation; researchers obtain standardized datasets; policy makers receive transparent frameworks for oversight.

       This breakthrough enables California's energy goals by accelerating distributed storage deployment essential for DER integration while ensuring fair access across all ratepayer types.

ii. Outcomes: Cost and Performance Improvements: Success would reduce optimization costs by 90% (from $100,000+ to under $10,000 annually) while delivering 15-25% revenue improvements through battery health-conscious operation. This transforms distributed storage economics, making previously unprofitable projects viable while extending battery equipment life.
    a. Impact at Scale: OpenBESS would bring advanced optimization to California's smaller battery installations, targeting a $5-10B addressable market for accessible optimization platforms. Hundreds of distributed storage systems operating intelligently would create combined benefits through better DER coordination and improved grid stability during peak demand. The platform also creates expansion opportunities to markets like ERCOT, which offers immediate potential with 7+ GW operational capacity.
    b. EPIC Principle Benefits:
        1. Affordability: Lower optimization costs enable more storage deployment while reducing grid costs passed to ratepayers
        2. Reliability: Battery health-conscious operation extends battery equipment life and prevents unexpected failures, improving grid reliability during critical periods
        3. Environmental Quality: Better asset utilization accelerates DER integration by optimizing storage throughout battery equipment lifecycles
        4. Safety: Transparent, auditable algorithms ensure compliance with operational safety requirements

The platform creates smart foundations for California's distributed energy transition with comprehensive optimization accessible to all operator types.

c. Metrics:
    1. Quantitative Performance Metrics:
        a. Revenue improvement: 15-25% increase over basic controls
        b. Cost reduction: 90% decrease in optimization expenses (target: <$10,000 annually)
        c. Battery life extension: cycles to 80% capacity remaining
        d. Time-series forecasting accuracy: prediction errors <5%
        e. System integration success rates with existing equipment
        f. Market adoption: 50% of smaller installations within 5 years
    2. Qualitative Assessment Indicators:
        a. Compliance rates for transparent frameworks
        b. Operator satisfaction with ease of use and integration
        c. Compliance success and regulatory acceptance
        d. DER integration improvements during peak periods
        e. Stakeholder participation rates
        f. Geographic spread ensuring fair access
    3. Evaluation Methods: Metrics tracked through operator data, regulatory filings, operator surveys, and independent assessments to ensure comprehensive evaluation of technical performance, market

d. References: The research addresses documented market barriers where commercial optimization platforms require six-figure annual budgets as primary deployment barriers, while the sub-20MW segment represents a significant underserved market with faster permitting and reduced regulatory requirements. Current platforms rely on simplified degradation models leading to significant prediction errors versus actual performance.
    1. Technical Potential: The project targets 10-15% reduction in Levelized Cost of Storage through battery health-aware optimization. California BESS market shows clear saturation indicators with revenue compression signaling a shift from basic arbitrage strategies to sophisticated optimization requirements. Current CAISO market data shows energy arbitrage constitutes approximately 90% of battery revenue, with average monthly revenues around $2.73/kW-month as of June 2025.

2. Market Barriers: No existing platform adequately addresses modular battery replacement scenarios, where operators replace 10-20% of modules every 3-5 years. Policy decision makers increasingly demand systematic tracing and validation of optimization decisions, while current black-box systems fail these transparency requirements.
3. Accessibility Benefits: California's Self-Generation Incentive Program provides $150-300/kWh standard incentives and up to $1,000/kWh for certain resiliency projects, with the 2025 Residential Solar and Storage Equity program adding $280 million in funding. Combined with the federal Investment Tax Credit's 30% base rate, these incentives can eliminate upfront hardware costs, making software optimization costs the dominant operational expense.
4. Market Integration: The modular design enables integration with existing energy management systems while providing pathways for capability enhancement as operator resources and expertise grow.
References: [1] "Optimal Capacity and Cost Analysis of Battery Energy Storage System in Standalone Microgrid Considering Battery Lifetime," MDPI, https://www.mdpi.com/2313-0105/9/2/76
5. CAISO BESS: The evolving revenue stack, June 2025, Modo Energy, https://modoenergy.com/research/ercot-caiso-june-2025-revenue-stack-batteries-bess-energy-arbitrage
6. "New battery storage on shaky ground in ancillary service markets," Utility Dive, https://www.utilitydive.com/news/new-battery-storage-on-shaky-ground-in-ancillary-service-markets/567303/
7. Self-Generation Incentive Program Handbook, California Public Utilities Commission, 2025, https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/self-generation-incentive-program/2025-sgip-handbook-v1.pdf
8. "How the 2025 Battery Storage Tax Credit Boosts Residential and Commercial Adoption" Infolink Group, https://www.infolink-group.com/energy-article/how-the-2025-battery-storage-tax-credit-boosts-residential-and-commercial-adoption

e. Strategic Goal: Primary Goal: Distributed Energy Resource Integration, Climate Adaption, and Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas
f. Support for Goal: OpenBESS directly supports California's distributed energy resource integration through several mechanisms:
    1. Enhanced Grid Integration: The platform optimizes distributed battery storage systems to better support DER integration by providing battery health-conscious operation that maximizes asset use while preserving battery equipment life. This enables more effective load shifting and grid stabilization services from distributed storage. With solar+storage systems approaching 50% of deployments by 2030, integrated optimization becomes increasingly critical for grid modernization.
    2. Improved Coordination: By making sophisticated optimization affordable across hundreds of distributed installations, OpenBESS enables coordinated participation in grid services. Municipal utilities, rural cooperatives, and local stakeholder organizations can effectively participate in demand response and grid stabilization programs previously accessible only to large-scale operators. The platform also supports Virtual Power Plant aggregation, a market growing from $5B to $16-24B by 2030.
    3. Market Participation Enhancement: The platform's transparent, auditable algorithms meet California grid operator requirements while providing the economic intelligence needed for effective market participation. This increases distributed resource participation in wholesale markets, improving overall grid efficiency and DER integration.
    4. Supporting Goals:
a. Achieving 100% Net-Zero Carbon Emissions: Enhanced distributed storage optimization accelerates DER integration by ensuring battery systems operate at peak efficiency throughout their lifecycles, maximizing the value of energy generation and storage.
b. Transportation Electrification: Optimized distributed storage provides the grid infrastructure needed to support widespread electric vehicle adoption, where state incentives make storage projects economically viable with proper optimization. The coordinated optimization of distributed storage resources creates the flexible grid capacity essential for EV charging infrastructure deployment.

The research directly enables California's energy transition by ensuring distributed storage resources—critical for grid modernization—operate optimally across all ratepayer types and geographic regions.

g. Contributors to This Concept Include: Stephen J. Harris

H. Increase Predictability of Weather, Intermittent Resources, and Load

1. AI Powered Hydro Meteorological Intelligence Platform

   i. Description: Projected intensification of extreme rainfall and worsening seasonal droughts in California are imposing dual threats on distribution infrastructure: flash flood saturation that undermines electrical distribution infrastructure, prolonged dry spells that amplify wildfire risk, damage overhead lines, and inflate outage related costs, and damages to housing sector from wildfires, and damage to property from flooding. We propose an AI powered Hydro Meteorological Intelligence Platform that fuses sub kilometer forecasts of both flood and drought hazards, ingesting real time gauge networks, NASA satellite data, and ancillary datasets, to deliver risk alerts that support immediate mitigation actions. Today, utilities pull in general weather forecasts from NOAA's HRRR (High-Resolution Rapid Refresh, 3km resolution hourly updated) and the regional WRF (Weather Research and Forecasting) model, check flood alerts on the National Weather Service site, track drought levels via the U.S. Drought Monitor, and consult fire-risk maps from CAL FIRE. These separate tools update on different schedules and do not share data. As a result, utilities cannot view combined flood–drought–fire scenarios or identify which power lines and substations face the greatest overall threat. Furthermore vulnerability assessment systems treat threats separately (Flood Risk-FEMA HAZUS, US Drought Monitor, CAL FIRE Hazards Severity Zones).

      a. Critical Objectives:

         1. AI Driven Downscaling: Develop and validate novel AI models that fuse multi-source hydrologic and meteorological datasets to generate reliable sub-kilometer forecasts of flood, drought, and wildfire hazards (ambitious), enabling truly localized risk mapping.
         2. Decision Support: Build an operational platform that ingests continuous hydrometeorological data and, within seconds, delivers dynamic scenario simulations and interactive risk dashboards, providing utilities, grid operators, and emergency responders with precise "when, where, and how severe" forecasts to inform their mitigation decisions.
         3. Asset Level Vulnerability Rankings: Generate a vulnerability score for each grid asset by overlaying detailed flood, drought, and wildfire forecasts onto asset locations, then produce a clear, ranked list of the highest-risk assets, allowing decision-makers to allocate

hardening investments where they achieve the greatest reduction in outage risk.

b. Stakeholder Pilot Coordination: Partnering with a utility and stakeholder advisors, we will install front- and behind-meter batteries in one high-risk neighborhood. Our tool will optimize sizing and dispatch to protect critical loads; performance data will refine deployments and pave the way for broader scaling.

By combining advanced AI downscaling, near-real-time decision support, and an investment-driven vulnerability ranking system, this research will transform how utilities forecast, prepare for, and respond to flood, drought, and wildfire threats—protecting critical energy assets, keeping communities safe, and reducing costs for California ratepayers. It directly fulfills the CEC's (California Energy Commission) Climate Adaptation mandate and represents an indispensable, innovative, and urgently needed investment for the resilience of California's grid.

ii. Breakthroughs: Our AI-powered platform harnesses deep learning and automated data fusion to overcome three persistent obstacles to grid resilience. First, to address kilometer-scale, multi-hour flood and drought forecasts (anticipating reduced hydropower generation and elevated wildfire risk) that leave utilities with insufficient lead time, we will deploy convolutional LSTM (Long Short-Term Memory) AI networks trained on rain and water-level (or stream-flow) observations collected by CDEC (California Data Exchange Center), NASA satellite data, radar rainfall estimates, and high-resolution terrain information) to downscale forecasts to sub-kilometer resolution (<1 km) and reduce end-to-end latency to under 60 minutes. We will teach the AI system to focus on the most critical part of each event, when flood or drought conditions peak, use simple, real-world rules to keep its predictions realistic, and feed it fresh data so it keeps improving over time. As a result, our alerts should arrive about 20–40 minutes earlier than they do today, and the overall accuracy of our forecasts should improve by roughly 5–10 % (In the recent and tragic Texas floods, Kerr County—where 130 lives were lost—did not receive CodeRED alerts until 90 minutes after floodwaters first rose. By contrast, in nearby Kendall County, sirens sounded within minutes of the rising waters, and no fatalities were reported). Second, to streamline data handling, we will implement AI-driven data-processing pipelines with built-in anomaly detection that consolidate multiple ingest streams into a single, standardized hazard data service, reducing processing overhead by 15–25

% and cutting operations and maintenance costs by approximately 10–20 %. Third, to translate raw forecasts into strategic action, machine-learning classifiers, trained on historical hazard (asset outcome pairs) will overlay hyper-local risk projections onto GIS-tagged poles, lines, and substations, producing ranked vulnerability scores. These scores empower investor-owned and municipal utilities to pre-position crews and orchestrate distributed energy resource dispatch (avoiding millions in costs per major event), enable Emergency Operations Centers to refine evacuation and staging decisions, and provide the California Public Utilities Commission with uniform, quantitative resilience metrics for benchmarking. We provide easy-to-use, actionable insights that close key data and software gaps, removing the roadblocks to better forecasts, smarter use of local energy resources, and cost-effective infrastructure upgrades, helping California hit its energy and grid-reliability goals.

iii. Outcomes: Upon successful implementation, this research will cut costs and boost grid performance. By converting high-resolution risk forecasts into actionable signals, utilities can target upgrades where they are needed most, potentially lowering hardening costs by 10–20 % and reducing downtime by 3–6 hours per event , which could save several million dollars.

Downscaling from 1–10 km to, for example, 500 m in under five minutes gives operators approximately 20–30 % more warning time. That extra lead time could reduce outage rates by 15–20 % during extreme weather.

Our modular system plugs into existing controls (SCADA: Supervisory Control and Data Acquisition) with minimal effort, so once one utility adopts it, others can quickly follow. The same AI+rainfall+soil-moisture+etc core can also aid water management, wildfire forecasts, and emergency response.

Aligned with EPIC's goals, this approach makes the grid more prepared and reliable, cuts capital and operational costs, reduces emissions by ~5–10 % during critical events (based on utility data showing DERs can offset 5–15 % of peaker-plant generation), and targets improvements in communities most affected by outages.

iv. Metrics: We will assess our success using clear metrics and real-world feedback. Quantitatively, we will measure how long it takes to issue an alert. from raw data to warning, aiming to cut latency < 1h. We will track forecast accuracy (RMSE) with a goal of 10 % error reduction and aim for

20–30 % longer lead times. We will also tally avoided grid-hardening upgrades (targeting a 10–20 % reduction) [We need a IOU contact to help with this] and planned-outage downtime saved (a few hours per event), while monitoring a 15–20 % drop in outage frequency and customer-hours lost during extreme weather. For environmental impact, we will compare peaker-plant fuel use before and after deployment, aiming for a 5–10 % emissions cut. Qualitatively, we will send quarterly surveys to utility operators and emergency responders to rate clarity, ease of use, and confidence in the alerts, seeking an average score of 4 out of 5 or higher, and we will map changes in outage-minutes per customer by ZIP code to ensure that local stakeholders see real gains. We will compile all these indicators into regular progress reports to keep stakeholders informed and drive continuous improvement. By linking specific targets to everyday operations, we make it easy to see what is on track and where adjustments are needed. Ultimately, this blend of hard data and user feedback will show that our platform not only works but makes the grid safer, fairer, and more cost-effective for everyone.

v. References:

a. AI-Driven Downscaling (500 m forecasts, RMSE reduction)
Oh et al (2022) fuse 1 km WRF/ERA5 inputs with fine-scale, multi-resolution topographic variables in a machine-learning framework. When compared to linear regression baselines, their ML model reduced RMSE by approximately 15 % over complex terrain and demonstrated markedly improved representation of sub-kilometer heterogeneity

b. Oh M, Lee J, Kim J, Kim H. (2022) Machine learning-based statistical downscaling of wind resource maps using multi-resolution topographical data. DOI: https://doi.org/10.1002/we.2718

c. Convolutional LSTM for Precipitation Nowcasting (lead time gains)
Klocek et al. (2021) showed 20–25 percent better skill scores and earlier and more reliable warnings for users and Kim et al. (2017) showed RMSE reductions.

d. Klocek S, Dong H, Dixon M, et al. (2021) MS-nowcasting: Operational Precipitation Nowcasting with Convolutional LSTMs at Microsoft Weather. DOI: https://doi.org/10.48550/arXiv.2111.09954

e. Kim S, Hong S, Joh M, Son S. (2017) Deeprain: ConvLSTM network for precipitation prediction using multichannel radar data. DOI: https://doi.org/10.48550/arXiv.1711.02316

f. Cost of Power Interruptions (outage cost savings)
La Commare et al (2018) provide an updated assessment of U.S.

electric-power customer interruption costs—revising the total annual cost to approximately $44 billion in 2015 dollars and detailing how costs vary by customer class and outage duration. Murphy (1977) lays out the classic cost–loss decision model, showing that the economic value of a forecast increases as its accuracy improves.

1. LaCommare K, Eto J, Dunn L, Sohn M (2018), Improving the estimated cost of sustained power interruptions to electricity customers, DOI: https://doi.org/10.1016/j.energy.2018.04.082
2. Murphy A (1977), The Value of Climatological, Categorical and Probabilistic Forecasts in the Cost-Loss Ratio Situation. DOI: https://doi.org/10.1175/1520-0493(1977)105<0803:TVOCCA>2.0.CO;2

g. Distributed Energy Resource (DER) Displacement of Peaker Plants
Denholm et al. (2013) uses production-cost simulations to show that bulk storage can replace a significant fraction of fast-ramping gas “peaker” capacity. Clean Energy Group reports document case studies where DER and storage deployment cut local emission in disadvantaged communities.

1. Denholm P, Ela E, Kirby B, Milligan M (2013) The Role of Energy Storage with Renewable Electricity Generation. Link: https://docs.nrel.gov/docs/fy10osti/47187.pdf
2. Clean Energy Group (2022), The Peaker problem , Link: https://www.cleanegroup.org/wp-content/uploads/The-Peaker-Problem.pdf

h. Reliability Metrics
Definitions for SAIFI, SAIDI, CAIDI metrics and EPIC reporting requirements:

1. IEEE Guide for Electric Power Distribution Reliability Indices, in IEEE Std 1366-2012 (Revision of IEEE Std 1366-2003) , vol., no., pp.1-43, 31 May 2012, doi: 10.1109/IEEESTD.2012.6209381.
2. California Public Utilities Commission Decision 12-05-037 (2013). Link: https://docs.cpuc.ca.gov/publisheddocs/word_pdf/final_decision/167664.pdf

vi. Strategic Goal: Climate Adaptation

vii. Support for Goal: The proposed AI powered Hydro Meteorological Intelligence Platform directly and measurably advances each of EPIC 5’s Climate Adaptation Strategic Goals:

a. Increase predictability of weather, intermittent resources, and load. We will deploy convolutional LSTM models that fuse CDEC gauge observations, NASA data, radar rainfall estimates, and high-resolution terrain data to produce sub-kilometer (e.g. 500 m) forecasts with end-to--end latency under 60 minutes. An AI-driven ETL (Extract, Transform Load) pipeline will automatically ingest, clean, and harmonize real-time gauge, satellite, radar, and terrain feeds into a single standardized API (service interface). Forecast outputs and analytics will be exposed via open APIs and interactive dashboards that integrate directly with utility SCADA systems, ISO (Independent System Operator)/RTO (Regional Transmission Organization) planning tools, and CPUC (California Public Utilities Commission) operations. Targets include a 15–20 % reduction in peak-event timing error (extending warning lead time from approximately 30 minutes to 45–60 minutes before impact) and a 10 % decrease in RMSE relative to legacy kilometer-scale forecasts. Impact: Operators will gain 20–30 % more actionable warning time, enabling proactive line reinforcement, targeted crew deployment, and optimized maintenance scheduling. Data-processing overhead will be cut by up to 30 % and Operations & Maintenance costs by 20 %, transforming reactive workflows into streamlined, anticipatory resilience.
b. Leveraging DERs for Grid and Community Resiliency. We will generate real-time vulnerability scores for each grid asset (poles, conductors, and substations) by overlaying hyper-local flood, drought, and wildfire risk projections onto GIS-tagged inventories and training machine-learning classifiers on historical hazard–asset outcome pairs. Phased field pilots include front- and behind-the-meter batteries, inverter-based resources, and microgrids, with a decision-support module recommending DER sizing, siting, and dispatch using social-burden and resilience metrics. Impact: DER portfolios will cover at least 10 % of peak event demand, reducing outage durations for critical facilities. Avoided downtime costs are expected to amount to savings of millions per major event. Demonstrated resilience gains and dispatch efficiencies will establish scalable, local stakeholder-focused DER deployment models.
c. Cost-effective long-term grid hardening: We will build an open, data-driven framework to guide capital investments. It will combine asset vulnerability scores, downscaled climate projections, and other indices to rank and prioritize grid-hardening projects. A field

demonstration on a single representative feeder will track key reliability metrics—SAIDI, SAIFI, and customer interruption duration—alongside actual cost outcomes. Those real-world results will be fed back into the ranking engine to continuously refine investment priorities. A public dashboard will transparently share assumptions, cost-benefit analyses, and performance results with regulators, ratepayers, and local stakeholders. Impact: We anticipate a 10–20 percent reduction in grid-hardening capital expenditures by 2033, saving millions annually while delivering measurable improvements in outage frequency and duration.

Overall, by combining cutting-edge AI downscaling, an automated data-fusion backbone, and an asset-centric resilience toolkit, this concept establishes a blueprint for scalable, and cost-effective grid resilience, directly advancing California toward its energy goals. This also addresses the strategic objectives K, L, and M - (K) Providing data input into a Value of DER Framework (L) Reducing feeder/circuit peaks (M) Cost-effective grid hardening for long-term climate impacts.

viii. Contributors to This Concept Include: Robinson Negron-Juarez, Qing Zhu (EESA), Max Wei (ETA)

2. Physics-driven toolkit for Wildland-Urban Interface (WUI) retrofits and new urban developments

   i. Description: The proposed concept delivers a scalable, physics-driven toolkit for both Wildland-Urban Interface (WUI) retrofits and new urban developments. By coupling high-resolution CFD simulations of wind-driven ember transport and radiative heat flux with urban morphology analysis, we will derive dynamic metrics (e.g., Ventilation Efficiency, Radiative Hazard Index) that inform adaptive zoning and design protocols. Planners and developers can use these metrics to reconfigure street orientations, stagger building clusters, and install strategic open-space buffers in WUI zones—reducing ember spread and fire propagation—while simultaneously optimizing airflow for urban heat island (UHI) mitigation, ensuring communities remain both cooler and safer during concurrent wildfires and heat waves.

   EPIC funding is essential to realize this ambitious, multi-year R&D effort and directly supports EPIC Strategic Goal V: Climate Adaptation. First, by enhancing the ability to simulate and predict urban fire and heat risks under extreme weather, our work increases predictability of weather impacts on utility infrastructure (V.A.1), enabling better coordination between forecasting and grid operations. Second, the optimized urban layouts and retrofit recommendations we develop will leverage distributed energy resources (DERs) more effectively—ensuring that solar, storage, and microgrids can maintain service in high-risk zones and reduce outage impacts (V.B.1). Finally, by providing data driven tools and frameworks for proactive urban and grid hardening, the concept will enable more cost effective, long term capital investments that lower overall outage risk and improve affordability (V.C.1). EPIC support will underwrite the computational resources, data acquisition, and municipal partnerships necessary to advance this next-generation resilience technology.

a. Breakthroughs: The proposed wind optimization framework overcomes key technical and market barriers by enabling integrated, data driven urban design that simultaneously mitigates wildfire risk and urban heat stress—two factors that currently inhibit broader deployment of distributed energy resources (DERs) and grid connected electrification. Current urban planning treats wildfire risk and urban heat islands (UHIs) as separate challenges, leading to siloed, static solutions that fail under extreme conditions. This gap forces conservative PSPS events and discourages rooftop solar + storage or electric vehicle charging infrastructure in high risk zones, as operators cannot accurately model localized fire and heat impacts. By delivering a validated toolkit that predicts ember transport, radiant-heat ignition, and microclimate cooling benefits, the concept unlocks DER adoption: for example, municipalities can confidently site distributed generation and battery backups in zones with optimized wind corridors, reducing outage risk and improving customer confidence.

   From a market perspective, developers and planners lack accessible, validated tools that integrate high-fidelity CFD insights with practical design guidelines—forcing costly retrofits or overbuilt systems. Our project fills critical data and analysis gaps by compiling an open numerical database of WUI-specific CFD scenarios, overlaying wind-fire-heat interaction maps on GIS parcel layers, and providing ready-to-use reference models for new and existing neighborhoods. End users—including city planning departments, utilities designing DER microgrid resiliency programs (V.B.1), and the California Office of Planning & Research drafting fire-aware General Plans—will leverage these resources to optimize defensible space, align solar + storage siting with safe airflow corridors, and prioritize cost-effective, long-term grid hardening investments (V.C.1). By standardizing complex simulations into actionable protocols, we accelerate the adoption of integrated, clean-energy–ready urban designs across California.

ii. Outcomes: If successful, this research will yield a first-of-its-kind urban design and planning framework that quantifies and resolves the tradeoffs between wildfire risk mitigation and passive cooling performance. Specifically, we will produce simulation-driven metrics—such as Radiative Hazard Index and Ventilation Effectiveness—that enable planners and utilities to identify high-risk zones, optimize retrofits, and guide new development layouts. These tools will help reduce cooling loads by up to 20% in dense neighborhoods, and reduce radiant fire risk by optimizing airflow patterns, vegetation corridors, and building massing strategies.

At scale, the outcomes will improve grid reliability (by lowering peak cooling demand and minimizing PSPS zones), public safety (by reducing heat and fire exposure), and long-term affordability (by enabling targeted, data-informed investments in both physical infrastructure and DER deployment). Environmental sustainability will also benefit, as cooler urban environments reduce energy use and emissions. Critically, this work prioritizes accessibility by delivering tools for local governments and local stakeholder organizations to better protect WUI-adjacent communities—ensuring resilience planning is proactive, science-based, and inclusive. Our integrated framework could be standardized across California, supporting utilities and municipalities in coordinating climate adaptation and wildfire resilience strategies.

iii. Metrics:

a. Quantitative Metrics
   1. PSPS Reduction: Percent reduction in the number and duration of Public Safety Power Shutoffs within pilot zones (target $\geq$ 10%).
   2. Prediction Accuracy: Error rate of structure level fire spread forecasts compared to historical events (goal $<$ 20%).
   3. UHI Cooling Benefit: Average decrease in daytime street level temperature (°C) in optimized vs. baseline layouts (target $\geq$ 2 °C).
   4. Energy/Peak Load Savings: Percent reduction in building cooling energy use and peak load (target $\geq$ 5%).
   5. Model Throughput: Time to run a full neighborhood “what if” scenario.

b. Qualitative Indicators

1. Planner & Utility Feedback: Survey scores on usability, clarity of guidance, and confidence in risk maps.
2. Adoption Rate: Number of cities or departments integrating the tool and guidelines into official planning processes.
3. Policy Uptake: Inclusion of our dynamic wind optimization metrics in local zoning codes or fire resilience standards.

iv. References:

1. California Department of Forestry and Fire Protection. (2024). 2024 fire perimeters and statistics. https://www.fire.ca.gov/media/xge5kky1/2024-Fire-Stats.pdf
2. Ding, C., & Lam, K. P. (2019). Data-driven model for cross-ventilation potential in high-density cities based on coupled CFD simulation and machine learning. Building and Environment, 165, 106394. https://doi.org/10.1016/j.buildenv.2019.106394
3. Ding C., Lam K.P. (2017). "An evaluation index for cross ventilation based on CFD simulations and ventilation prediction model using machine learning algorithms." Procedia Engineering, 205, 2948–2955.
4. Mockrin, M. H., Radeloff, V. C., & Syphard, A. D. (2023). The entanglement of California's housing crisis with WUI growth and wildfire risk. Proceedings of the National Academy of Sciences, 120(12), e2310080121. https://doi.org/10.1073/pnas.2310080121
5. Radeloff, Volker C.; Helmers, David P.; Mockrin, Miranda H.; Carlson, Amanda R.; Hawbaker, Todd J.; Martinuzzi, Sebastián. 2022. The 1990-2020 wildland-urban interface of the conterminous United States - geospatial data. 3rd Edition. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2015-0012-3

v. Strategic Goal: Climate Adaptation, Distributed Energy Resource Integration, Building Decarbonization

vi. Support for Goal: Climate Adaptation: By providing a physics driven, microclimate modeling toolkit and adaptive zoning guidelines, our project enables cities to proactively retrofit existing neighborhoods and design new developments that are both wildfire resilient and heat mitigating. Planners will use our dynamic risk maps to identify critical wind corridors and ember exposure zones, guiding strategic placement of defensible space, wind break street layouts, and building clusters that slow fire spread while preserving airflow for cooling. This data driven approach directly supports

California's resilience objectives—reducing wildfire losses, protecting infrastructure (including energy assets), and safeguarding public health during extreme heat events.

Distributed Energy Resource Integration: Optimized urban layouts that maintain targeted wind flows for cooling also create predictable microclimate conditions around rooftop solar arrays, battery storage installations, and microgrid nodes. By minimizing fire spread risk in DER dense corridors, utilities and communities can deploy and operate solar + storage systems with greater confidence, reducing PSPS frequency and ensuring continuous power during emergencies. Our tool's scenario analyses will help DER planners site and size resources to maximize both safety and performance.

Building Decarbonization: The same wind optimized street and building configurations that suppress ember transport also enhance natural ventilation and reduce cooling loads by up to 5–10%. Lower summertime cooling demand directly supports building electrification, making all electric HVAC systems more cost effective and lowering peak grid stress. In this way, our concept accelerates adoption of heat pump technologies and other decarbonization measures, helping California meet its building goals.

vii. Contributors to This Concept Include: Chao Ding, Nihar Shah

3. AI-powered urban fire spread prediction system for built environments as fuel sources

   i. Description: Current wildfire models fail to capture the dynamics of fires in urban and Wildland-Urban Interface (WUI) areas, where structures themselves become the primary fuel. Catastrophic events, such as the 2017 Tubbs Fire, the 2021 Marshall Fire, the 2023 Lahaina Fire, and the 2025 Eaton and Palisades fires, highlight the urgent need for advanced modeling tools that can accurately simulate urban fire dynamics to improve risk mitigation and emergency response.

      In this work, we propose an AI-powered urban fire spread prediction system that provides real-time, granular predictions of urban fire spread by modeling built environments as fuel sources. The purpose of this project is to create a novel, publicly available system that delivers actionable intelligence for wildfire risk mitigation and enhanced grid resilience. Specifically, our multi-modal AI platform integrates several advanced techniques. For automated asset mapping, we use computer vision (e.g., YOLOv8, U-Net) to automatically map urban fuels such as buildings, fences, and vegetation from satellite and street-view imagery. For material identification, our AI model classifies building materials (e.g., roofing) using "few-shot" learning and foundation models. Then, we use a hybrid AI approach, incorporating physics-informed Neural Networks and Graph Neural Networks (GNNs), to simulate ember transport and house-to-house fire spread with high granularity.

      Commercial incentives are insufficient to develop this foundational, pre-competitive technology because the benefits such as enhanced public safety and grid reliability are diffuse and accrue to the public good rather than to a single private entity. EPIC funding is essential to develop a system that can be used by a wide range of stakeholders, including utilities, state agencies, and local communities. The proposed concept is too foundational for any single utility to undertake alone but provides immense value to all California ratepayers.

ii. Breakthroughs: This concept directly addresses critical data and information gaps identified in California's energy strategy. As noted in the EPIC Strategic Objectives Workshop (SOW) report (July 2024), there is a "Lack of tools to support coordinated planning for the impact of high-impact widespread, and long-duration events." Our proposed AI-powered prediction system fills this gap by providing a tool to accurately model and predict urban fire spread, which is a high-impact event.
   a. Barriers Addressed: The primary technical barrier is the inability of current models to simulate fires where urban structures are the primary fuel source. This leads to market and policy barriers, such as inefficient allocation of resources for grid hardening and local stakeholder protection. Our prediction system overcomes this by creating a novel modeling capability with high granularity that involves automatic asset mapping and physics-informed Neural Networks and Graph Neural Networks.
   b. Data Gaps Filled: It will provide granular data on fire spread dynamics in WUI and urban areas, addressing the gap in understanding the "lack of actual and expected performance, health, lifespan, and failures of grid equipment under new scenarios," as identified in the EPIC SOW report.
   c. End Users & Purpose:
      1. Utilities (e.g., PG&E, SCE, SDG&E): To conduct cost-effective grid hardening, prioritize infrastructure investments, and de-risk operations, directly supporting the Strategic Objective of "cost-effective grid hardening for long-term impacts" stated in the EPIC SOW report.
      2. State and Local Agencies (e.g., CEC, CalFire): For enhanced emergency response, evacuation planning, and development of local stakeholder resilience strategies.
      3. Ratepayers/Communities: To benefit from a safer, more reliable, and affordable electricity grid.

iii. Outcomes: Successful development of this research concept will yield significant benefits for California ratepayers, aligning with all five of EPIC's mandatory guiding principles.
   a. Ratepayer Benefits:
      1. Safety: The primary outcome is a dramatic improvement in public safety. By predicting fire spread, the system enables proactive measures like targeted vegetation management, public safety power shutoffs (PSPS), and efficient emergency response, saving lives and property.

2. Reliability: The system will allow utilities to identify and protect critical infrastructure, reducing the frequency and duration of wildfire-caused outages. This directly supports the goal of "reducing outage risk and reducing social burdens of outages," stated in the EPIC SOW report.
3. Affordability: It enables a shift from reactive recovery to proactive, data-driven hardening of the grid. By identifying the highest-risk areas, the system ensures that investments are cost-effective, preventing over-investment and keeping ratepayer costs down.
4. Environmental Quality: Preventing catastrophic urban wildfires reduces massive amounts of air pollution and protects California's natural and built environments.
5. Accessibility: The system can be used to prioritize investments and protective measures in geographies that bear a disproportionate burden from wildfires and power outages.
6. Value Proposition & Scalability: The value proposition is a highly accurate, scalable, and low-cost tool for wildfire risk assessment. At scale, this platform can be deployed statewide, integrating real-time data from weather forecasting models, weather observation sensors, and utility infrastructure to provide a dynamic, constantly improving fire prediction service. The core AI technology can be adapted to other climate-driven hazards, such as floods or extreme heat events.

iv. Metrics: The impact of this research will be evaluated using a combination of quantitative and qualitative metrics, aligned with the EPIC success measures described in the EPIC SOW report.

a. Quantitative Metrics:

1. Model Accuracy: Predictive accuracy of the fire spread model (e.g., F1 score, Jaccard index) benchmarked against historical fire data (e.g., the 2025 Eaton and Palisades fires).
2. Grid Resilience: Modeled reduction in the number of utility assets (e.g., power lines, substations) impacted by wildfires under various scenarios.
3. Outage Reduction: Projected decrease in wildfire-related reliability metrics (e.g., System Average Interruption Duration Index; SAIDI) in high-risk circuits.
4. Cost-Effectiveness: Calculated reduction in capital investment for grid hardening based on the tool's optimized prioritization, compared to a baseline approach.

    5. Adoption Potential: Number of utilities, fire districts, and other agencies that could potentially benefit from the system for planning and operational decisions.
  b. Qualitative Metrics:
    1. Stakeholder Feedback: Surveys of end-users (utility planners, emergency managers) to assess the system's usability, actionability, and impact on their decision-making processes.
    2. Case Studies: Deployment of detailed case studies demonstrating how the system could be used to inform a specific grid hardening project or improve a local stakeholder wildfire protection plan.
    3. Contribution to Policy: Assessment of how the system's outputs could enhance informed public policy decisions, regulatory proceedings, or industry standards for wildfire mitigation.
c. References: The merits of this research concept are strongly supported by the EPIC Strategic Objectives Workshop (SOW) report, the clear need demonstrated by recent catastrophic wildfires, and a growing body of scientific literature.
    1. Alignment with EPIC Goals: The concept directly aligns with the Climate Adaptation Strategic Goal and its supporting objectives. It targets identified gaps in planning tools for high-impact events and provides a framework for cost-effective grid hardening.
    2. Technical Barrier - Modeling Gaps: The proposal addresses a well-documented technical barrier: the failure of traditional wildland fire models in the Wildland-Urban Interface. This gap is noted in numerous studies (e.g., Mell et al., 2010) that highlight how most operational models do not account for structures as a primary fuel source.
    3. Mell, W. E., Manzello, S. L., Maranghides, A., Butry, D., & Rehm, R. G. (2010). The wildland–urban interface fire problem – current approaches and research needs. International Journal of Wildland Fire, 19(2), 238–251. https://doi.org/10.1071/wf07131
    4. Feasibility of AI-based Solutions: The proposed technical approach is grounded in recent, validated advancements in artificial intelligence.
    5. Automated Fuel Mapping: Recent studies (e.g., Li et al., 2022) have shown the utility of deep learning and computer vision to map fuel loads, including building characteristics, from satellite and aerial imagery, validating our proposed method for asset mapping.Li, S., Dao, V., Kumar, M., Nguyen, P., & Banerjee, T. (2022). Mapping the

wildland-urban interface in California using remote sensing data. Scientific Reports, 12(1), 5789. https://doi.org/10.1038/s41598-022-09707-7.

6. Predictive Simulation: The use of AI/machine learning for wildfire prediction has gained attention (Huot et al., 2022). The Graph Neural Network (GNN) for simulating complex, dynamic systems like wildfires is a cutting-edge approach. GNNs are particularly well-suited to modeling the irregular spread patterns and complex interactions inherent in fire behavior.
7. Huot, F., Hu, R. L., Goyal, N., Sankar, T., Ihme, M., & Chen, Y.-F. (2022). Next Day Wildfire Spread: A Machine Learning Dataset to Predict Wildfire Spreading From Remote-Sensing Data. IEEE Transactions on Geoscience and Remote Sensing, 60, 1–13. https://doi.org/10.1109/tgrs.2022.3192974.

v. Strategic Goal: Climate Adaptation

vi. Support for Goal: This concept is fundamentally aligned with and directly supports the "Climate Adaptation" strategic goal. It addresses the increasing threat of wildfires, a key hazard in California, by providing an innovative system for prediction, mitigation, and resilience.

Our proposed AI-powered fire prediction system includes automatic asset mapping, material identification (e.g., roofing material), and Graph Neural Network-based fire simulation components and thus supports the Climate Adaptation goal in the following ways:

Preventing and Mitigating Wildfire Effects: The core function of the system is to predict fire spread, which is the first step in mitigation. This allows utilities and stakeholders to take proactive measures to prevent ignitions and reduce the damage from fires that do occur, directly supporting the goal of "preventing and mitigating the effects of wildfires."

Improving Grid Resiliency and Stability: By identifying which parts of the electrical grid are most vulnerable to urban fire spread, the system helps utilities to make targeted, cost-effective investments in grid hardening. This leads to a more resilient grid that is less susceptible to outages, "hardening the grid and improving resiliency especially in the most remote grid edge locations."

Reducing Outages: A more resilient grid means fewer and shorter power outages for customers. This directly addresses the goal of reducing the number of customers experiencing long-duration outages.

Addressing Identified Gaps: As documented in the EPIC SOW report, a primary gap is the “lack of tools to support coordinated planning for the impact of high-impact widespread, and long-duration events.” Our project is precisely the kind of tool needed to fill this gap.

Protecting Vulnerable Communities: The proposed system will enable the prioritization of resilience investments , ensuring that the benefits of a safer grid are distributed across ratepayers
In essence, this project provides the foundational data and analytics required to make California’s communities and its energy infrastructure more resilient to the growing threat of wildfires in a changing climate.

vii. Contributors to This Concept Include: Seongeun Jeong and Jovan Tadic

4. Forecasting and Planning Strategies for Demand-side Planning that Integrate Socio-economic Megatrends
   i. Description: Forecasting the Human Factor: How Social Megatrends are Reshaping California's Energy Future.
   California's energy landscape is undergoing a massive transformation driven by rapid technological and social shifts. These trends are not just impacting overall energy demand, but are fundamentally reshaping the state's entire energy system. While conventional energy forecasting models account for general population growth, they often lack specific, critical insights into how consumption patterns are changing as a result of profound societal megatrends.
   We have identified three such complex socio-economic trends:
      a. A rapidly aging population, with the proportion of Californians aged 65 and older projected to increase significantly from 14% in 2020 to 22% by 2040. This demographic shift means more people may spend more time at home, requiring higher levels of comfort and a reliable supply of power for health needs. There could be potential increase in HVAC load during shoulder seasons or a higher demand for backup power.
      b. A generational shift from a model of high residential and transportation fossil fuel demand (e.g., baby boomers) to a new era of massive, high-tech electricity demand from Generation Z. There could be increased rental homes or co-housing, and continued use of smart

home devices and digital demand. This requires a shift in consumption patterns and presents a new set of grid challenges.

c. Climate migration, as the increasing frequency and intensity of wildfires force temporary and permanent moves and as heat in the Central Valley becomes more and more deadly. This is not about a total increase in energy demand, but a major geographic redistribution that can strain existing infrastructure and, if poorly coordinated, could worsen the cost burden on ratepayers.

These trends collectively demonstrate that the challenge is not just about meeting a growing load, but about managing its changing characteristics. Leveraging LBNL's extensive research in energy demand system modeling, aging, wildfire migration research, and other socio-demographic data, as well as additional statewide surveys and stakeholder engagements, we propose to better understand the energy patterns of these societal megatrends to inform the state's demand forecasting efforts. Our research questions include:

a. What are the key economic, social, and technical factors contributing to changing energy demand patterns at the state, regional, and local levels?
b. What strategies are most effective at responding to evolving energy needs due to changes in load patterns and varying locations around the state?
c. What coordination mechanisms are needed to effectively manage and operate energy systems given these changing demand patterns?
This improved forecasting can lead to informed energy policies, reduce the risk of blackouts, and support a smoother transition to a lower emissions energy future.

ii. Breakthroughs: The key technological advancement is the development of sophisticated forecasting and planning strategies that integrate socio-economic megatrends, overcoming the limitations of current demand-side planning. This will help to improve energy planning and mitigate grid strain by providing the data needed for proactive, not reactive, infrastructure decisions.

iii. Outcomes: Successful research will lead to more accurate demand forecasts, reduced ratepayer costs, and improved grid reliability. At a statewide scale, this innovation will enable California to transition from reactive to proactive energy management, ensuring a smoother, more accessible, and efficient shift to low-emissions energy.

iv. Metrics: Metrics would include quantitative indicators like the forecasted load curve changes by locations or population segments. Qualitative indicators would include stakeholder feedback and the degree to which the research's recommendations are adopted into state policy and utility planning.

v. References:

vi. Strategic Goal: Building Decarbonization, Climate Adaptation, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Distributed Energy Resource Integration

vii. Support for Goal: The proposal supports four EPIC strategic goals:
   a. Distributed Energy Resource Integration: It provides the data to better manage changing load patterns and locations.
   b. Building Decarbonization: It offers insights into residential energy use for an aging population and demand patterns from changing housing conditions.
   c. Accelerating 100 Percent Net-Zero: Its improved forecasting is essential for efficient and reliable grid transitions.
   d. Climate Adaptation: It directly addresses climate migration as a factor reshaping the energy landscape.

viii. Contributors to This Concept Include: Jingjing Zhang, Max Wei

5. Dynamic Planning Tool Integrating Multiple Low Emissions Energy Pathways

i. Description: As California advances toward its goals, multiple low emissions energy pathways, such as hydrogen, geothermal, and emissions removal and abatement, are being deployed in overlapping geographies and timeframes. Such a transition requires holistic and systems-level planning strategies in California. Without integrated assessment, these efforts risk creating interdependent trade-offs and unintended environmental or social consequences. It is important for the state to support the development of a dynamic planning tool that can help assess the interactions between various technologies, taking into account spatial and temporal dimensions, environmental and social impacts, to enable decision-makers and policy-makers to anticipate resource conflicts, optimize siting decisions, and better understand cumulative impacts across sectors.

   EPIC funding is essential to support this concept because it addresses a critical knowledge and planning gap not covered by current siloed assessment methods. An integrated framework could provide

California-specific insights that are vital for informed,and cost-effective emissions reduction investments.

a. Breakthroughs: The project offers a three-dimensional breakthrough in assessing the environmental and social impacts of energy transition pathways.
    1. Cross-pathway integration: This project will be the first one to model competition and interactions among energy transition pathways with a California-focused case study.
    2. Spatiotemporal trade-off modeling: The model suggested by this project will incorporate spatial resource constraints to reveal cumulative impacts and synergetic effects across pathways.
    3. ML-based and data-driven multi-criteria decision support: By applying advanced analytical algorithms, this project will evaluate siting strategies, resource consumption, and social burdens in a holistic picture.

ii. Outcomes: A decision-support tool that simulates multiple energy transition pathways and maps their spatial distribution, resource dependencies, and environmental and social impacts, under varying climate and policy scenarios. Trade-off visualizations and cumulative impact maps that help identify regions with resource conflicts, increasing risks, or burdens on local stakeholders. A case study to offer a system-level lens for demonstrating the value of an integrated management and planning framework. Local and state-level workshops for stakeholders' feedback on the usefulness of the tool and their further needs,

iii. Metrics:

a. Quantitative: Integrated impact assessment of the resources at the spatial scale across varying pathways and under different scenarios.
b. Qualitative: Stakeholder feedback on the value and usability of the tool. CEC's input on the value of potential adoption of siting insights and regional infrastructure decisions.

iv. References:

a. Pascale, A. C., Watson, J. E. M., Davis, D., Smart, S., Brear, M., Jones, R., & Greig, C. (2025). Negotiating risks to natural capital in net-zero transitions. *Nature Sustainability*, *8*(6), 619–628. https://doi.org/10.1038/s41893-025-01576-y
b. Williams, J. H., Jones, R. A., Haley, B., Kwok, G., Hargreaves, J., Farbes, J., & Torn, M. S. (2021). Carbon-Neutral Pathways for the

United States. *AGU Advances*, *2*(1), e2020AV000284. https://doi.org/10.1029/2020AV000284

v. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Climate Adaptation

vi. Support for Goal: This concept directly supports the EPIC goal listed above.

vii. Contributors to This Concept Include: Newsha Ajami, Beichen Zhang

I. Leveraging DERs for grid and local stakeholder resiliency

1. Solar PV Parking Canopies
   i. Description: The full scope of benefits that can come from solar PV parking canopies is not yet discovered and quantified. With full knowledge of benefits, this highly valuable solar PV structure can be better promoted for the benefit of California ratepayers. A large number of highly valuable potential benefits can result from the shade, power, shelter, and staging areas these structures provide.
   ii. Breakthroughs: Solar parking canopies are higher cost than roof and ground mounted systems however present a large list of potential benefits that are not fully appreciated as they have not been quantified yet.
   iii. Outcomes: Through research and demonstrations, the full benefits of solar parking canopies can be quantified which will justify the extra costs of these structures. The value of emergency response functions for example would increase the uptake of this very important distributed generation technology.
   iv. Metrics:
      a. Thermal interactions with parked cars, energy use for air conditioning, EV range impacts, vehicle asset protection.
      b. Use of solar parking canopies in an emergency response role in communities as these spaces offer ready-made staging areas with the overhead solar (with BESS) to support a multitude of use cases needed to support local ratepayers during a multi-day power outage. Use cases range from but are not limited to food storage to hoteling, medical services to water purification and communications.
      c. Future proofing new designs and existing systems to enable low cost EV infrastructure installation (shared trenches and main electrical service panels) to hosting of microgrid components for general site resilience.
      d. Vehicle to grid (V2G) infrastructure, also made lower cost through sharing open trenches and main service panels.
   v. References:

      a. Matai,, Khushal Influence of SPV Installations on the Thermal Character of the Urban Milieu.
      b. Levinson, R., Pan, H., Ban-Weiss, G., Rosado, P., Paolini, R., Akbari, H., 2011. Potential benefits of solar reflective car shells: Cooler cabins, fuel savings and emission reductions. Applied Energy 88, 4343–4357. https://doi.org/10.1016/j.apenergy.2011.05.006

c. Robinson, Gerald - Memorandum to FEMP - "Resilience Ready" for community benefits
https://www.nature.com/articles/s41598-023-29223-6

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Climate Adaptation

vii. Support for Goal:

a. Thermal interactions with EVs and passenger cars - research needed to quantify impacts on energy use needed to cool vehicles with a look at impact on EV range due to reduced need for AC.

b. Resilience ready - research design concepts and costs, operational characteristics, emergency planning logistics needs.

c. Develop future proofing designs vetted through demonstration to show the cost benefits of utilizing share trench pathways and main electrical service panels.

viii. Contributors to This Concept Include: Ronnnen Levinson, Gerald Robinson

2. PV-Integrated Exterior Shading

i. Description: PV-integrated exterior shading. Exterior shading is a very effective solution for solar control and increased thermal insulation. It works well in both cooling- and heating-dominated climates. Addition of PV cells to the shading surfaces exposed to Sun works very well with shading, because when the maximum protection from the Sun is desired, the largest solar-exposed surface of the shading is available and vice versa. Coupled with the initiative to develop DC power infrastructure (see above), this provides a simple solution to install over windows in either new construction or as a retrofit.

ii. Breakthroughs: A major market barrier for PV-shading is the uncertainty in performance for a specific site, this forces product manufacturers to under-promise which makes the ROI calculations more conservative. Improving the simulation methods to get more accurate predictions on electricity generation for specific sites. By specifying the workflow of combining whole building energy simulation (EnergyPlus) with detailed solar energy production tools (NREL's System Advisor Model).
In addition to accuracy there is also a level of trust from the consumer to get performance metrics from LBNL/CEC compared to the manufacturer. LBNL has a long history of doing research that leads to broadly accepted performance metrics.

iii. Outcomes: Making it easier for manufacturers to sell PV shading, and for consumers to trust the performance predicted will increase the market

size. With increased market follows competition and lower prices.
Increasing the visibility and trust in already existing products is a path that does not rely on developing new technology and manufacturing pathways.

iv. Metrics: Accurate predictions of performance of PV shading.

v. References:

a. Gao, Y., Dong, J., Isabella, O., Santbergen, R., Tan, H., Zeman, M. & Zhang, G. "A photovoltaic window with suntracking shading elements towards maximum power generation and non-glare daylighting." Applied Energy 228,1454–1472 (2018).

vi. Strategic Goal: Climate Adaptation, Distributed Energy Resource Integration, Building Decarbonization

vii. Support for Goal: Climate Adaptation: PV shading can be optimized with respect to solar angles, this allows ideal performance both during hot summer days, and winter days when the sun is at lower angles in the sky. Distributed Energy Resource Integration: By providing on-site electricity generation PV shading provides increased resilience for buildings. Building decarbonization: External PV shading reduces the cooling load on a building and at the same time generates electricity.

viii. Contributors to This Concept Include: Jacob Jonsson, Charlie Curcija, Luis Fernandes

3. Workforce Development: Commercial Buildings and District Energy Systems

i. Description: We propose that EPIC invest in workforce development and training programs and related enabling technology and resources for building operators, facility managers, and other HVAC or building technicians involved in the maintenance and operation of large commercial buildings and district energy systems. New operational goals for buildings set forth by California relating to managing energy use, integrating with DER and the grid, and improving reliability are leading to new equipment, system, monitoring, and control approaches that are unfamiliar or more complex than traditional implementations. The long-term success of such approaches will rely on the skills and abilities for maintenance and operations professionals to operate, manage, and troubleshoot them.

EPIC can support development of a workforce that can enact California's energy goals in practice by investing in research, development, and piloting of training technology and programs. In particular, resources that allow trainees to obtain hands-on experience in low-risk, safe environments that are realistic, controllable, and able to scale to many trainees at once and over time. Real-world labs and equipment could help serve this purpose, while simulation and model-based methods are particularly valuable, especially for monitoring and control-related training. This concept is akin to “flight simulators” for buildings. Development of the modeling and simulation methods, software architectures, implementation workflows, and associated curriculum, as well as piloting of such approaches, would contribute greatly to improving the resources available for new and existing workforce training programs.

EPIC funds are needed for such research and development because training programs often lack enough budget or expertise to develop such capabilities, and pre-commercial development of capabilities made publicly available would help scale their usage.

ii. Breakthroughs: This concept addresses the market barrier of a workforce with the skills necessary to install, maintain, and operate commercial buildings with novel HVAC systems (i.e. all-electric or hybrid plants, integrated DER, data centers) and control approaches (i.e. demand flexible, grid-interactive, climate-adaptive). This concept addresses the technical barrier of providing resources for training centers and programs to use to develop necessary skills.

This concept would provide more information on the following data and information gaps: 1) identify what new skills are needed, 2) develop capabilities and resources for training programs to address identified skills gaps and 3) report on the effectiveness of such developed resources in providing such training and skill development, as well as lessons learned for future consideration.

Specific parties and end-users that would benefit from the results are HVAC technicians, building operators, facility managers, building owners, contractors and installers, training instructors, training program administrators.

iii. Outcomes: The anticipated primary outcomes are tools and resources instructors and administrators can use to execute training programs. These could include, but not limited to, recommended relevant literature (i.e. ASHRAE standards, guidelines, and publications, research studies, demonstration reports, textbooks, etc.), simulation-based hands-on training tools, hardware-based lab set ups that can be used or replicated, developed curriculum and courses, and training videos.

The research would primarily increase performance and value proposition of new technology by ensuring it is installed, maintained, and operated properly. It would reduce technology costs by reducing commissioning and maintenance time and effort, and reduce ratepayer costs by systems operating more effectively, for example reducing energy costs.

Text and software-based resources can be made publicly available, for example curriculum/course examples, recommended literature, and simulation-based training tools. Hardware-based resources are more difficult to scale, but could scale with good documentation for replicability as well as availability of equipment or lab set ups for continued usage after initial research investment. Climate and region-specific training needs should be considered.

The concept will improve the effectiveness and reliability of new technology by ensuring it is properly installed, maintained, and operated. This will also improve the affordability as it will decrease payback periods with more efficient installation, commissioning, and operation (i.e. reduced energy costs). The concept will also ensure upskilling that will enable the existing workforce to keep their jobs and new entrants to obtain jobs.

iv. Metrics: Number of courses/curriculum developed, number of students that can participate in a course at one time, accessibility of developed resources and material, needed skills and associated training requirements, how certain resources map to those skills and requirements, resource user counts (i.e. software downloads, video views, etc.)

v. References:

a. L. Paul, E. Zanetti, J. Liu, A. Casillas, A. K. Prakash, D. Blum, R. Nirenberg, and M. Pritoni (2025). “BOPTEST as a Platform for Building Controls and Grid-Interactive Buildings Workforce Training.” In Proc. of the ASHRAE Annual Conference 2025, June 21-25, Phoenix, AZ.

b. Blum, David, Javier Arroyo, Sen Huang, Ján Drgoňa, Filip Jorissen, Harald Taxt Walnum, Yan Chen, Kyle Benne, Draguna Vrabie, Michael Wetter, and Lieve Helsen. "Building optimization testing framework (BOPTEST) for simulation-based benchmarking of control strategies in buildings." Journal of Building Performance Simulation 14, no. 5

(2021): 586–610.
https://doi.org/10.1080/19401493.2021.1986574.

c. The Building Efficiency for a Sustainable Tomorrow (BEST) Center was founded in 2012 to support publicly-funded 2- and 4-year colleges with programs in heating, ventilation, air conditioning and refrigeration (HVAC/R), controls, building automation, and energy/facilities management: https://bestctr.org/about-us/.

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Climate Adaptation

vii. Support for Goal: DER Integration: The integration of on-site storage and generation adds new systems that facility managers and operators need to oversee in order to effectively lower peak demand, enable load flexibility, and generally keep energy costs low. This research concept would support training for new control and maintenance requirements for effective operation of these systems.

a. Decarbonization: Especially in large commercial buildings, central plants that utilize heat pumps, storage, and energy recovery, necessary for building decarbonization, require new and more complex sequences of operation than conventional boiler plants. Furthermore, new controls are being developed and used to enable demand response. Finally, high-performance sequences of operation that promote energy efficiency in buildings are also more complex than traditional sequences. Training for managers and operators with such new controls is needed to ensure successful performance of systems in all of these contexts.

b. Climate Adaptation: New modes of operation for HVAC systems are being introduced to account for changing weather patterns, for example to account for low air quality from wildfires, calls for demand response, or grid outages. Training for managers and operators to enter into, monitor, and exit from different modes would ensure successful responses to these, or other, situations.

viii. Contributors to This Concept Include: David Blum, Ettore Zanetti

4. Advanced Mobile Power and Energy Distribution System For Enhancing Customer Resiliency and Grid Benefits

i. Description: The proposed concept is an Advanced Mobile Power and Energy Distribution System designed to enhance customer resiliency and provide grid benefits across California. The system utilizes large-scale, mobile battery containers (2 MWh each), a central charging hub, and satellite discharging depots, all transported by electric tractors. The purpose is to provide flexible, rapid-deployment backup power, support electrification of freight and fleets, and offer emergency energy services during grid outages or Public Safety Power Shutoffs (PSPS). The project seeks to develop a comprehensive deployment plan, including cost-benefit analyses and site-specific deployment strategies, to enable widespread adoption of mobile battery systems.

EPIC funds are essential to bridge the gap between proof-of-concept demonstrations and large-scale, replicable deployments. The project requires rigorous technical, logistical, and economic analysis to optimize system design, deployment, and integration with California's grid and emergency response infrastructure. EPIC support will accelerate innovation, de-risk investment, and ensure that the benefits of mobile battery technology are broadly distributed across all localities served.

ii. Breakthroughs: The proposed Advanced Mobile Power and Energy Distribution System will drive technological advancement by overcoming key barriers that limit California's progress toward its energy goals, including grid resiliency, generation sources integration, and access to backup power. Unlike fixed battery storage, mobile systems can be rapidly deployed to areas impacted by outages, PSPS events, or grid congestion, directly addressing the challenge of providing flexible, reliable energy where and when it is most needed. This approach also resolves market barriers faced by fleet operators, such as limited space and inadequate grid infrastructure for charging electric vehicles, by delivering scalable, mobile charging solutions. Furthermore, the project will generate critical data on deployment logistics, site-specific constraints, and real-world performance, filling information gaps that currently impede broader adoption.

iii. Outcomes:

a. Cost Reduction: Lower total cost of backup and peak power compared to diesel generators and fixed storage.
b. Performance Gains: Increased grid flexibility, faster restoration after outages, and improved integration of generation sources.
c. Scalability: Demonstrated pathways for statewide deployment and replication.
d. Ratepayer Benefits: Enhanced reliability (fewer and shorter outages), affordability (lower emergency power costs),and environmental quality improvement (zero-emission backup).

e. Potential at Scale: Widespread adoption could displace thousands of diesel generators, cut emissions by tens of thousands of tons annually, and enable rapid electrification of freight and public fleets.

ii. Metrics: Number of communities and critical sites served by mobile battery deployments.

a. Reduction in diesel generator usage (hours and emissions avoided).
b. Cost per kWh of emergency power delivered.
c. Response time from dispatch to site energization.
d. Grid services provided (e.g., peak shaving, congestion relief, DER integration).

iv. References:

a. Spurlock, C. A., et al. (2024). Behavior, Energy, Autonomy & Mobility Comprehensive Regional Evaluator Overview, calibration and validation summary of an agent-based integrated regional transportation modeling workflow. https://eta.lbl.gov/publications/behavior-energy-autonomy-mobility
b. Xu, X., Yang, H., and Ravulaparthy, S (2024). Firm Synthesizer and Supply-chain Simulator (SynthFirm) v1.0. Computer Software. https://github.com/LBNL-UCB-STI/SynthFirm. USDOE. 03 Jun. 2024. Web. doi: https://doi.org/10.11578/dc.20240621.2.
Port of Long Beach Statistics.
c. https://polb.com/business/port-statistics/#latest-statistics; Port of LA Statistics: https://www.portoflosangeles.org/business/statistics/facts-and-figure
d. Zhang, B., Bewley, R.L., Tanim, T.R. and Walker, L.K., 2022. Electric vehicle post-crash Recovery—Stranded energy issues and mitigation strategy. Journal of Power Sources, 552, p.232239.
e. Pipeline and Hazardous Materials Safety Administration (2025) Transporting Lithium Batteries. Available at: https://www.phmsa.dot.gov/lithiumbatteries (Accessed: 31 March 2025).
f. National Transportation Safety Board (2024) Highway HWY24FH015 - Tesla Semi crash investigation. Available at: https://www.ntsb.gov/investigations/Pages/HWY24FH015.aspx (Accessed: 31 March 2025).

v. Strategic Goal: Distributed Energy Resource Integration, Transportation Electrification

vi. Support for Goal: Transportation Electrification: The proposed Advanced Mobile Power and Energy Distribution System improves access to reliable, high-capacity charging infrastructure for fleet operators and public agencies. By leveraging mobile 2 MWh battery containers and electric tractors, the system enables rapid, flexible deployment of charging resources to locations where grid upgrades are not immediately feasible or where space constraints prevent installation of permanent infrastructure. This solution is especially valuable for medium- and heavy-duty vehicle fleets, such as those operating at ports, distribution centers, and in transit applications, which often face challenges related to power availability and operational flexibility. By providing mobile charging "Power Hubs," the system ensures that electric trucks and equipment can remain in service even during grid outages or periods of high demand, thereby reducing reliance on diesel vehicles, supporting compliance with California's related policies, and accelerating the transition to zero-emission transportation across the state.

Distributed Energy Resources Integration:
This concept also supports the integration of distributed energy resources (DERs) by enabling mobile batteries to function as flexible grid assets that can be dispatched to locations experiencing congestion, overgeneration, or reliability challenges. Mobile battery containers can absorb excess intermittent energy when and where it is available, such as during periods of high solar or wind production, and then discharge that energy at satellite depots or directly to critical loads during peak demand or outages at different locations. This capability not only helps balance local supply and demand but also provides valuable grid services such as peak shaving, load shifting, and emergency backup, all without requiring permanent infrastructure upgrades. By seamlessly integrating with existing DERs and grid management systems, the mobile battery system enhances grid flexibility, DERs, and reduces the need for costly and time-consuming distribution infrastructure investments, thereby facilitating a more resilient and distributed energy future for California.

This also addresses the strategic objective L - Reducing feeder/circuit peaks.

vii. Contributors to This Concept Include: Haitam Laarabi, Youba Nait Belaid, Xiaodan Xu

K. Providing data input into a Value of DER Framework

1. Decision support framework for cross-sectoral demand flexibility

   i. Description: In California, all sectors are expected to experience a significant growth in electricity demand in the next decade. In each individual sector, an array of regulatory developments and technological upgrades are expected to reshape the landscape of energy use systems and to facilitate those upcoming changes by introducing more flexibility on the demand side. As more substantial progress has been made in sector-specific research and development, the critical question arises on how to strategically couple these sectors to maximize the value proposition for the grid, consumers, the market, and other stakeholders. We propose EPIC undertake a cross-sector integration study that synthesizes policy impacts and techno-economic inputs from multiple sectors. This study can build off of load flexibility research performed in the residential and commercial sectors (e.g. CalFlexHub), research in industrial load flexibility, and impacts of battery-powered transportation. The objective of the study is to quantify risks and benefits associated with the planned and anticipated measures at different timescales and from different stakeholder perspectives. With this work, EPIC 5 would help identify and evaluate multiple technology deployment pathways to integrate flexible loads and other technological advancements across sectors under various policy and market scenarios.

   ii. Breakthroughs: Current research and implemented strategies remain largely sector dependent, which imposes limits to the identification of opportunities between sectors. However, reshaping end-use load using flexible technologies in one sector will consequently impact the load flexibility potential available in another sector. For example, effectively managing residential and commercial HVAC loads can complement EV charging and industrial demand-response. This analytical study quantifying the cross-sectoral power system modernization measures addresses the needs for integrated strategies and considerations that cut across sectors and increases the visibility into the resulting risks and benefits on the path to achieving the state’s energy goals.

       The work will fill critical cross-sector data gaps by analyzing disparate datasets and modeling approaches, leading to identification of cross-sector technical and market barriers, under various scenarios. In addition, an insight into cross-sector effects can help anticipate, prevent, or alleviate otherwise opaque market barriers and customer pain points. For example, for residential consumers to participate in demand response programs, it is imperative to include cross-sector effects when assessing the benefits they are facing, such as energy bill savings, emission reductions, system reliability and other incentives to make the proposition compelling in order to improve the adoption rate and consumer trust.

For each load flexibility measure pathway and sector, the outcomes will provide technology upgrade cost targets, under viable load flexibility valuing and financing scenarios. The proposed analysis and tools will fill the knowledge gap related to short and long term cross-sectoral projected load flexibility impacts with cost and performance targets required for the market transformation and identify opportunities to promote benefits across communities. Furthermore, the analytical platform will be informed by the latest results from sector-specific studies as they become available to update the analysis and generate new results as the grid modernization progresses based on performance metrics and benchmarks.

Ultimately, this study aims to set up a clear understanding of the costs, benefits, consumer impacts, and grid impacts of the technologies and policy measures that would be deployed in combination for decision makers to plan and invest with greater confidence, as well as to generate actionable insights for state agencies, utilities, technology researchers and consumers across the residential, commercial and industrial sectors.

iii. Outcomes: The successfully carried out work would help:
   a. Generate a comprehensive decision-support framework that quantifies the costs, benefits, and trade-offs associated with deploying flexible load technologies and strategies across key sectors—residential, commercial and industrial for various stakeholders
   b. Lay the foundation of a modular approach to sector integration which can be adapted to local grid conditions and policy measures. By modeling outcomes of different pathways under different policy and market scenarios, this study can help improve innovation adoption rate and estimate the achievable performance as well as the associated costs
   c. Orchestrate the deployment of load flexibility in a grid-optimal way, reducing energy cost to all and improving environmental quality

d. Optimize and coordinate cross sector flexibility to reduce the need for high-cost peaking resources and to lower long term system costs and rate impacts
e. Avoid the need for funding new infrastructure by enhancing utilization of existing assets through better cross-sector coordination of flexible demand programs
f. Enable more accurate electricity demand forecasts, and improved grid resilience with the help of integrated flexibility strategies, reducing stress on the grid and the associated outage risks and improving safety and reliability
g. Identify and provide insight into grid modernization impacts and opportunities for customers most sensitive to affordability. Can provide actionable strategies that deliver additional benefits such as targeted incentives, or local resilience investments.

iv. Metrics: Typically research and development of load flexible technologies measure the impacts of load modifications with respect to the grid net load. The net load depends on the changes to load management, consumer choices concerning energy source, and addition of DER, including energy storage, in all sectors. This study would offer a methodical approach to evaluating the load impacts on the sector level and its impact on loads in other sectors. Some of the metrics used to describe the impact are:
   a. On the grid side:
      1. Peak load reduction
      2. Flexible load (shifting potential)
      3. Avoided grid expansion costs
   b. On the customer side:
      1. Energy bill savings associated with being a part of a flexible load program
      2. Life-cycle cost and the payback period of upgrading to new technology, new and more efficient equipment, load flexibility enabling technology, DER products, such as battery storage, solar PV, etc.
   c. On the technology deployment side:
      1. Consumer participation rate
      2. Flexible load response time
      3. Accuracy of the forecasting model.

   The work also produces longer term studies (10yr, 30yr) of the cumulative impacts (energy, costs, accessibility and emissions) on the economy by consumer segment, along with perceived barriers and motivators, creating the possibility to identify market segments that are particularly impacted positively or negatively in each studied scenario.

Additionally, the analysis can produce cost targets for each studied measure in each sector under the selected technological and policy constraints in order to help inform program design and strategy.

v. References:
   a. https://ees.lbl.gov/product-lifecycle-cost-payback-period-analysis
   b. https://ees.lbl.gov/national-impacts-assessment
   c. https://ees.lbl.gov/energy-price-analysis
   d. https://ees.lbl.gov/market-assessment-forecasting
   e. https://buildings.lbl.gov/potential-studies
   f. https://calflexhub.lbl.gov/the-flex-library/
   g. https://eta.lbl.gov/publications/2024-lbnl-data-center-energy-usage-report
   h. https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Climate Adaptation, Transportation Electrification

vii. Support for Goal: Our proposed concept supports transportation goals by enabling demand flexibility across sectors, particularly in managing EV charging related loads. By taking into account the impact of EV charging on residential (home), commercial or public infrastructure (work, or commercial charging stations), the proposed framework can:
   a. Reduce grid stress by identifying sector-optimized charging strategies at both the individual level and at the grid level with DERs incorporated
   b. Inform proposals of pricing structure or demand response program to motivate shifting EV charging load
   c. Quantify the characteristics of flexible load and EV adoption trends
   d. Incorporate findings from load flexibility pilot programs such as CalFlexHub to inform further development of EV demand management tools and technologies

   Our proposed concept facilitates the integration of DERs by:
   a. Incorporating and evaluating the DER load flexibility capability to promote site-consumption and avoid unnecessary grid expansion (generation, transmission, and distribution)

b. Supporting the design of pricing structure of consumer rebate programs to increase DER capacity while ensuring quality and reliability
c. Coordinating between DER output and sector specific loads such as data centers and HVAC systems

Our proposed concept directly addresses building related goals by:

a. Investigating load flexibility and DER output to minimize the peak load
b. Evaluating the market penetration of heat pumps, electric water heating with forecasting of impact on future load shape, to prepare for infrastructure upgrade and grid planning
c. Developing decision guides to identify how emerging technologies can be leveraged for consumer affordability and environmental quality

Our proposed concept supports emissions goals by:

a. Quantifying the location where energy mix might be optimized
b. Evaluating applications where thermal systems are necessary and cannot be replaced for reliability or high cost reasons especially in challenging sectors
c. Modeling different policy scenarios, including EV and DER penetration rate, the associated load growth projection and viable demand shifting strategies.

Our proposed concept supports resilience goals by:

a. Evaluating DER and EV charging flexibility as a part of local resilience strategies
b. Informing requirement of infrastructure update based on grid stress and future load growth forecasting based on various policy and natural event scenarios
c. Studying scenarios of extreme weather events and evaluating how sector coupling can support grid reliability during those times, especially assessing ways to reduce outage risk to low income consumers

viii. Contributors to This Concept Include: Milica Grahovac, Yuting Chen, Mohan Ganeshalingam

2. Expanding Load Shifting Capabilities of California's Electrical Demand

i. Description: Recent advances in load shifting control have created the potential to use electricity pricing as a signal to coordinate grid operation and use low prices to encourage device operation at opportune times. Specific examples include algorithms responding to highly dynamic prices to reduce pool pump operation costs by up to 80%, and heat pump water heater costs by up to 77%. These solutions create the opportunity to shift electric loads to times of power abundance, supporting grid resilience and reducing emissions. While these technologies are powerful, their market uptake remains limited largely caused by a lack of awareness, market uncertainty, some remaining technical challenges, and limited support and recognition in utility programs.

This project will resolve those remaining challenges by building upon the changes in the market to date to support manufacturers adopting existing technology, provide field demonstrations, awareness programs, and collaborations with California's utilities to increase support for emerging technologies and dynamic rate programs. Field demonstrations will utilize currently available dynamic pricing programs, such as PG&E's Hourly Flex Pricing pilot, to demonstrate the reality that modern devices can shift load in response to dynamic prices and support public awareness. Technical studies will resolve some remaining technical issues, such as integration of price-responsive control into pool circulation pumps with solar thermal heaters. And collaboration with utility programs will provide data sets and relationship building needed to integrate price-responsive control into their emerging technologies programs, and to create compliance options recognizing their value in Title 24, Part 6.

ii. Breakthroughs: Price-responsive control is a technology that enables participants to reduce their utility bills by consuming low price electricity, providing a strong financial incentive for consumers to shift electric loads. Since electricity production, transmission, and distribution prices are very low when solar power is plentiful, widespread adoption of price-responsive control will drive electricity consumption to times of power production. This project will primarily address market barriers limiting adoption of price-responsive control. Specifically

    a. While the control algorithms exist, manufacturing companies have not yet integrated them into products. This project will support manufacturer adoption, increasing the number of commercially available products including price-responsive control as a feature
    b. Consumer adoption of price-responsive control has to-date been limited due to a) a lack of awareness, and b) low trust that existing devices will reduce their utility bills. This project will publicly demonstrate the availability of time-varying prices, the availability of products which can respond to dynamic prices, and the reduction in utility bills if these changes are adopted

c. Devices with price-responsive control have not yet been integrated into utility programs, limiting a) support for market awareness, b) incentives for adopting these technologies, and c) inclusion into California's building practices. This project will collaborate with utilities to introduce the technologies into their programs and enhance adoption across multiple stakeholder groups.

iii. Outcomes: While this technology currently exists, it is not commercially available. This concept would encourage collaboration between and among researchers and private industry technology developers to advance commercial availability, providing access to the financial savings and grid resilience benefits for ratepayers. It would also build awareness and support for the technology across the utility ecosystem.

For some particular deployments the project would add new capabilities, expanding the pool of homes for which the technology is applicable. For instance, existing price-responsive controls for pool pumps are not capable of taking into account the needs of a connected solar thermal system, preventing them from being adopted by homes with solar pool heaters. Improving the control logic to enable operation in those systems would expand the potential market for price-responsive pool pumps in California.

iv. Metrics:
a. Number of manufacturers who collaborate with the project to adopt price-responsive the control technology
b. Number of technologies adopted into the broader utility ecosystem
c. Number of new buildings capable of adopting the technology due to the technical enhancements
d. Electricity cost savings within buildings adopting the technology
e. Amount of load shifted, peak load reductions, and the associated improvement in grid resilience
f. Emissions reductions caused by shifting load

v. References:

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: This project will advance market adoption and utility program support of devices with native price-responsive controls, expanding the load shifting capabilities of California's electrical demand. In doing so, it will leverage electricity pricing signals, supporting existing programs such as PG&E's existing Hourly Flex Pricing pilot, as a unified coordination platform integrating several different distributed energy resources without needing to explicitly communicate with and control each device individually. These outcomes will also drive building related emissions reductions by automatically shifting loads to times of low electricity prices and by reducing the cost of operating electric devices. This will also support the grid by aligning loads with periods when solar power is plentiful and when flexible pricing is usually the lowest.

viii. Contributors to This Concept Include: Peter Grant

3. Analytical Framework for New Rate Designs

i. Description: California is at a critical point in its energy landscape. The state is facing rapidly increasing electricity rates, which are outpacing both inflation and the growth seen in other states (LAO, 2025). While the state pursues ambitious goals for resilience, a significant challenge is to address the various factors contributing to these rising costs while preserving affordability for all Californians.

The issue of rising rates can be exacerbated by uncoordinated policies that can have unintended financial impacts on ratepayers. As the state's energy system evolves, a key challenge is how to fairly distribute the costs of infrastructure upgrades. For example, uncoordinated increases in electrical utilization may inadvertently lead to higher utility bills for users of other energy sources. A recent study showed that certain households may bear a 46% increase in gas bills on average over the next 15 years (relative to current costs) (Garibay-Rodriguez, J. et al., 2025). Similarly, grid cost recovery has led to a situation where Californians without rooftop solar panels are essentially subsidizing those with it, with this cost shift estimated at about $8.5 billion annually (Institute for Energy Research, 2024). The complexity is further compounded by demand-side activities, such as efficiency programs, building performance standards, and other utility policies.

Policymakers armed with better insights from a standardized and centralized analytics framework could avoid unintended impacts while inherently driving better coordination. We propose the development of a coordination framework by integrating existing, proven rate impact and energy modeling tools leveraged in combination with state-level data and local policy information. Demand-side energy modeling would inform the rate impact modeling, allowing it to consider how different levels of technology adoption and customer behavior might impact the grid and customer bills.

For a given set of policy factors, the framework would aim to provide:

a. Changes in utility costs and revenues.
b. The impact on customers who adopt energy efficiency and distributed energy resources (DERs) versus those who don't.
c. The magnitude of cross-subsidization between different customer classes.
d. The effects of alternative rate designs, such as time-of-use, tiered rates, rate caps, income-graduated fixed charges, or electric technology rates.

ii. Breakthroughs: This concept's breakthrough is a methodological and analytical framework that helps policymakers overcome critical market and policy barriers. It uses integrated modeling to simulate the complex impacts of proposed policies before implementation. This addresses key customer pain points, such as the cost-shift barrier for solar and the "death spiral" barrier - uncoordinated addition of electrical loads can lead to rising bills for natural gas users as the customer base shrinks. Our concept models this transition to find a strategic path that mitigates financial harm to ratepayers. By addressing these barriers, the concept leads to more effective policies, which in turn accelerate adoption of advanced energy technologies by making them more financially viable for all Californians.

iii. Outcomes: This research aims to deliver rich insights to inform decision makers and other stakeholders about rate structures that lead to tangible ratepayer benefits, including mitigating cost shifts and the "death spiral" effect.

iv. Metrics: We could consider both quantitative and qualitative metrics to evaluate the research's impact:

a. Quantitative:
    1. The modeled change in average utility bills for different customer segments under new rate designs.
    2. Projected increases in the adoption rate of DERs, energy efficiency and heat pumps.
    3. The number of new rate designs considered by CEC or other stakeholders.
b. Qualitative:

1. Stakeholder support and feedback on the proposed framework.
2. The perceived clarity and fairness of new rate designs by customers or relevant stakeholders.

v. References:
   a. https://lao.ca.gov/Publications/Report/4950
   b. https://www.nature.com/articles/s41598-025-09543-5
   c. https://www.instituteforenergyresearch.org/renewable/californias-rooftop-solar-subsidy-will-cost-about-8-5-billion-in-2024-paid-for-by-non-rooftop-solar-consumers/
   d. https://emp.lbl.gov/projects/finder-model

vi. Strategic Goal: Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Distributed Energy Resource Integration

vii. Support for Goal: This concept directly supports three key EPIC strategic goals by providing coordinated, data-driven methodologies.
   a. The research proposes to analyze and optimize the financial and grid impacts of integrating various DERs, such as solar and battery storage.
   b. The research specifically addresses challenges around fuel source optimization helping to find a strategic path forward that mitigates financial harm to ratepayers.

viii. Contributors to This Concept Include: Jingjing Zhang, Joshua Kace, Jeff Deason

4. A Non-Energy Valuation Toolkit

i. Description: The concept described here is a non-energy valuation toolkit. CEC is actively working to incorporate the value of "non-energy impacts" (NEIs) into its energy planning and decision-making processes, aiming to better understand the benefits and costs to low-income households. Home energy technologies offer significant benefits to society, the grid, and customers—such as improved comfort, health, resilience, and reliability. Yet, these significant NEIs are often overlooked and difficult to quantify, even though their value frequently outweighs initial costs. Accurately valuing NEIs would enable the state to capture the broader value of home upgrades and optimize the energy policy impacts to ratepayers.

   Recognizing the complexity of NEIs, no single "catch-all" methodology could sufficiently encompass every indicator relevant to every stakeholder. This project aims to provide state and utility program managers with a generalized valuation toolkit for assessing NEIs. We will develop improved metrics, data, and methodologies for NEI valuation, leveraging existing state efforts and our research in valuing energy demand, well-being, and cost-benefit methodologies. By providing a fuller valuation of NEIs—such as health, comfort, and reliability—across a range of increasingly extreme future weather conditions, the toolkit will help maximize the full spectrum of benefits to ratepayers and support energy program development.

ii. Breakthroughs: This concept will advance technology by overcoming the market barrier of undervaluing home energy upgrades. The current focus on only energy savings overlooks significant NEIs like improved health and resilience. The proposed toolkit will quantify these benefits, making the full value proposition of energy efficient technologies clear to customers and policymakers. This will directly address customer pain points and lead to increased adoption and more efficient use of funds, which is a key breakthrough for achieving the state's energy goals.

iii. Outcomes: If successful, this research will create a generalized valuation toolkit that increases the perceived value of energy technologies. While it won't directly lower costs, it will improve the cost-benefit ratio by accurately measuring benefits, leading to more effective programs. At scale, this innovation will enable the state to optimize energy policy impacts, ensuring ratepayer funds are used efficiently. The innovation will lead to ratepayer benefits by improving safety and reliability (valuing resilience), affordability (optimizing program design), environment (increasing adoption), and accessibility (considering the unique characteristics of various communities).

iv. Metrics: The impacts will be measured using both quantitative and qualitative metrics:
  a. Quantitative:
    1. Monetary value of selected NEIs quantified.
    2. Changes in cost-benefit ratios of selected energy programs.
  b. Qualitative:
    1. Case studies and testimonials from policy analysts and program managers.
    2. Feedback from ratepayers.

v. References:
  a. Location value of DERs - https://emp.lbl.gov/news/value-distributed-energy-resources#:~:text=DERs%20can%20provide%20significant%20benefits,for%20traditional%20distribution%20system%20upgrades.

vi. Strategic Goal: Building decarbonization

vii. Support for Goal: The toolkit will make the economic case for building technologies (like heat pumps and energy upgrades) more compelling by quantifying benefits beyond energy savings. By valuing improved indoor air quality and resilience to extreme weather, the project will accelerate the adoption of these technologies, directly supporting the state's efforts in the building sector.

viii. Contributors to This Concept Include: Jingjing Zhang, Max Wei

5. Impacts of Updated ASHRAE Indoor Air Quality Best Practices

i. Description: The recently published best practices from ASHRAE seek to improve indoor air quality in response to the pandemic (Standard 241) and more frequent wildfires (Guideline 44). The industry consensus calls for increased building ventilation, improved filtration, and implementation of air cleaning where applicable, which could lead to higher energy consumption relative to our state's current building code Title 24. CEC EPIC funds are needed to evaluate the impacts of these changes on energy use across the different building sectors in California. Recommendations to building owners and operators on energy efficient approaches to implement such changes would greatly benefit Californians by improving indoor air quality while managing any impacts on energy costs.

ii. Breakthroughs: The proposed concept fills a knowledge gap about the cost and benefit of different approaches to better manage indoor air quality, as recommended by latest ASHRAE standards and guidelines. The evaluation of energy impacts from different approaches is useful for CEC to understand the impacts on different building sectors, if ASHRAE Standard 241 and Guideline 44 were to be adopted at scale. There are potential health benefits to Californians that can be realized through implementation of these best practices. The modeling analysis will also inform building owners and operators on energy efficient approaches and their expected outcomes, given their existing building and system type.

iii. Outcomes: The proposed modeling concept will identify cost effective approaches to better manage indoor air quality and benefit ratepayers by addressing affordability. It generally supports EPIC's environmental goals by reducing emissions associated with energy use to provide building ventilation, filtration and air cleaning. It is anticipated that certain building types, given their occupants are more vulnerable to respiratory infection and poor air quality (for example, schools and assisted living facilitates), would benefit the most if the best practices recommended by ASHRAE were implemented.

iv. Metrics: The proposed research concept will need to gather data to properly characterize the current conditions of existing buildings with respect to how they manage indoor air quality through ventilation, filtration, and air cleaning. The proposed work needs to gather inputs from practitioners to determine energy-efficient approaches to achieve the recommendations per ASHRAE guidance, including costs and expected in-situ performance when installed in different building types. Scenario modeling will consider occupant factors, operation and maintenance, as they can impact the actual performance. Success of the proposed research concept can be determined by how the modeling results are synthesized to inform policy and investment decisions for different building sectors in California. Once energy-efficient approaches are identified, future funding can support testing of the proposed technology packages, where measured data (such as energy use, provision of clean, filtered air in buildings) can be used to validate modeling results.

v. References:

a. Faulkner C., T.I. Salsbury, B. Abboushi, C. Mouchref, B.C. Singer, M.D. Sohn, and G. Arnold. 2024. Comparison of effectiveness and energy use of airborne pathogen mitigation measures to meet air quality targets in a prototypical office building. Building and Environment. DOI: 10.1016/j.buildenv.2024.111466.

b. ASHRAE Standard 241-2023. Control of Infectious Aerosols.

c. ASHRAE Guideline 44-2024. Protecting Building Occupants from Smoke During Wildfire and Prescribed Burn Events.

vi. Strategic Goal: Building Decarbonization

vii. Support for Goal: This proposed concept aligns with EPIC's strategic goals by evaluating other factors driving building and system retrofits, such as the need to better manage indoor air quality in response to wildfires following ASHRAE recommendations. These are motivating factors for building retrofits that CEC needs to evaluate for their impacts on energy consumption. Modeling results from this proposed concept can be used to inform policy and investment decisions.

viii. Contributors to This Concept Include: Rengie Chan, Brett Singer

6. Kitchen Retrofits in K-12 Schools

i. Description: CEC EPIC funds are needed to support K-12 schools in their pathway to reduced energy consumption and emissions. A particular challenge faced by schools is kitchen upgrades for electric equipment. In addition to uncertainty about upfront installation costs, schools are also reluctant because of concerns about implications to their utility costs in the long run. There is a need to gather data to inform the lifetime costs of kitchen upgrades in K-12 schools, including interactions between electric kitchen equipment and HVAC energy use in different types of locations and settings. For projects to be successful and replicable, schools are interested in telling the story of the other benefits that electric kitchen equipment can bring, such as reducing emissions, and improving thermal comfort for their kitchen staff. CEC EPIC funds can be used to support demonstration projects, where implementation and energy costs, as well as data to document other benefits, can be gathered systemically in a wide range of school kitchens and structures, and in different parts of California.

ii. Breakthroughs: The proposed concept to document energy cost savings and other benefits from electric kitchen equipment will motivate more K-12 schools to implement this type of retrofit. Currently, only a limited number of school districts in California have implemented this type of retrofit in some of their sites. A recent CEC sponsored project – Demonstration of High-Efficiency Commercial Cooking Equipment and Kitchen Ventilation Systems (CEC-500-2021-021) – quantified such benefits in several types of commercial foodservice operations other than K-12 schools. The proposed work will bring about much needed data to make the case to school administrators and their communities to invest in these retrofits.

iii. Outcomes: In limited pilot projects, these kitchen retrofits in K-12 schools have shown to reduce energy costs, improve productivity, and create a more comfortable work environment for staff. This proposed research concept is anticipated to document energy cost savings and other benefits in different settings, from central kitchens to schools with individual onsite kitchens, and present approaches for kitchen upgrades to electric equipment that are broadly applicable. These benefits align with EPIC's guiding principles to improve affordability by lowering the energy consumption of school kitchens. It generally supports EPIC's environmental goals by reducing emissions through equipment upgrades and other energy efficiency improvements. Schools in many California communities can benefit from this proposed concept by being included as part of the demonstration projects.

iv. Metrics: The proposed research concept should be evaluated by the number of demonstration sites, and whether or not it is able to engage with a wide range of school districts and different kitchen settings in the study. The success of this type of project would be determined by proper documentation of costs (installation and operation), monitoring of energy consumption, productivity, and changes to the work environment. The proposed research could include surveying of school districts in California to understand their view on kitchen equipment upgrades, and to what extent the demonstration projects and lessons learned are relevant in addressing their key concerns.

v. References:

a. Livchak, Denis, Edward Ruan, Michael Karsz, and David Zabrowski. 2021. Demonstration of High -Efficiency Commercial Cooking Equipment and Kitchen Ventilation Systems. California Energy Commission. Publication Number: CEC-500-2021-021.

b. The Building Decarbonization Practice Guide. Vol. 5: All-Electric Kitchens: Residential + Commercial. 2022. https://worthenfoundation.org/get-the-guide-bdpg

c. School Decarbonization Strategy Spotlight: Kitchen Electrification. New Buildings Institute. 2024. https://filesnewbuilding.s3.amazonaws.com/wp-content/uploads/2024/03/School-Decarbonization-Spotlight_Kitchens_NBI-122923.pdf

vi. Strategic Goal: Building Decarbonization

vii. Support for Goal: School kitchens are energy intensive and contribute substantially to emissions. The proposed research concept would support EPIC's strategic goal related to buildings by capturing energy cost savings and other benefits through kitchen electric upgrades. Successful demonstrations in a broad range of kitchen and school settings are needed to motivate investments for retrofit.

viii. Contributors to This Concept Include: Rengie Chan, Brett Singer

L. Reducing feeder/circuit peaks

1. Widespread Rollout of Plug-in DERs
   i. Description: Plug-in distributed energy resources (DERs) backfeed power to the home through a standard plug. The concept scope includes balcony solar, plug-in car ports, battery-integrated equipment, bidirectional EV (but not hardwired), among others. The concept would seek to award projects that engage in a widespread rollout of plug-in DERs throughout CA. Teams should include capabilities for both product and deployment. Today's deployers struggle with compliance and workforce barriers. EPIC funds would greatly support identification of such barriers and engagement with relevant stakeholders, authorities having jurisdiction, and policy makers in CA. Funds would also support the widespread plug-in DER rollout over multiple communities, benefiting them directly and understanding usage patterns to qualify the utility of this technology.
   ii. Breakthroughs: CA's energy goals will require a combination of utility and resident participation. However, today NEM 3.0 removes cost incentives for residential participation due to its expected 14+ year payback period. Plug-in DERs' main value proposition is cost: European balcony solar systems have payback periods as low as 3 years. Plug-in DERs provide renters with a unique option to participate in the solar and storage markets that can be easily moved between homes and apartments. As such, these systems may represent the future of residential solar and storage, as long as payback periods could remain within 5 years. While plug-in DERs have seen widespread success in Europe, their U.S. market is stagnant due to the barriers mentioned above. Overcoming these barriers may be a necessity for potential projects as well, in order for the CA market for plug-in power to flourish.
   iii. Outcomes: The purpose of projects within this concept would be to grease the runway for the plug-in power industry to prosper in CA. Anything to that end is a successful step in the right direction. German adoption of plug-in power took nearly a decade, and much of the early work involved engagement at the municipal level with utilities and even building inspectors. Fully successful projects would make energy more affordable and reliable. In addition, a highly-public deployment would demonstrate statewide to utilities and inspectors that plug-in power is truly harmless and entirely beneficial.
   iv. Metrics: First Cost and Payback Period, Average Reduction in Energy Bills, Average Resilience Provided, and Utilities or Inspector Engaged

v. References:
   a. For European payback period: https://plugin-solar.eu/
   b. For regulatory barriers in US: https://www.mdpi.com/1996-1073/18/8/2132
   c. For an example of successful legislation around plug-in power: https://pv-magazine-usa.com/2025/03/05/balcony-solar-gains-unanimous-bipartisan-support-in-utah
vi. Strategic Goal: Distributed Energy Resource Integration
vii. Support for Goal: This concept supports goals (b), (d), and (e), though primarily targets (b).This projects' success would support improving the economic value proposition of residential solar and also open its market to renters and low-income families. It is the only viable future of residential-scale DER integration. This is CA's opportunity to become the hotspot state for the emerging plug-in power industry.
viii. Contributors to This Concept Include: Daniel Gerber

2. Thermal Performance Enhancement Through Commercial Reglazing
   i. Description: The proposed concept of thermal performance enhancement through commercial reglazing aims to advance the widespread adoption of reglazing as a cost-effective strategy for improving the energy efficiency of existing commercial buildings. The purpose of this concept is to develop and demonstrate standardized thermal and infiltration rating methodologies for commercial reglazing products, as well as provide best practices guidance for their installation.

      This concept seeks to address the current lack of standardized ratings and guidelines, which hinders the ability of building owners and architects to make informed decisions about reglazing projects. By establishing a clear framework for evaluating the thermal performance of commercial reglazing products, this project would facilitate the specification and procurement of high-performance glazing solutions, ultimately leading to significant energy savings and improved occupant comfort.

      EPIC funds are needed to support this concept because they would enable the development of comprehensive rating methodologies and best practices guidance, which would require collaboration with industry stakeholders, research, and testing. Additionally, funding would be necessary to demonstrate the effectiveness of commercial reglazing through field installations and monitoring, providing critical validation of the technology's performance in real-world settings. The investment would help to overcome existing market barriers, accelerate the adoption of energy-efficient reglazing solutions, and contribute to California's energy goals.

ii. Breakthroughs: The proposed concept aims to overcome technical and market barriers that hinder the widespread adoption of energy-efficient reglazing solutions in commercial buildings. By addressing these barriers, the concept will contribute to achieving California's energy goals.

   a. Technical barriers:
      1. Lack of standardized thermal and infiltration rating methodologies: Currently, there is no standardized framework for evaluating the thermal performance of commercial reglazing products. This makes it difficult for building owners and architects to compare products and make informed decisions. The proposed concept will develop and demonstrate standardized rating methodologies, enabling the industry to establish clear performance targets.
      2. Uncertainty about installation best practices: The absence of widely accepted installation guidelines leads to variability in installation quality, which can compromise the performance of reglazing products. The concept will develop and disseminate best practices guidance, ensuring that installations meet performance expectations.
   b. Market barriers:
      1. Higher upfront costs: While reglazing is a cost-effective alternative to full window replacement, the initial investment can still be a barrier for building owners. The proposed concept will help to reduce costs by identifying cost-effective solutions and providing data on long-term energy savings.
      2. Limited awareness and understanding of reglazing benefits: Building owners and architects may not be familiar with the benefits of reglazing or may be skeptical about its effectiveness. The concept will provide data and case studies demonstrating the energy-saving potential of commercial reglazing, increasing awareness and confidence in the technology.
      3. Payback period: The concept targets a payback period of 5 to 7 years for commercial reglazing projects, making it a more attractive investment for building owners.

4. Thermal performance: The proposed concept will establish standardized thermal performance targets for commercial reglazing products.

iii. Outcomes: If the research concept is successful, the anticipated outcomes are:

a. Reduced technology costs: The development of standardized thermal and infiltration rating methodologies, as well as best practices guidance, will help reduce the costs associated with commercial reglazing projects. This will be achieved by: Streamlining the design and specification process, minimizing installation errors and variability, enabling building owners and architects to make informed decisions about reglazing products.

b. Increased performance: The research will lead to the development of high-performance commercial reglazing products. This will result in improved thermal performance, enhanced energy efficiency, and increased comfort for building occupants.

c. Improved overall value proposition: The work will improve the overall value proposition of commercial reglazing by providing a cost-effective alternative to full window replacement, offering a solution that is compatible with existing window frames, reducing waste and minimizing disruption, and demonstrating the energy-saving potential of commercial reglazing, making it a more attractive investment for building owners.

d. Widespread adoption: If successful, this work has the potential to be widely adopted across California's commercial building stock, leading to significant energy savings and peak loading.

e. Ratepayer benefits:

1. Affordability: The innovation will help reduce energy costs for building owners and occupants, making buildings more affordable and competitive.
2. Reliability: The innovation will improve the reliability of commercial buildings by reducing the risk of energy-related disruptions and improving occupant comfort.

iv. Metrics: To evaluate the impacts of the proposed research concept the quantitative metrics should include energy savings, payback period, cost savings, and thermal performance. Qualitative metrics should include adoption rate, stakeholder engagement, market barriers, compliance issues, scalability and replicability. Potential indicators include number of potential commercial reglazing projects, energy efficiency ratings, customer satisfaction, and market trends.

By using these metrics and indicators, the impacts of the proposed research concept can be evaluated, and the effectiveness of commercial reglazing solutions in achieving energy efficiency, cost savings, and environmental goals can be assessed.

v. References:
vi. Strategic Goal: Building Decarbonization, Climate Adaptation
vii. Support for Goal: The proposed concept supports California's strategic goals by reducing energy consumption and emissions from buildings, improving building resilience and enhancing occupant comfort. By enabling buildings to operate more efficiently, commercial reglazing can help achieve California's goals and align the State's strategies , ultimately contributing to a more resilient built environment.
viii. Contributors to This Concept Include: Robert Hart, Charlie Curcija

3. Critical Barriers to Improving Building Energy Control Systems
   i. Description: The proposed concept addresses critical barriers to improving the design, deployment, and operation of building energy control systems. In particular, the industry lacks standardized processes and interoperable tools for testing, verifying, and benchmarking controls, making it difficult to compare control algorithm performance, ensure correct implementation, and scale solutions across the vast building stocks. Currently, building control systems, especially in commercial buildings, are complex, often manually specified, and prone to errors, leading to significant energy waste (up to 29% in commercial buildings), hindering adoption of high-performance, data-driven, grid-interactive, and/or predictive controls, and could jeopardize the successful deployment of novel HVAC systems. California is starting to recognize these needs, as Title 24 2026 will require new commercial buildings to follow ASHRAE Guideline 36 controls and for control contractors to verify conformance of their products to the Guideline. However, ASHRAE Guideline 36 only addresses a subset of control objectives and applicable system types, and the Title 24 verification requirements, along with any methods or tools to help industry meet such requirements, are nascent.

   We believe EPIC should invest in the development and deployment of open-source, standardized frameworks and tools for digitization of the control delivery process, simulation-based testing, formal verification, and benchmarking of building control strategies. This includes leveraging emerging standards like ASHRAE 231P (Control Description Language - CDL) and 223P (Semantic Data Model), along with high-fidelity emulators and Key Performance Indicators (KPIs) through platforms such as BOPTEST and ConStrain. These tools will enable manufacturers and mechanical designers to test control performance early, automate code generation, and formally verify installed products and systems against digital specifications and other performance requirements, thereby reducing manual effort, costs, and errors throughout the design-build-operate process.

EPIC funding is essential because the fragmented building industry will not independently develop open-source, standardized tools needed to test and verify controls. This public investment is required to create shared, non-proprietary frameworks that overcome current market barriers, allowing all stakeholders to reliably deploy the efficient control technologies necessary for future building operation.

ii. Breakthroughs: Current building control implementation methods are primarily manual, error-prone, and expensive, hindering the widespread adoption of high-performance, grid-interactive controls and jeopardizing the successful deployment of novel HVAC systems and DER needed to achieve California's energy goals. The industry currently lacks standardized processes and interoperable tools for developing, testing, verifying, comparing, and deploying control algorithms and products. By leveraging ASHRAE 231P (Control Description Language - CDL) and ASHRAE 223P (Semantic Data Model), alongside high-fidelity emulators and compliance tools through platforms like BOPTEST and ConStrain, the concept enables early control performance testing, automated code generation, and formal verification of installed products and systems against digital specifications. This approach mitigates issues such as pervasive control programming errors and the inherent complexity of modern advanced control sequences, such as ASHRAE Guideline 36 required by Title 24.

The proposed concept addresses critical data and information gaps by providing tools, workflows, and frameworks for simulation-based development, testing, and benchmarking of control algorithms, as well as for streamlining deployment through digitization and standardization.

The beneficiaries and their purposes include:

a. Manufacturers and mechanical designers: Gaining the ability to test control performance early in the design phase.
b. Control vendors and contractors: Benefiting from automated code generation and formal verification of installed products and systems against digital specifications.
c. Building owners, operators, and occupants: Realizing reduced energy and operational costs, improved quality and reliability, and enhanced overall building performance.
d. Utilities and energy providers: Achieving improved energy efficiency and demand flexibility in buildings, along with better integration of electric equipment like heat pumps. Also enabling incentive program development using prescriptive or performance-based measures.
e. Governmental bodies: Enhance information available with which to carry out programs.

iii. Outcomes: Digitization of the controls design and implementation processes would streamline the control implementation process, reducing errors and malfunctions. Simulation-based control testing and benchmarking frameworks allow for rapid prototyping of new control strategies by industry and research with low risk compared to real-world testing and direct comparison to the established state-of-the-art, ensuring high-performing strategies are deployed. Such methods are more scalable than physical lab or real-world testing since software tools can be shared at-scale. Formal verification processes ensure systems will operate correctly and according to established guidelines (e.g. ASHRAE Guideline 36) or other performance expectations (e.g. responding to demand response events).

These advances reduce implementation and commissioning costs due to fewer errors, reduce energy use and costs due to better performance, and improve system reliability due to additional verification that can be completed before installation. Such developments are needed as energy systems become more integrated and complex, such as integrating new technology like heat pumps, storage, and DER, and performance objectives evolve, such as needing to provide demand flexibility to the grid or respond to emergency events like wildfires.

iv. Metrics: Quantitative metrics that would measure improved control performance include energy use and cost, indoor air quality, peak load reduction and other demand flexibility metrics, and equipment COPs and efficiency measures. Quantitative metrics that would measure improved implementation and commissioning include effort to code sequences of operation, number of control installation or coding errors, time required to install and commission, pass/fail rate of verification tests, time required to execute verification tests. Qualitative metrics would include building owner and facility manager trust in new controls and systems, ease of controls delivery across the stakeholders in the process (designer, contractor, installer, commissioning agent, operator).

v. References:

a. Wetter, Michael, Milica Grahovac, and Jianjun Hu. "Control description language." In Proceedings of The American Modelica Conference, no. 154, pp. 17-26. 2018.
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f. Wetter, Michael, and Matthias Sulzer. "A call to action for building energy system modelling in the age of decarbonization." Journal of Building Performance Simulation 17, no. 3 (2024): 383–393. https://doi.org/10.1080/19401493.2023.2285824.

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Climate Adaptation

vii. Support for Goal: Distributed Energy Resource (DER) Integration: Controls enable buildings to become dispatchable resources for the grid through actively managing load flexibility and demand response, as well as integrating on-site DER with HVAC and other energy systems. Especially with such interconnected and complex systems, as well as emerging control objectives, this research concept will enable well-tested, properly functioning controls and systems that reliability meet performance objectives.

Regarding Buildings: Especially in large commercial buildings and district systems, central plants that utilize heat pumps, storage, and energy recovery require new and more complex sequences of operation than conventional boiler plants. High-performance sequences of operation that promote energy efficiency in buildings are also more complex than traditional sequences. This research concept will de-risk the installation and operation of these novel systems and control strategies, reduce commissioning effort and prevent costly change orders from failures in the field, and improve the overall reliability of systems.

Regarding Resilience: This concept enhances resilience by making buildings safer, more reliable, and more resilient during extreme events like heat waves. By enabling early control performance testing, automated code generation, and formal verification against digital specifications, the proposed research ensures that control systems are robust and perform as intended under various conditions. This improved reliability and resilience of building operations is vital for maintaining comfort and functionality.

viii. Contributors to This Concept Include: David Blum, Ettore Zanetti, Michael Wetter, Marco Pritoni

4. Optimizing Air Management in California Data Centers

i. Description: This concept will establish standardized workflows and validated reference geometries for applying Computational Fluid Dynamics

(CFD) to optimize air management in California data centers. We will conduct experiments on representative rack configurations and plenum designs, then perform high-resolution CFD simulations to map airflow, temperature, and pressure profiles. The project will deliver a publicly accessible CFD Modeling Guidance Document, a numerical database of benchmark cases, and reference CFD models that operators can adopt for both new designs and retrofit projects.

EPIC support is essential because scaling accurate CFD analysis across varying geographies with unique weather patterns and rack densities requires significant computational and experimental resources. No existing guidance from independent entities offers the reproducible, peer-reviewed protocols needed to mainstream CFD best practices in California's data centers. EPIC funding will underwrite the compute time, model validation tests, and stakeholder workshops needed to produce a CFD reference toolkit—breaking down technical barriers and accelerating industry-wide adoption.

ii. Breakthroughs: Data centers today often rely on conservative safety margins, over-cooling, because operators lack confidence in airflow models and continuity. This inefficiency is exacerbated by rapidly evolving rack densities and AI-driven load profiles, creating highly non-uniform heat maps. Our concept breaks through these barriers by developing reference CFD models—analogous to DOE's EnergyPlus reference buildings—that are tailored to common California weather patterns and data center types. We will create validated CFD guidelines: mesh-resolutions, boundary-condition setups, and validation benchmarks that ensure accuracy between simulated and measured temperatures.

    Equipment vendors and consulting firms currently provide proprietary CFD services with opaque assumptions, leaving small operators unable to access or validate findings. By publishing open, peer-reviewed CFD protocols and baseline case studies, we fill a critical data gap—trusted, reproducible parameters for data center air management design.

    Beneficiaries include data center engineers seeking to justify investments in containment retrofits, utility partners designing incentive programs for energy-efficient upgrades, and DER aggregators planning thermal storage integration.

iii. Outcomes: The concept will enable data centers to cut cooling-related electricity use. Reduced peak loads will decrease grid stress and minimize

Public Safety Power Shutoff (PSPS) impacts during summer heat events. Individual facilities leveraging the reference models can expect a retrofit payback period under three years, spurring widespread implementation.

Aligned with EPIC's guiding principles, our CFD framework enhances safety by preventing thermal-induced server failures, reliability by maintaining consistent inlet temperatures, affordability via lower energy bills, environmental goals by making advanced cooling practices accessible to smaller data centers without proprietary costs.

iv. Metrics:
  a. Quantitative:
    1. Cooling Energy Reduction (%): Drop in fan and chiller power
    2. Supply-Air Volume Reduction (%): Lowered CFM requirements.
    3. Simulation Accuracy (°C): Mean error between CFD predictions and sensor data
    4. Scenario Turnaround Time (hrs): Time to run full-scale CFD analysis
    5. Adoption Rate: % of California data centers using the reference models
  b. Qualitative:
    1. Stakeholder Confidence: Surveyed usability and trust scores
    2. Policy Uptake: Inclusion of CFD guidelines in utility incentive programs or local energy practices.
    3. Training Impact: Number of engineers trained at CEC-hosted workshops.

v. References:

  a. ENERGY STAR. (2024). Managing airflow for cooling efficiency. ENERGY STAR Data Center Equipment Efficiency Resources. Retrieved from https://www.energystar.gov/products/data_center_equipment/16-more-ways-cut-energy-waste-data-center/manage-airflow-cooling-efficiency
  b. Shehabi, A., Hubbard, A., Newkirk, A., Lei, N., Siddik, M. A. B., Holecek, B., ... & Sartor, D. (2024). 2024 United States Data Center Energy Usage Report.
  c. Van Geet, Otto and Sickinger, David. "Best Practices Guide for Energy-Efficient Data Center Design.", Jul. 2024. https://doi.org/10.2172/2417618

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Climate Adaptation

vii. Support for Goal:

a. Distributed Energy Resource Integration: Lower cooling loads free capacity for on-site solar, storage, and demand response, enhancing grid flexibility and DER value.
b. Buildings: Significant electricity reductions directly reduce emissions from data center operations.
c. Resilience: Resilient CFD-guided air management ensures uninterrupted digital services and grid stability during extreme heat events, strengthening statewide resilience.

viii. Contributors to This Concept Include: Chao Ding, Nihar Shah

5. Emerging Battery-Integrated End Use Equipment

i. Description: Many electrical end-use technologies and devices have a role in supporting CA's energy goals, but increases to the peak electric power of the building can increase energy costs (UC Davis CEC study), and are limited in their demand flexibility potential. This research will enable development and valuation of a new class of emerging battery-integrated end use equipment, that can provide deeper energy cost savings, larger capacity demand flexibility at a longer, more reliable duration, and resilience benefits to customers. Presently this technology is emerging in the market, but lacks the control methods to fully capture the potential value, and industry needs this technology to be well validated in order to reliably reduce costly electrical infrastructure upgrades. Further, the adoption of electrical devices creates load growth and electrical system constraints. Technologies that support utilities in deferring capital investments in distribution system grid upgrades should have compensation mechanisms that enable this valuation. Last, this technology can address building electrical panel or service upgrade needs if controls are developed and validated to demonstrate this capability reliably to code officials, reducing building owner costs.

Research is needed to develop and demonstrate the value of these grid services. Further, evaluation methods will need to be developed to ensure appropriate assessment of the benefits. Some of these emerging technologies are being developed by small companies, with limited ability to both develop and pilot these technologies, as well as support the kinds of analysis needed to generate utility interest in capturing their value. EPIC funds are needed to support these efforts to ensure that controls are developed that reliably provide these benefits to customers and the grid.

ii. Breakthroughs: The research will develop each end use technology to ensure that peak load/electrical draw is managed in a reliable manner to enable reduced capacity electrical connections for the equipment. Without such research, consumers will require significant and costly electrical panel and service upgrades which will deter technology adoption. These controls can be made in a specific manufacturer-agnostic way, and made open source, which will enable manufacturers in general to benefit. Equipment electrical connectivity ratings could be downsized, saving the customer in implementation costs.

    Research is also needed to develop distribution grid services compensation mechanisms and values for the utility, aggregator and customer. Presently the market has very limited examples of programs that address grid constraints, PG&E's managed EV pilot program Flex Connect, being an exception. Further technologies should be eligible for providing similar grid services reliably. Without these mechanisms, this market will not be developed and promoted, and industry will not benefit from the full extent of this technology.

iii. Outcomes: Successful controls development will by definition improve energy costs for the customer, and make these technologies a more viable proposition for customer adoption. It will also reduce implementation costs for electrical end-use devices, where panel upgrades can run from $2k-6k per installation.

iv. Metrics: Technology energy cost savings estimates should be provided, in comparison with a business as usual operations case. Demonstrations should also monitor the service levels of the equipment, to ensure no disruption to the thermal comfort, domestic hot water supply temperature or other service disruptions. Pre- and post- consumer surveys should also be included to ensure the technologies performed as they had expected. Other technical performance criteria should include peak electrical draw measurement under a full range of operational conditions, as well as the performance of any grid services.

v. References:
    a. Electrical panel upgrade costs - https://newbuildings.org/we-can-power-the-homes-of-the-future-with-electric-panels-of-the-past/#:~:text=Electrifying%20and%20decarbonizing%20existing%20buildings,the%20TECH%20Clean%20California%20Database.

b. Location value of DERs - https://emp.lbl.gov/news/value-distributed-energy-resources#:~:text=DERs%20can%20provide%20significant%20benefits,for%20traditional%20distribution%20system%20upgrades.
Electrical cost impacts from heat pump installations - https://www.energy.ca.gov/sites/default/files/2025-06/CEC-500-2025-026.pdf

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Climate adaptation

vii. Support for Goal: The proposed technologies support DER adoption and integration to offset end use electrical loads, reducing customer energy costs. Further, these technologies, if developed with suitable controls, can support the State's goal related to buildings while managing customer energy bills to ensure cost effective operation occurs. Last, the demand flexibility potential of these technologies can provide greater flexible capacity than their counterpart technologies (e.g. smart thermostats), with longer, more reliable provision of grid service without occupant behavioral impacts (overrides) or 'snapback' of system performance after the demand flexibility event. This capability benefits the building stock, without increasing peak power, or strain on the grid. Last, these technologies may also provide a resilience benefit, enabling key building services to be maintained during a power outage, enabling buildings to adapt to events such as Public Safety Power Shutoff (PSPS) to help prevent wildfires.

viii. Contributors to This Concept Include: Cindy Regnier

6. Overcoming Adoption Barriers for Commercial Refrigeration Systems

i. Description: Supermarkets, restaurants, and convenience stores have some of the highest building energy intensities, in large part due to the amount of refrigeration needed to hold stored food. Increasing the efficiency of the self-contained and remote refrigeration systems used in these locations could help save energy, make their businesses more profitable, and reduce the large demands that these facilities place on the grid. EPIC funds are needed to investigate cost-effective ways to drive commercial refrigeration systems to higher average installed efficiency by using laboratory-tested/validated efficient and novel designs and market/survey analysis to develop effective pathways to overcome adoption barriers.

ii. Breakthroughs: Advanced, energy-efficient commercial refrigeration equipment systems already exist but fail to achieve significant market penetration, especially among small and medium-sized businesses. This represents a major barrier to achieving California's energy goals. The "breakthrough" for this project is the combination of lab-tested and validated performance data with market analysis to bridge the gap between technical potential and real-world adoption and estimate the potential resulting energy savings. The project will target several critical barriers and customer pain points (e.g. high upfront capital costs for small businesses, lack of trusted third-party performance data specific to California, lack of trusted third-party performance data specific to new technologies, and split incentives). The research will provide data on the performance of commercial refrigeration equipment under California-specific conditions and evaluate the performance of new refrigeration technologies. It will also investigate the drivers influencing purchasing decisions and suggest effective ways to design incentive programs.

    Results will benefit the CEC, utilities, equipment manufacturers, and business owners by providing validated performance data for decision-making, and accelerating the market penetration of more efficient equipment, reducing grid load, and saving ratepayers money.

iii. Outcomes: If successful, this research will provide lab-validated performance benchmarks and recommend effective ways to design incentive programs, as well as estimate the potential impact on the market in terms of projected energy savings and market share increase.

    At scale, this research will lower overall system costs by contributing to reducing the energy used by commercial refrigeration equipment, accelerate progress toward California's reduced emission goals, and enhance grid reliability. Ratepayer benefits include lower electricity bills for business owners (specifically small businesses), and reduced infrastructure costs for all ratepayers – aligning with EPIC’s core principles.

iv. Metrics:
    a. Quantitative metrics: validated efficiency gains; optimal incentive levels (in $ or as a % of upfront costs); projected market impacts in terms of statewide energy savings and market share increase of more efficient equipment.
    b. Qualitative metrics: analysis of purchase drivers, potential feedback from stakeholders (manufacturers, contractors, etc) on the

effectiveness and feasibility of the recommended incentive programs and tested performance results.

v. References:

a. EIA CBECS, Table E5. Electricity consumption (in kilowatthours [kWh]) by end use, 2018 which shows that refrigeration is one of the largest end-uses of electricity in specific commercial building types (45-50% of total electricity consumption in "Food Sales", which includes supermarkets and grocery stores)

b. SB 100. De León, Chapter 312, Statutes of 2018. The 100 Percent Clean Energy Act of 2018.
– Provides the overarching mandate for reducing emissions from the grid, making the reduction of large, constant loads like commercial refrigeration a state priority.

c. ACEEE (2014). Foster, A., et al. Engaging Small and Medium-Sized Businesses in Energy Efficiency: A Review of Program Strategies. American Council for an Energy-Efficient Economy. Report Number U1405.

d. Documents the specific barriers, such as lack of capital, time, and trusted information, that prevent small and medium-sized businesses from investing in energy efficiency.

vi. Strategic Goal: Building Decarbonization, Climate Adaptation, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: Lab-validated data and incentive programs will increase the adoption of efficient refrigeration systems, directly supporting the State's goals related to buildings by reducing energy load in the commercial sector. Further, improving the efficiency of refrigeration equipment will help lower the electricity demand during extreme weather events (e.g. heat waves) and reduce stress on the grid, making it more resilient and reliable. Indirectly, this effort also supports the transportation goals by reducing load and providing capacity for EVs, and supports Distributed Energy Resource goals by reducing the peak demand in the evening when solar generation drops.

viii. Contributors to This Concept Include: Mo Ganeshalingam, Tom Burke, Sanaee Iyama, Colleen Kantner, Scott Young

7. Development of the Framework for the Open DC Power Infrastructure

i. Description: An increasing number of loads in buildings are DC powered, but because standardized wiring is all based on AC Power, each device needs to have a converter from AC to DC, reducing energy efficiency and increasing system cost. The concept proposes to establish open system architecture for “Building Power and Data Networks” for both power and data, to link together shading control (indoor and outdoor), lighting, and other DC loads and sensors and tie it into the BIPV (Building Integrated PV) and distributed battery storage. DC wiring and infrastructure would be added to the building in much the same way that traditional AC power infrastructure exists (wiring, standardized outlets placed throughout the building, etc.).

ii. Breakthroughs: The proposed concept would transform how the electric power would be distributed in the building. Currently, if you use DC powered devices, such as computers, LED lighting, TVs, smart phones, etc., you need to plug a converter with the proper voltage and amperage into the AC outlet and convert AC into DC power. If an occupant wants to have motorized shades, which can also be automated, it usually needs batteries that need to be regularly replaced. If there is localized PV generation (e.g., PV glazing, PV shading), each location needs to have a microinverter that plugs into the AC outlet and feeds into the grid. These microinverters are expensive and prone to failure. This type of direct feed into the building AC network can also be hazardous as the grid would stay alive even after the major power sources are disconnected. This represents a significant barrier to the adoption of localized energy generation technologies, as well as dynamic windows and shading. While power is central to this technology, it also enables standard Internet Protocol communications across all of the wired links, and can connect to the main building LAN. This allows sensing data and control signals to pass seamlessly among all of the devices inside and out of the building. There is currently no standard system for comprehensive integration of generation, storage, and loads for buildings. As such, either systems must be custom-created, or be simply extensions of the existing AC distribution within buildings. Both of these result in energy efficiency penalties, high costs, or both. Lack of a standard system also means that products from different companies are rarely interoperable

iii. Outcomes: The goal of this concept is to establish a standardized (open) system architecture for building power and data networks for both power and data, to link together BIPV (Building Integrated PV), distributed battery storage, DC plug loads, outdoor lighting, shading control (indoor and outdoor), and many other devices and sensors on the interior and exterior of buildings or nearby. With this, DC power distribution is not competing with existing AC infrastructure and so can compete directly on its merits. Most of the technology components exist in some form, but have never been combined. The least tested part is the network model of power, which has been demonstrated working in simulation, but not yet in hardware. An important outcome of this concept is the development of a standard system for comprehensive integration of generation, storage, and loads for buildings.

iv. Metrics:

   a. Quantifiable outcomes: (a) industry standard, (b) Measurable increase in efficiency of electric loads in building, (c) DC power sensing efficacy
   b. Qualitative outcomes: a) Accuracy and reliability of embedded sensing systems, (b) Streamlined access to AC and DC power sources, (c) Streamlined and robust data networks

v. References:

   a. Vossos, Vagelis, Daniel L Gerber, Melanie Gaillet-Tournier, Bruce Nordman, Richard E Brown, Willy Bernal Heredia, Omkar Ghatpande, Avijit Saha, Gabe Arnold, and Stephen M Frank. 2022. "Adoption Pathways for DC Power Distribution in Buildings." MDPI (2022). https://dx.doi.org/https://doi.org/10.3390/en15030786
   b. Nordman, Bruce, Margarita Kloss, Bijit Kundu, Nate Dewart, Callie Clark, Rebecca Aviles, Anand Prakash, Laura Wong, Alana Torres, Chris Uraine, Rachel Levine, Marco Pritoni, Jordan Shackelford, Heidi Werner, Rahul Athalye, and Aditya Khandekar. 2021. "Energy Reporting: Device Demonstration, Communication Protocols, and Codes and Standards". California Energy Commission Final Project Report. CEC-500-2024-103. https://buildings.lbl.gov/publications/energy-reporting-device
   c. Gerber, Daniel L, Vagelis Vossos, Wei Feng, Chris Marnay, Bruce Nordman, and Richard E Brown. 2018. "A simulation-based efficiency comparison of AC and DC power distribution networks in commercial buildings. "Applied Energy 210 (2018) 1167-1187. https://dx.doi.org/10.1016/j.apenergy.2017.05.179
   d. Peng, J; Goudey, H.; Thanachareonkit, A.; Curcija, C; and Lee, E. 2017. "Measurement & Verification of the Performance of Solaria BIPV in FLEXLAB Test Facility". LBNL Technical Report. https://flexlab.lbl.gov/sites/default/files/solaria-bipv-flexlab.pdf

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization

vii. Support for Goal: A comprehensive integration of onsite generation, storage, and loads for buildings based on DC power networks will increase the efficiency of electric loads in buildings, reducing load on the grid and allow for better planning of grid upgrades to service newer loads that may not be part of DC networks.

viii. Contributors to This Concept Include: Charlie Curcija, Daniel Gerber

8. Integrated Operation of Automated Shading Systems in Real Buildings

   i. Description: The operation of automated shading can have substantial impacts on the amount and timing of energy use in commercial buildings, especially if these buildings have a significant glazed envelope area. This has been shown through extensive experimental and simulation work, some of which funded by previous CEC EPIC rounds. For example, a recent study shows that, when controlled in an integrated fashion with HVAC and lighting, automated shading has the potential to result in 20% and 14% whole building peak and energy cost savings across US climates by taking advantage of diurnal variations in incident solar radiation and electricity rates. By modulating the building's thermal loads through the glazed facade, automated shading can be a key element in managing demand flexibility and demand response.

      While integrated operation of automated shading systems has been successful in laboratory studies, EPIC funding is needed in order to realize its benefits in real buildings. Work needed includes 1) developing and demonstrating tools that enable the practical aspects of implementing and operating integrated, automated shading systems in real buildings, where, even if automated, building systems are siloed and not operated in sync with each other, 2) field demonstrations are needed in order to document energy, cost, and occupant comfort performance, overall benefits, and best practices, 3) identifying how the technology can be best articulated with California utility programs. The work described in this concept will help reduce risks and maximize cost savings for adopters, as well as deliver a more stable and efficient electric grid for all California ratepayers.

      This work would benefit from the results of the Open DC Power concept's proposed framework included earlier.

   ii. Breakthroughs: The proposed concept will address the cost and practical barriers to implementing integrated, automated facades in California commercial buildings. Due to the lack of publicly-available tools, implementing this type of integrated controls for automated facades is currently out of the reach of small and medium sized vendors, even when customers ask for them. Larger vendors, who may have the engineering capability to deliver integrated solutions, can end up convincing interested customers to opt for simpler, lower performing facade automation solutions due to perceived maintenance cost risks (e.g., increased callbacks to the vendor). The proposed concept would provide 1) publicly-available tools that automated facade vendors can use to implement integrated facade automation without having to develop in-house solutions, 2) data from field studies documenting the energy, cost, and occupant comfort performance, overall benefits, and best practices regarding integrated facade automation in real buildings, which is important for a) reducing risks for potential customers such as building owners and ESCOs, b) providing data for potential co-financers such as state/local government and utility programs, and c) provide data that could support local or state energy practices implementation.

iii. Outcomes: If successful, this research concept will result in lower energy costs for commercial buildings and better-managed impacts of commercial buildings on the electricity grid (e.g., reduced peaks, increased volume of load shifting, increased temporal alignment between building energy use and lower emission energy production). By reducing costs and contributing to a less strained grid, this research concept aligns with EPIC's principles. Results from previous studies (Gehbauer et al., 2023) indicate that, in ASHRAE climate zones 3A and 3B, which comprise most of California's buildings, whole building peak savings from integrated, automated facade operation can reach 18%, with approximately 12% electricity cost savings (with small variations depending on energy tariff structure).

iv. Metrics: Metrics or indicators that will be used to evaluate the impacts of the proposed research include reduction in annual building energy costs, reduction in annual energy peaks, reduction in annual emissions, reported occupant satisfaction with visual and thermal comfort in perimeter areas, installation costs, and impacts on the building's maintenance and operations processes and costs.

v. References: Gehbauer, C., et al, An evaluation of the demand response potential of integrated dynamic window and HVAC systems, Energy & Buildings 298 (2023) 113481. This paper reports results from a simulation study on the impacts of integrated, automated facades on commercial buildings across US climates. Peak reductions reached 55% (perimeter zones) and 20% (whole building), cost savings were up to 44% (perimeter) and 14% (whole building), with up to 10% whole building emissions reductions. Occupant comfort was maintained at all times.

vi. Strategic Goal: Building Decarbonization, Climate Adaptation, Distributed Energy Resource Integration

vii. Support for Goal: This concept addresses CEC's goals by using integrated, automated facades that can enable load shifting according to the temporal variation of the grid's emissions intensity in order to shift energy use towards lower-emission grid mix periods. This ability is bolstered if the building has local electricity generation or energy storage.

This concept addresses resilience because the facades take into account weather forecasts and automatically adjust to gradual changes in weather. Furthermore, integrated, automated facades are able to optimize a building's response to periods of extreme weather or grid disruption, maintaining comfort and the ability of the building to continue functioning for longer during these periods.

Lastly, this concept addresses DER Integration as integrated, automated facades are able to take into account the presence of local generation and storage, factoring those resources into their optimization of energy costs, energy demand, occupant comfort, and other relevant metrics.

viii. Contributors to This Concept Include: Luis Fernandes, Christoph Gehbauer

9. Integration of AI with Commercial Building Simulation for Compliance Automation

i. Description: This concept proposes an AI-driven application that automates Title 24 Building Energy Code compliance modeling for commercial buildings. The application leverages an existing EnergyPlus Model Context Protocol (MCP) server, developed by LBNL, which provides standardized tool interfaces that enable Large Language Model (LLM) based AI agents to automatically read, modify, validate, and run building energy models, and conduct post-processing for compliance check. The AI-enabled modeling workflow can seamlessly integrate both unstructured data (design documents, architectural drawings, field measurements) and structured data (e.g., BIM models), creating comprehensive compliance models from multiple input sources. Currently, Title 24 performance-based compliance requires specialized expertise, commercial code compliance tools, and significant manual efforts with high costs. Our AI-assisted application would parse compliance rules, conduct simulations, diagnose failures, and suggest corrections in an iterative loop until designs meet code requirements, while automatically generating and submitting standardized compliance reports—reducing this entire process to minutes. EPIC funding is needed because this integration of AI with building simulation for compliance automation doesn't exist commercially. The research requires extending MCP toolsets, developing robust compliance rule-parsing AI, and ensuring accuracy for code compliance use. The outcome is a proof-of-concept AI compliance assistant that handles Title 24's performance approach, producing compliance reports and recommendations rapidly while democratizing access to advanced energy modeling for meeting California's targets.

ii. Breakthroughs: This AI-driven compliance tool addresses existing technological barriers and gaps, including the intensive manual effort required by current compliance methods, the complexity and frequent updates of Title 24, and limitations of existing state-mandated software in modeling advanced technologies like heat pumps and battery storage systems. A critical barrier is the fragmented nature of building design data, where information exists across unstructured formats (drawings, specifications, field notes) and various structured models (BIM, legacy simulation files), requiring time-intensive manual translation into compliance models. By automating rule parsing and iterative modeling, the proposed solution significantly reduces the expertise and resources required to comply with these stringent codes. The AI-enabled workflow addresses data integration challenges by automatically processing a wide range of input sources and converting them into standardized EnergyPlus models for compliance analysis. It fills critical gaps in existing software capabilities by enabling custom and flexible modeling for emerging technologies, facilitating easier compliance for innovative designs. Furthermore, the integration of generative AI and EnergyPlus via MCP provides a novel capability currently absent from the market—enabling automated diagnostics, iterative optimization loops, and robust data generation to inform better design decisions, ultimately enabling broader adoption of advanced building energy and resilience strategies.

iii. Outcomes: Successful implementation will deliver three primary ratepayer benefits. First, the tool will dramatically reduce compliance analysis time from days to minutes and cut costs by 50-80%, lowering soft costs in building design and construction while speeding permitting timelines. Second, automated compliance checking will increase actual compliance rates as more projects correctly implement energy efficiency measures rather than relying on conservative assumptions, leading to buildings that achieve the energy savings envisioned by policy and resulting in lower utility bills for ratepayers. Third, the AI's ability to explore multiple design iterations will optimize building solutions, potentially discovering combinations that exceed Title 24 by 10% or enabling all-electric designs with minimal cost impact — research suggests this could contribute 8-19% reduction in building energy use by 2050 when widely applied. Additional benefits include improved grid reliability through better DER integration, transparent compliance reporting that demystifies requirements, and enhanced accessibility by making advanced energy modeling available to more market participants.

iv. Metrics: Several metrics will evaluate the impact of this project, including quantitative measures like the reduction in time and costs for compliance modeling, improvements in compliance accuracy rates, energy savings, and emissions reductions achieved through optimized designs. Additional metrics include user adoption rates, satisfaction levels, and accessibility. Specific AI-related performance metrics will assess the accuracy of requirement interpretation, the effectiveness of generative recommendations in achieving compliance, and the computational efficiency of iterative optimization processes. Long-term market impact metrics will track broader adoption patterns and overall benefits realized by ratepayers. Combined, these metrics will comprehensively demonstrate the practical, economic, environmental, and societal value of the developed AI-driven compliance automation solution.

v. References: EnergyPlus-MCP GitHub repo https://github.com/LBNL-ETA/EnergyPlus-MCP

vi. Strategic Goal: Building Decarbonization, Climate Adaptation, Distributed Energy Resource Integration

vii. Support for Goal: Support streamline and increase rate of Title 24 code compliance for new constructions and major renovations. Current workflow and tools for Title 24 code compliance are complex (leading to the use of outdated versions of EnergyPlus and lack capabilities to model emerging technologies) and need significant CEC investment for support and maintenance. The proposed AI based approach can significantly reduce costs for code compliance and enables beyond code programs on emerging technologies run by IOUs.

viii. Contributors to This Concept Include: Tianzhen Hong, Han Li

10. AI-Enhanced Building Emissions and Retrofit Planning Tool

i. Description: In light of CEC's Building Energy Performance Strategy efforts (Docket 24-BPS-01), large building owners and the commercial real estate industry face ever-growing challenges and opportunities related to energy performance of their assets. This concept proposes to develop and pilot an AI-Enhanced Building Emissions and Retrofit Planning tool to accelerate California's energy goals. We will leverage advancements in artificial intelligence (AI), particularly large language models (LLMs) to create a dynamic, public-interest tool. The purpose is to empower building owners, municipalities, and utilities with sophisticated, data-driven tools to more effectively identify, prioritize, and implement cost-effective retrofits that enhance energy affordability, system reliability, and infrastructure safety.

The proposed initiative seeks to advance the current state of building energy analysis by integrating new information and technologies into a unified platform - new or existing - based on the following objectives:

Assess opportunities for energy performance retrofits or operational changes and capability gaps in retrofit design performance and current suite of retrofit analysis tools relative to the state’s energy goals
Develop and pilot AI-enhanced prototypes with key stakeholders (e.g., portfolio owners, municipalities, utilities) to mitigate identified gaps and improve decision-making, uncertainty management, and risk assessment.

Create a roadmap to integrate these tools into California’s broader building modernization strategies, and energy infrastructure planning efforts, fostering empirically proven strategies for financially attractive retrofits.

EPIC funds are essential to support, validate, and deploy this public-interest research and development (R&D) because the integration of AI into freely-available retrofit planning tools lacks a strong private-sector business case—yet offers substantial ratepayer benefits. These AI-enabled tools can reduce retrofit costs, improve strategic capital planning, strengthen infrastructure resilience and safety, and reduce the financial burden on building owners and communities —particularly for public buildings, small businesses, and local communities across California.

ii. Breakthroughs: The proposed concept directly supports the objectives of Senate Bill 96 by advancing technological innovation to overcome persistent barriers to widespread retrofit adoption while using performance-backed techniques to iteratively model California’s existing building stock. While several public software tools (e.g., ENERGY STAR® Portfolio Manager® , BETTER, BEopt) and benchmarking data are currently

in use, they fail to leverage the wealth of data available specific to California (e.g. 25-EDAP-01), and future data that could become available through implementation of Docket 24-BPS-01. Existing tools also lack critical capabilities such as multi-objective optimization, risk quantification, and strategic planning—features essential for scaling retrofit targeting and implementation across different building types and ownership models. This concept addresses these limitations by integrating AI and LLMs into new or existing tools to enhance their effectiveness, usability, and alignment with California's broader energy and infrastructure priorities, while leveraging CEC's uniquely rich building energy data infrastructure.
The project targets several key technical and market barriers: (1) fragmented and reactive decision-making across large building portfolios; (2) lack of integrated analytics to assess risks related to energy price volatility, future weather conditions, equipment performance, and cost variability; and (3) limited ability to bundle or phase retrofit projects in alignment with procurement cycles and financing structures. The proposed solution would fill these gaps by developing and piloting AI- and LLM-enhanced tools that incorporate: (1) informed decision-making through clearly interpreted multi-objective optimization results, balancing cost-effectiveness, energy performance, and operational priorities such as occupant safety and equipment reliability; (2) improved understanding of stochastic risk analyses to quantify uncertainties and increase confidence in retrofit outcomes; and (3) strategic procurement and financing processes by synthesizing best practices to facilitate project bundling, phased implementation, and alignment with financing mechanisms such as ESCOs and PPAs.

This innovation will benefit public agencies, school districts, small businesses, utilities, and building portfolio owners by reducing retrofit screening and transaction costs, enhancing capital planning, and enabling durable energy cost savings. By addressing functionality and data gaps in current tools, the concept will help modernize California's building stock in ways that improve infrastructure safety, support grid reliability, advance environmental quality through efficient energy use and performance, and expand access to retrofit benefits—particularly for low-income communities. In doing so, it directly contributes to EPIC's mission to deliver high quality, safe, reliable, and affordable energy.

iii. Outcomes: If successful, this research concept will significantly enhance the effectiveness of targeting, planning and implementing energy retrofits in California's existing buildings. By embedding artificial intelligence (AI) and large language models (LLMs) into public-interest retrofit analysis tools, the innovation will reduce the time, cost, and uncertainty associated with identifying, prioritizing, and financing retrofit projects across varied building portfolios. In parallel, each project or activity reported back to the platform would provide new information to enhance model accuracy and capabilities.

Anticipated outcomes include a measurable reduction in screening and transaction costs for building owners and managers, increased accuracy and confidence in project performance, and improved ability to strategically phase and bundle retrofits to align with procurement cycles and financing mechanisms - while leveraging empirically proven performance strategies. These improvements will lower barriers to entry for public agencies, school districts, small businesses, and other resource-constrained stakeholders, making retrofit implementation more feasible and less capital-intensive. At scale, the integration of AI into retrofit planning tools could unlock a self-sustaining pipeline of building upgrades that contribute to long-term energy affordability, reduce strain on the electric grid, and enhance system-level reliability. By reducing dependence on reactive maintenance and enabling proactive planning for equipment replacement and energy cost management, the tools will help modernize California's building stock in a safer and more cost-effective manner that preserves and enhances California's environmental quality.

In alignment with EPIC's guiding principles, the innovation supports affordability through lower retrofit costs, improves reliability through strategic asset planning, and enhances safety by enabling timely replacement of aging infrastructure. The tools will still support broader state goals by increasing retrofit uptake especially in buildings and communities disproportionately affected by pollution.

iv. Metrics: The impacts of the proposed research concept will be evaluated using a combination of quantitative and qualitative metrics that reflect its core objectives: improving retrofit planning efficiency, reducing costs and risks, and enhancing energy affordability, infrastructure reliability, and long-term system resilience.
   a. Quantitative indicators will include:
      1. The percentage reduction in retrofit screening and transaction costs
      2. Time savings in identifying and prioritizing retrofit opportunities

    3. Improvements in the accuracy and confidence of predicted retrofit outcomes through stochastic modeling
    4. The number of projects or buildings analyzed
    5. Tool adoption rates among stakeholders
    6. Modeled ratepayer cost savings.
  b. Qualitative metrics will include:
    1. Feedback from users on usability, trust in AI-generated recommendations, and integration with existing workflows
    2. Documented improvements in decision-making processes, such as earlier identification of high-value retrofit opportunities
    3. Stakeholder-reported reductions in planning complexity and uncertainty.
  c. Technology Readiness: Advancement of key components (materials, sensing systems, construction methods) by at least 2 TRL levels.
    These indicators will be used to assess the effectiveness of the AI-enhanced tools in addressing current technical and market barriers, and to support recommendations for broader deployment across California's building sector.

v. References:

  a. Title: Building Decarbonization Assessment Pursuant to AB 3232. Discussed fragmented decision-making, limited retrofit planning capacity, and insufficient tools to model risk and cost-effectiveness as key barriers to achieving widespread decarbonization retrofits in existing buildings. Citation: California Energy Commission. (2021). Building decarbonization assessment pursuant to Assembly Bill 3232. California Energy Commission. https://downloads.regulations.gov/EPA-R09-OAR-2023-0352-0020/attachment_25.pdf
  b. Title: Decoding Building Decarbonization: A Research Agenda. Identified the absence of standardized deployment strategies, scalable planning tools, and actionable decision-making support as major barriers to retrofitting varied building portfolios. Citation: Building Decarbonization Coalition. (2020). Decoding building decarbonization: A research agenda. Gridworks. https://gridworks.org/wp-content/uploads/2020/02/Decoding-Building-Decarb-Research-Agenda_final.pdf
  c. Title: REALIZE-CA: Demonstrating Scalable, Zero-Carbon Retrofit Solutions. REALIZE-CA demonstrated that standardized retrofit strategies—especially those that allow bundling, phasing, and

streamlined procurement—are essential to scaling upgrades across California's multifamily and affordable housing sectors. Citation: Rocky Mountain Institute. (n.d.). REALIZE-CA: Demonstrating scalable, zero-carbon retrofit solutions. https://rmi.org/our-work/buildings/realize/realize-ca/

d. Title: Integrated Whole-Building Zero Net Energy Retrofits for Small Commercial Offices. Showed that small commercial buildings face significant informational and cost barriers—such as limited access to centralized retrofit analysis tools—hindering scalable retrofit uptake. Citation: Regnier, C., Engel-Moss, P., Fernandes, L., Abram, T., Sun, K., McGuire, L., & Rathod, R. (2023). Integrated whole-building zero net energy retrofits for small commercial offices (CEC-500-2023-022). California Energy Commission. https://www.energy.ca.gov/sites/default/files/2023-05/CEC-500-2023-022.pdf
e. Two projects demonstrating how better characterization of building stock enabled creation of detailed analytics or energy models that can be used to identify and evaluate energy efficiency and demand flexibility measures to reduce energy use and costs, reduce peak demand and improve resilience.
    1. Informing Electrification Strategies of Residential Neighborhoods with Urban Building Energy Modeling. https://doi.org/10.1007/s12273-024-1214-6
    2. Assessment of Energy and Thermal Resilience Performance to Inform Climate Mitigation of Multifamily Buildings in Disadvantaged Communities. https://doi.org/10.1016/j.scs.2024.105319
f. Title: Lawrence Berkeley National Lab Comments-Building Energy Performance Strategy Report - LBNL provided comments towards implementation of Docket 24-BPS-01, with specific reference to the wealth of data that could be evinced through a well-structured and administered BPS policy. https://efiling.energy.ca.gov/GetDocument.aspx?tn=257449&DocumentContentId=93325

vi. Strategic Goal: Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: Achieving California's energy and policy goals requires upgrading the entire building stock - an effort that cannot be easily accomplished through the current approach, which relies heavily on manual processes. With the increasing availability of a large volume of public data for CA's building stock, combined with the AI techniques and large-scale modeling, it is feasible to generate compelling, relevant retrofit opportunities for buildings across California to enhance their energy management. These models can provide key insights into retrofits and improvement opportunities and inform decision-making by CEC, utilities and local governments supporting widespread adoption of strategies.

This concept advances California's emissions and building related goals and by enhancing public retrofit planning tools with AI capabilities. These enhancements will accelerate the identification and implementation of cost-effective energy performance upgrades. By integrating risk analysis, financing alignment, and strategic sequencing, the tools will streamline upgrades and enable smoother transitions to more reliable electric alternatives. Additionally, the platform could support coordinated planning across energy sources, helping to inform utility and policy decisions aligned with California's long-term goals.

viii. Contributors to This Concept Include: Carolyn Szum, Josh Kace, Tianzehn Hong, Han Li

11. Small Commercial Sector Infrastructure Characterization

i. Description: Approaches to add electric load to single family homes and larger commercial buildings have gained more research attention and traction than similar efforts in the small commercial sector, which will need to be addressed to achieve California's energy policy goals. Notably, the small commercial sector also has a significant proportion of owner/tenant structures, with the inherent split incentive issue complicating the value proposition and viability of adding electric load in these spaces. This sector also supports many small businesses, as well as stakeholders disproportionately affected by pollution, which is why it should be supported with technical solutions and approaches that meet their particular conditions, and unique barriers.

Research in the small commercial sector will help to characterize the unique infrastructure (e.g. equipment, electrical panel sizes, peak power draws), condition and obstacles faced. It will develop approaches to overcome those obstacles such as technology innovations and market approaches. An emphasis will be on cost reduction, and avoidance of electrical panel or service upgrades, while reducing peak electrical power reliably in order to enhance grid stability. A further emphasis would be on developing and demonstrating approaches suitable for the product types most common in this sector, such as packaged HVAC equipment.

EPIC funds are needed to support this work because the market lacks incentive structures adequate enough to motivate individual participants without coordinated research demonstrating the systemic benefits that could be achieved.

ii. Breakthroughs: By characterizing the sector and pointing to opportunities for common solutions that could address the biggest challenges, we could enable manufacturers and service providers to better tailor their offerings to this sector's specific needs, and can point towards market development for cost effective energy upgrades. Without this work, manufacturers and service providers won't inherently develop market specific offerings due to the complexity and breadth of the sector. To achieve California's energy goals, we need to empower industry and lower barriers to market entry by solving this sector's challenges.

iii. Outcomes: Assuming electrical service and panel sizes are on par with some single family homes in California, successful research would enable avoidance of panel or service upgrades in electrification, saving $3k-25k. The small commercial buildings sector in California uses a significant amount of energy. Small offices alone consumed 6,871 GWh in 2022 (CEUS). In addition, controls should be developed to ensure that energy costs are not increased over standard practice.

iv. Metrics: Metrics on the electrical service and panel size and peak power draw are precursor data needed to inform success metrics. Once this is characterized, performance metrics could include electrical service options that maintain peak power within typical service and panel sizes. Energy cost reduction should also be demonstrated using developed controls, over the standard base case.

v. References: HVAC Heat Pump Upgrades and their Impact on Household Maximum Power Demand, Less, B., Walker, I., 2024. https://eta.lbl.gov/publications/hvac-heat-pump-upgrades-and-their

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

vii. Support for Goal: Successful approaches to meet electricity demand from the small commercial buildings sector will support this hard to reach sector in achieving the state's energy policy goals. In addition, it is anticipated that the developed technologies and solutions may incorporate demand flexibility and/or DERs in order to manage peak power in support of grid stability.

viii. Contributors to This Concept Include: Cindy Regnier

12. Scalable Digital Twin Software Platforms

i. Description: This project proposes developing a scalable digital twin software platform that integrates electric vehicle (EV) charging management with building energy loads. The platform provides real-time monitoring of EV status (driving, parking, charging, discharging) and simulates EV and building energy consumption. Utilizing advanced control techniques such as Model Predictive Control (MPC) and reinforcement learning, it can optimize EV charging to achieve demand flexibility, reducing peak loads and enhancing energy efficiency. The digital twin facilitates bi-directional communication between the virtual models and physical assets, enabling advanced functionalities such as Vehicle-to-Building (V2B) power flows where EV batteries can discharge to power building loads, providing demand flexibility during peak periods and critical backup power during extreme weather events and grid blackouts. This capability allows aggregating EV batteries as Virtual Power Plants (VPP), creating resilient energy systems that can operate independently when grid power is unavailable. EPIC funding is essential to transition this platform from lab-tested prototypes to real-world building deployments, proving its technical and economic viability at scale.

ii. Breakthroughs: Currently, unmanaged EV charging can strain electrical grids and increase costs through infrastructure upgrades. This platform addresses the barrier of integrating large-scale EV adoption into existing grid infrastructure by intelligently managing EV charging and building loads. It also overcomes the technological gap between isolated EV chargers and building management systems through unified optimization. By enabling coordinated charging, the platform significantly reduces peak demand, avoiding expensive infrastructure upgrades and enhancing grid reliability, thus directly supporting California's energy goals.

iii. Outcomes: Successful implementation will lower building operational costs and improve grid reliability. By reducing peak electricity demand through coordinated charging, facilities will experience significant savings on demand charges, which can amount to thousands of dollars annually. Furthermore, optimized charging schedules will improve use of energy across fuel sources, lower emissions, and enhance environmental quality.

Additionally, the ability to leverage EV batteries for V2B operations provides backup power during outages, improving community resilience. At scale, the digital twin platform can aggregate numerous EV batteries as a VPP, providing grid services and further stabilizing grid operations. Overall, the technology promises tangible economic, environmental, and resilience benefits to California ratepayers.

iv. Metrics: Impact evaluation metrics will include quantifiable reductions in peak electrical demand, energy cost savings, percentage of intermittent energy utilization, and total emissions reductions. Additionally, user satisfaction and acceptance rates among EV owners and building managers will be monitored to gauge market readiness. Operational performance metrics, such as the accuracy of predictive modeling and effectiveness of load shifting, will also be tracked. Battery health and asset utilization metrics, including battery cycling and degradation rates, will be assessed to ensure EV battery management. These metrics collectively provide a comprehensive evaluation of technical performance, economic viability, environmental benefits, and scalability potential.

v. References: Research and demonstrations conducted by entities such as the California Energy Commission, Eaton, Itron, and UCLA support the viability of integrated EV-grid systems. Studies have shown smart charging and V2B systems achieving peak demand reductions up to 35%, yielding substantial economic savings and significantly improving intermittent energy utilization. Fermata Energy's V2B projects demonstrated annual savings exceeding $3,200 per charger, emphasizing economic benefits and feasibility. These precedents highlight both the technical feasibility and the economic rationale for pursuing large-scale implementation of digitally coordinated EV and building load management systems.

vi. Strategic Goal: Transportation Electrification, Distributed Energy Resource Integration

vii. Support for Goal: Optimal controls of integrated buildings and energy systems to reduce energy use and costs, manage peak demand, and improve reliability and resilience. Digital twins are essential technologies to test and de-risk energy technologies for scale up deployment.

viii. Contributors to This Concept Include: Han Li, Bin Wang, Tianzhen Hong

13. AI-assisted Design and Optimized Operation for Next-generation Data Centers

i. Description: We propose EPIC to invest in AI-assisted design and optimized operation for next-generation data centers, unlocking efficiency, flexibility, reliability, and optimal cost, including exploration of waste heat recovery applications. Data centers currently consume approximately 2% of California's total electricity demand, and are expected to double in 10 years without additional action. This concept aims at reducing total net energy consumption and emissions (building emissions, and hard to abate sectors), ease grid system pressure by improving load flexibility (DER integration), while ensuring reliability and optimal cost for data center owners and operators.

Policies and incentives also need to catch up to promote the targeted efficiency and flexibility, especially for large data centers. For example, data center energy usage reporting and modeling (AB222 2025), special rate structure design for data centers (SB57 2025), DR incentives for battery and load shedding to improve flexibility and reliability.

EPIC funds are necessary because no other funding source in California is positioned to de-risk and accelerate the pre-commercial R&D, full-scale demonstrations, and policy considerations needed to transform data-center energy use. Private operators view advanced efficient and flexible controls, grid-interactive hardware, and waste-heat recovery systems as high-risk capital expenses with uncertain payback, so the market alone will not move fast enough to avoid the projected doubling of load in the next decade. EPIC funding can provide the seed capital and technical validation that will generate the needed open data, models, and software tools that data center designers and operators can use to improve efficiency and flexibility, and that utilities and other decision makers can use to craft new rate designs, demand-response incentives, and DER integration strategies.

ii. Breakthroughs: Data centers currently consume approximately 2% of California's total electricity demand, and are expected to double in 10 years without additional action.

This concept targets mitigating this significant threat to the state's energy goals by addressing the following technical and/or market barriers:

a. Lack of grid-interactive controls that coordinate IT load, cooling, and on-site storage in real time, with proven effectiveness
b. Lack of proven cost-effective heat-recovery facilities for data center heat
c. Lack of testbeds where vendors, utilities, and researchers can de-risk full-scale hardware and software

d. Water consumption is significant in data centers using evaporative cooling, which needs to be reduced in water scarcity regions.

Specific cost and performance targets:

a. Whole-site PUE <= 1.15 in settings with mild weather, <=1.20 in hot-dry regions.
b. Whole-site Water Usage Effectiveness (WUE) <= 0.20 L / kWh delivered IT load statewide by 2030
c. Net-site emission reductions of 30% relative to 2023 baseline, even after adding batteries and heat-recovery equipment.
d. Achieve these without compromising “five-nines” (99.999 %) uptime.

iii. Outcomes: If this concept is successful, it will:

a. Reduce the peak load pressure of California grid system, thus avoiding more generation capacity building and resulting utility rate increase
b. Reduce the operational cost of data centers while retaining required reliability
c. Reduce the water usage from cooling data centers

Once the advanced design and control technologies are proven to be effective and cost-saving, it can be adopted at scale by all data centers in California and the U.S.

iv. Metrics:

a. Total data center IT loads that adopted the technologies
b. Energy consumption reduction/PUE
c. Water usage reduction/WUE
d. Grid-scale load flexibility increase/grid peak load shedding
e. Amount of waste heat reuse

v. References:

a. Multi-Objective Simulation Tool for Cooling Optimization and Operational Longevity, funded by ARPA-E COOLERCHIPS program. https://arpa-e.energy.gov/programs-and-initiatives/search-all-projects/multi-objective-optimization-software-coolerchips.
b. Demonstration of Low-Cost Data Center Liquid Cooling, CEC report by LBNL https://www.energy.ca.gov/sites/default/files/2024-06/CEC-500-2024-061.pdf.
c. 2024 United States Data Center Energy Usage Report, LBNL report [https://eta-publications.lbl.gov/sites/default/files/2024-12/lbnl-2024

-united-states-data-center-energy-usage-report.pdf?utm_source=substack&utm_medium=email].

vi. Strategic Goal: Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Building Decarbonization, Distributed Energy Resource Integration

vii. Support for Goal: Existing and new data centers are large energy consumers that are not covered yet by existing efforts to reduce impacts. Optimizing design and operation of data centers for reduced energy use, reduced water usage, and improved load flexibility will help to minimize negative externalities related to the growth of this sector. DER integration: data center load flexibility, equipped by (not limited to) battery storage and grid-interactive flexible control, enables data centers to serve as DER hubs.

viii. Contributors to This Concept Include: Kaiyu Sun, Tianzhen Hong, Donghun Kim

14. Demonstrating Advanced Multi Objective Control Strategies for Grid-interactive Buildings

i. Description: We propose that the EPIC program invests in developing and field demonstrating advanced multi objective control strategies for grid-interactive buildings. For example, advanced control technologies such as Model Predictive Control (MPC) and Artificial Intelligence (AI)-based control approaches, for Heating, Ventilation, and Air Conditioning (HVAC) systems. Such investments can build on the success of the CalFlexHub initiative, which showed that advanced control can utilize building HVAC systems as flexible grid assets that can optimize load shapes in real-time response to dynamic electricity prices, providing substantial demand flexibility. Field studies showed significant reduction in energy consumption and emissions associated with HVAC operations, with approximately 45% energy savings and 61% annual cost savings in one example commercial building field study. We believe that these methods can be extended to better integrate distributed energy resources within buildings, accurately predict day-ahead load for grid stability and interactions, and improve Climate Adaptation (Resilience) to maintain thermal comfort and functionality during extreme weather events. For example, better air circulation management during wild fires and building preconditioning in case of faults or heat waves.

EPIC funds are necessary because, despite the significant potential of MPC and AI for HVAC, their widespread industry adoption is slow due to market barriers and deployment challenges, including the potential high cost and expert knowledge required for installation, especially for customized solutions needed in large commercial buildings, and too few real-world data points demonstrating the value of proposed solutions. EPIC would directly support the necessary field demonstrations to provide real-world data and implementation strategies to overcome these barriers. This funding would help reduce implementation costs and improve scalability through innovations that include fault-tolerance, semantic data models, reusable implementation templates, deployment guidelines, and automated discovery and access to control points in Building Management Systems (BMS).

ii. Breakthroughs: The widespread adoption of advanced controls is slow due to several barriers: high integration costs, the need for specialized expertise—often requiring months of work for custom solutions in large buildings—and a lack of real-world data demonstrating their value. This is especially true for applications beyond energy savings, such as improving grid stability and resilience to extreme events like wildfires and heatwaves.

    This investment will overcome these barriers by funding field demonstrations to generate real-world data and practical strategies, thereby driving down implementation costs and improving scalability. It will also lead to technological breakthroughs, including fault-tolerant advanced controls, semantic data model integration, reusable implementation templates, deployment guidelines, and automated methods for discovering and accessing control points in Building Management Systems (BMS).

    The results will benefit building occupants, owners, and operators by enabling informed investment decisions, improving operations, reducing costs, and enhancing indoor environmental quality. The HVAC industry—including manufacturers, designers, vendors, and installers—will benefit from scalable solutions that reduce manual effort for implementation and improve performance. Ultimately, this work will help utilities and government agencies, such as the California Energy Commission, achieve ambitious decarbonization targets, integrate distributed energy resources, increase load flexibility, and enhance grid stability, providing greater value for California's electricity ratepayers.

iii. Outcomes: Technological breakthroughs will help reduce the payback time for advanced controls to 3-4 years, making them comparable to other standard industry retrofits. These innovations include fault-tolerant controls, semantic data model integration, reusable templates, deployment guidelines, and demonstrations of automated processes for finding and accessing control points in Building Management Systems (BMS).

Further field demonstrations will provide data and strategies to lower costs, improve scalability, and enhance occupant comfort and resilience. Past field studies have demonstrated on average substantial performance improvements, including an average of 25% annual energy cost savings. One recent field study from CalFlexHub showed advanced controls in a large commercial building HVAC system achieved 40 to 65% demand decrease percentage during peak hours, and approximately up to 61% annual cost savings in response to dynamic prices. Other field studies have shown 27% cost reduction and elimination of gas furnace usage with 23% thermal load shifting in dual-fuel systems, and 32% peak demand reduction for multi-zone Variable Refrigerant Flow (VRF) systems. For K-12 schools, a 24% peak demand reduction and up to 16% load shifting were achieved.

By enabling large-scale load flexibility in HVAC systems, advanced controls help California meet ambitious grid goals, such as achieving 7GW of load-shifting capacity. Advanced controls also provide accurate day-ahead load predictions, giving utilities and grid operators a clearer picture as buildings become dispatchable resources for the grid. This innovation aligns with EPIC's guiding principles by providing significant benefits to ratepayers and the state, and increases the reliability of California's electric grid through load flexibility, demand response, and stable load predictions.

The concept benefits ratepayers from lower energy costs and peak demand charges, while also enhancing safety by optimizing building operations to maintain comfort during extreme weather and improved indoor environmental quality. By streamlining deployment processes, the research would reduce implementation and maintenance costs for advanced control, making high-performance systems more accessible. The overall reduction in ratepayer energy costs enabled by advanced control and improved indoor environmental quality are broad benefits that extend to all Californians.

iv. Metrics:

a. Quantitative Metrics:

1. Payback Period: Reduce the payback time for advanced controls to 3-4 years, making them comparable to other standard industry retrofits.
2. Annual Energy Cost Savings: On average 25% annual cost savings.
3. Load shifting: Expected reductions of at least 15 to 20% of demand during peak hours for large office buildings.
4. Peak Demand Reduction: Up to 32% peak demand reduction.
5. Reduced Implementation and Maintenance Costs for advanced controls: Automation processes are expected to reduce these costs, making high-performance systems more accessible.
6. Comfort and Indoor Air Quality (IAQ).

b. Qualitative Metrics:

1. Grid Reliability and Stability: The concept will increase the reliability of California's electric grid through load flexibility, demand response, and reliable load predictions, including providing accurate day-ahead load predictions for utilities and grid operators.
2. Safety and Resilience: The concept enhances safety by optimizing building operations to maintain comfort during extreme weather events like heat waves or in response to faults, and can improve air circulation management during wildfires.
3. Trust and usability of advanced controls by facility managers, operators, and building owners.

v. References:

a. Kim, Donghun, Zhe Wang, James Brugger, David Blum, Michael Wetter, Tianzhen Hong, and Mary Ann Piette. "Site demonstration and performance evaluation of MPC for a large chiller plant with TES for renewable energy integration and grid decarbonization." Applied Energy 321 (2022): 119343. https://doi.org/10.1016/j.apenergy.2022.119343

b. Ham, Sang woo, Donghun Kim, Tanya Barham, and Kent Ramseyer. "The first field application of a low-cost MPC for grid-interactive K-12 schools: Lessons-learned and savings assessment." Energy & Buildings 296 (2023): 113351. https://doi.org/10.1016/j.enbuild.2023.113351.

c. Ham, Sang woo, Donghun Kim, and Lazlo Paul. "Design and Experimental Performance of Practical MPC for Multi-zone VRF system for Small and Medium Commercial Buildings." Paper presented at the International High Performance Buildings Conference, West Lafayette, IN, July 15, 2024. https://docs.lib.purdue.edu/ihpbc/474.

d. Ham, Sang woo, Lazlo Paul, Donghun Kim, Marco Pritoni, Richard Brown, and Jingjuan(Dove) Feng. "Decarbonization of heat pump dual fuel systems using a practical model predictive control: Field demonstration in a small commercial building." Applied Energy 361 (2024): 122935. https://doi.org/10.1016/j.apenergy.2024.122935.
e. Ham, Sang woo, Lazlo Paul, Armando Casillas, Michael Wetter, Weiping Huang, Marco Pritoni, Steven Bushby, Parastoo Delgoshaei, Michael Poplawski, Avijit Saha, Gabe Fierro, Matt Steen, Joel Bender, and Paul Ehrlich. "Practical challenges of model predictive control (MPC) for grid interactive small and medium commercial buildings." UC Berkeley Previously Published Works, August 5, 2024. https://escholarship.org/uc/item/9jv9p8rj.
f. Khabbazi, Arash J., Elias N. Pergantis, Levi D. Reyes Premer, Panagiotis Papageorgiou, Alex H. Lee, James E. Braun, Gregor P. Henze, and Kevin J. Kircher. "Lessons learned from field demonstrations of model predictive control and reinforcement learning for residential and commercial HVAC: A review." Applied Energy 399 (2025): 126459. https://doi.org/10.1016/j.apenergy.2025.126459.
g. Zanetti, Ettore, David Blum, Hongxiang Fu, Chris Weyandt, Marco Pritoni, and Mary Ann Piette. "Commercial building HVAC demand flexibility with model predictive control: Field demonstration and literature insights." Energy & Buildings 345 (2025): 116097. https://doi.org/10.1016/j.enbuild.2025.116097

vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Climate Adaptation

vii. Support for Goal: Distributed Energy Resource (DER) Integration: advanced controls enable buildings to become dispatchable resources for the grid through actively managing load flexibility and demand response. This is achieved by the controller's ability to consider dynamic electricity prices, grid signals, make accurate day-ahead load predictions, and optimize operations in real-time, thereby integrating DERs like PV, batteries, and other types of storage.
   a. Building Decarbonization: advanced controls allow to maximize efficiency of equipment like heat pumps in buildings. Previous advanced controls demonstrations have shown that eliminating gas furnace usage in dual-fuel systems can result in a 27% cost reduction and 52 kg CO2 monthly reduction, while providing an average 20 to 25% energy consumption reduction.

b. Climate Adaptation: advanced controls make buildings more resilient by enabling proactive measures like building preconditioning in case of faults or heat waves and better air circulation management during wildfires. Fault-tolerant advanced controls leverage predictive modeling to anticipate extreme events, maintaining thermal comfort and functionality, thereby increasing building safety and reliability.

This also addresses the strategic objective K - Providing data input into a Value of DER Framework

viii. Contributors to This Concept Include: David Blum, Ettore Zanetti

15. Addressing Barriers to Purchasing More Efficient Equipment

i. Description: In order to enable consumer energy savings and reduced energy costs, consumers can install efficient equipment. In most cases, however, equipment purchased is on the least-efficient end of the spectrum. This creates additional energy loads and costs that persist for years and that could be prevented by making different purchasing decisions. EPIC funds are needed to support research to understand and address barriers to purchasing more efficient equipment. This could include the availability of products on the market, consumer decision processes, contractor skills and knowledge, contractor interaction with consumers, and other factors.

ii. Breakthroughs: Advanced, energy-efficient equipment already exists but fails to achieve significant market penetration. This represents a major barrier to achieving California's energy goals. The "breakthrough" for this project is the development of a data-driven strategy to overcome the gap between technical potential and real-world adoption and identify specific actions and their associated range of impact on the market. This project will target several barriers and customer pain points that prevent the adoption of efficient equipment (e.g. emergency replacement, sensitivity to high upfront costs, split incentives, role of contractors, information gap) and, where possible, identify potential solutions and associated costs needed to increase market penetration. The research fills critical data gaps on consumer decision-making, role of contractors, and effectiveness of current programs. The results will support the CEC, utilities, and manufacturers in designing more effective policies and incentive programs. An increase in the market share of efficient equipment would reduce grid load, and save ratepayers money.

iii. Outcomes: If successful, this research will enable a shift in consumer purchasing behavior, increase the adoption of high-efficiency equipment, and result in energy savings. Anticipated outcomes include a strategy for market transformation that could lead to a reduction in household equipment energy use and make ratepayer-funded incentive programs more effective. The strategic roadmap will quantitatively rank the most significant barriers to adoption (e.g., high upfront cost, lack of contractor knowledge/skills, the "emergency purchase" problem) for different income-based market segments as well as housing tenure (owner occupancy vs rental tenancy). Then, for each identified barrier, the roadmap could identify a targeted action. For example, for the upfront costs, a rebate level could be identified based on research on consumer willingness to pay, and for the contractor knowledge barrier, specific training module(s) could be developed. The roadmap could also estimate the impact of each action on the market in terms of projected market share increase of efficient equipment (either qualitatively or quantitatively) and ease of implementation.

   At scale, this research will lower overall system costs by contributing to reducing peak grid demand, accelerate progress toward California's reduced emission goals, and enhance grid safety by reducing strain during critical events. Ratepayer benefits include utility bill savings, increased grid reliability, reduced emissions —aligning with EPIC's core principles.

iv. Metrics:
   a. Forecast and actual percentage point increase in market penetration of efficient equipment resulting from the roadmap's implementation.
   b. Associated consumer benefits (in terms of life-cycle costs and payback period)
   c. Statewide energy, peak demand, and emissions reductions
   d. Qualitative feedback from stakeholders (manufacturers, contractors, etc) on the effectiveness and feasibility of the proposed strategies.

v. References:

   a. CEC (2021). California Energy Commission. 2021. Assembly Bill 3232 Report: Building Decarbonization Assessment. Publication Number: CEC-400-2021-001-CMF.
   b. CEC (2023). California Energy Commission. 2023. 2023 Integrated Energy Policy Report, Volume I. Publication Number: CEC-100-2023-001-V1.

c. CEC (2020). California Energy Commission. 2020. Low-Income Barriers Study, Part A: Overcoming Barriers to Energy Efficiency and Renewables for Low-Income Customers and Small Business Contracting Opportunities in Disadvantaged Communities. Publication Number: CEC-300-2020-001-F.
d. SB 96. Skinner, Chapter 69, Statutes of 2021. Public resources: energy: Electric Program Investment Charge program.
e. SB 100. De León, Chapter 312, Statutes of 2018. The 100 Percent Clean Energy Act of 2018.
f. SB 350. De León, Chapter 547, Statutes of 2015. The Clean Energy and Pollution Reduction Act of 2015.

vi. Strategic Goal: Building Decarbonization, Climate Adaptation, Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas, Distributed Energy Resource Integration

vii. Support for Goal: This concept supports goals related to buildings by increasing the stock of more efficient equipment and reducing the strain on electrical systems; by potentially avoiding the cost of electrical panel upgrades (a key market barrier); and by gaining a deeper understanding of consumer behavior in technology adoption.

In regards to resilience goals, adoption of high efficiency air conditioning and refrigeration equipment will help lower the electricity demand during extreme weather events (e.g. heat waves) and reduce stress on the grid, making it more resilient and reliable.

This research promotes energy efficiency, a cost-effective approach to reduce emissions. By lowering total electricity demand, it reduces the scale and cost of new generation and storage infrastructure.

This concept indirectly supports DER Integration by increasing the stock of more efficient equipment and reducing the total energy needed in a home, which means smaller and cheaper solar and battery systems can meet the home's needs. More efficient equipment also help reduce the peak demand in the evening when generation from other sources may wane.

Lastly, this concept indirectly supports transportation goals by reducing load and providing capacity for EVs.

viii. Contributors to This Concept Include: Mo Ganeshalingam, Tom Burke, Sanaee Iyama, Colleen Kantner, Scott Young

M. Cost-effective grid hardening for long-term climate impacts

1. Materials to Improve Fire Resistance of Buildings
   i. Description: EPIC funding is needed to identify, characterize, rate, and develop fire-reflective window, wall, and roof materials that improve the fire resistance of buildings. Breaching of the building envelope accelerates fire spread, so it is essential to maintain the building envelope's integrity for as long as possible. At the radiative loads of an uncontrolled fire, glass in windows can easily shatter, and frame materials can melt. By utilizing low-E metallic coatings optimized for the fire spectrum, windows can maintain their integrity for much longer, providing a much-needed time delay in the spread of fire and potentially saving the structure. Enhanced reflectance of radiant heat from fires will also keep walls and roofs cooler during a fire event and make them less likely to ignite. Strong fire reflectance will not limit color choices for roofs and walls or the visible transmittance of windows because the spectrum of fire radiation (1 - 10 μm) is separate from that of visible light (0.4 - 0.7 μm). Boosting reflectance in the fire spectrum (1 - 10 μm) is also compatible with the key radiative properties needed for energy efficiency, such as low thermal emittance for windows (low emittance/high reflectance in the thermal infrared spectrum, 4 - 40 μm), solar-control for windows (high near-infrared reflectance, 0.7 - 2.5 μm), high solar reflectance for light-colored "cool" roof and wall materials (0.3 - 2.5 μm), and high near-infrared reflectance for cool-colored roofs and wall materials (0.7 - 2.5 μm).
   ii. Breakthroughs: This research will lead to a technological breakthrough by creating a new class of building materials specifically optimized to reflect thermal radiation in the fire spectrum (1–10 μm). The primary technical barrier is that conventional building envelopes are not designed to withstand the intense radiant heat from modern wildfires, leading to glass shattering and material ignition. This concept overcomes that barrier by developing and characterizing novel coatings to maintain envelope integrity. It also aims to develop a characterization procedure and/or instrumentation that will be able to measure properties of coatings in the fire spectrum range.

      The market barrier is the lack of rated, commercially available, and validated fire-reflective products. By establishing performance targets (e.g., >50% reflectance in the fire spectrum) and a standardized rating system, this research enables manufacturers to develop them. End users—homeowners, builders, and insurers—will gain a new, science-based tool to harden homes against wildfire, directly addressing the urgent customer pain point of increasing wildfire risk and soaring insurance costs.

iii. Outcomes: Successful research will result in commercially available, fire-rated reflective materials, leading to reduced structural losses and increased occupant evacuation times. Another outcome of the research is the establishment of a standardized procedure to measure and rate such products. This provides direct ratepayer benefits across EPIC's guiding principles. Safety is improved by making homes more resistant to ignition and collapse. Reliability is enhanced by protecting grid assets like rooftop solar and service connections from fire, preventing localized outages. Affordability is addressed by mitigating catastrophic financial losses from destroyed homes and potentially stabilizing insurance costs. Additional environmental goals are achieved by avoiding the significant emissions and landfill waste generated by rebuilding. This will provide a scalable solution that can protect all housing types, including affordable housing, in the Wildland-Urban Interface (WUI), adding safeguards that make these communities more resilient.

iv. Metrics:

   a. Quantitative indicators will include:
      1. Spectral reflectance and (for glazing) transmittance of materials within the 1–10 μm wavelength range.
      2. Time-to-failure (e.g., window cracking, wall ignition) when exposed to standardized radiant heat fluxes simulating wildfire conditions.
      3. Surface temperature reduction compared to conventional materials under identical heat loads.
      4. The incremental cost per square foot for the fire-reflective technology over standard materials.
      5. Number of new or updated fire-reflective roof, wall, and window products developed in partnership with industry
      6. Number of fire-reflective products rated by the Cool Roof Rating Council and the National Fenestration Rating Council
   b. Qualitative indicators will include:
      1. The successful development of a new, repeatable testing and rating scale for fire reflectance.
      2. Adoption of this scale by key stakeholders in the residential building including voluntary consensus standards groups (e.g., ASTM), and

insurance companies that can provide incentive programs (e.g., premium discounts for use of these risk mitigating technologies).

v. References:

a. Berdahl, P., 1995. Building energy efficiency and fire safety aspects of reflective coatings. Energy and Buildings 22, 187–191. https://doi.org/10.1016/0378-7788(95)00921-J. This article explores the dual benefits of reflective coatings for building energy efficiency and fire safety. Due to overlapping radiation spectra for sunlight, thermal exchange, and fire, spectrally selective coatings can be developed to reduce cooling loads while also reflecting infrared radiation from fires, presenting significant synergistic research opportunities.

b. Berdahl, P., 1995. Pigments to reflect the infrared radiation from fire. Journal of Heat Transfer 117, 355–358. https://doi.org/10.1115/1.2822529. This research demonstrates that conventional paints absorb infrared radiation, contributing to fire spread. By significantly increasing pigment particle size—for example, using 1-2 μm titanium dioxide particles instead of conventional ones—coatings can be engineered to reflect over 80% of fire radiation, enhancing the fire safety of combustible materials.

c. Cool Roof Rating Council. 2025. Roof and wall product directories. https://coolroofs.org/directory/. The Cool Roof Rating Council (CRRC) website features a directory of roofing and exterior wall products with rated radiative properties. This non-profit organization develops and implements these rating systems to help consumers, contractors, and policymakers identify energy-efficient building materials. The site also provides resources and information on membership.

d. IGSDB. 2025. International Glazing and Shading Database. https://igsdb.lbl.gov. The International Glazing Database (IGDB) is a comprehensive, publicly available collection of optical and thermal data for over 4,800 glazing products from manufacturers worldwide. Maintained by Lawrence Berkeley National Laboratory (LBNL), it provides essential data for designing energy-efficient windows and is a key resource for the National Fenestration Rating Council (NFRC).

vi. Strategic Goal: Climate Adaptation, Building Decarbonization

vii. Support for Goal: This concept primarily supports Strategic Goal 5 as it is a direct response to the increasing threat of wildfires, proposing a targeted initiative to improve local resiliency by hardening buildings—the last line of defense. By preventing structural ignition, the technology helps mitigate wildfire effects and harden the grid edge.

The concept also strongly supports Strategic Goal 3 as the fire-reflective coatings are designed to be fully compatible with energy-saving technologies like cool roofs and low-E windows, ensuring compatible adaptation measures. Furthermore, by preventing the destruction of buildings, the research avoids the massive emissions inherent in demolition and reconstruction. This preserves the embodied emissions in California's building stock, promoting a more lasting approach to the built environment.

viii. Contributors to This Concept Include: Ronnen Levinson, Charlie Curcija, Jacob Jonsson, Robert Hart

2. Wildfire Resilience Framework for Grid Operation and Planning

i. Description: California's energy infrastructure is increasingly threatened by wildfires, especially in the wildland-urban interface (WUI). Wildfires not only disrupt electricity supply through direct damage but also pose significant ignition risk from power lines under high fuel load and extreme fire weather. Despite growing urgency, California still lacks high-resolution (hundred meter scale), dynamic fire risk intelligence tailored to infrastructure vulnerabilities under current and future natural weather event scenarios. This concept aims to develop FireGrid-AI, a wildfire-aware climate resilience framework for grid operation and planning. By building upon LBNL's prior work with AI-based satellite image super-resolution and fire perimeter prediction, this concept would integrate multi-resolution fire, fuel, and weather pattern data with grid vulnerability maps, producing a predictive and uncertainty-aware wildfire risk model. It will directly inform infrastructure development and strategies in high-risk regions.

ii. Breakthroughs: The proposed FireGrid-AI framework would directly address a critical technological and informational gap that impedes the reliability and resilience of California's energy infrastructure, particularly in the context of wildfires exacerbated by California's unique, extreme weather patterns. This concept will drive technological advancement by developing a dynamic, high-resolution wildfire risk intelligence platform tailored for energy system resilience planning under current and future weather pattern scenarios.

iii. Outcomes: If successful, FireGrid-AI will deliver transformative improvements in wildfire risk intelligence for California's energy sector, with significant benefits for ratepayers in terms of safety, reliability, affordability, and environmental quality. For example, by providing dynamic, high-resolution wildfire risk forecasts tailored to energy infrastructure, FireGrid-AI will enable utilities to proactively mitigate risks through optimized strategic vegetation management, and infrastructure upgrades. Once developed, the FireGrid-AI framework is easily scalable across other western U.S. states and globally fire-prone regions. It is also adaptable to new data sources (e.g., real-time satellite observations, next-gen weather projections) and evolving fire regimes.

iv. Metrics: Adoption Potential: Uptake of innovations by developers or incorporation into design guidelines and permitting frameworks

v. References:

a. Li, F., Zhu, Q., Yuan, K., Huang, H., Radeloff, V. C., & Chen, M. (2025). Exacerbating risk in human-ignited large fires over western United States due to lower flammability thresholds and greenhouse gas emissions. PNAS nexus, 4(2), pgaf012.

b. Di Giuseppe, F., McNorton, J., Lombardi, A., & Wetterhall, F. (2025). Global data-driven prediction of fire activity. Nature Communications, 16(1), 2918.

vi. Strategic Goal: Climate Adaptation

vii. Support for Goal: FireGrid-AI directly supports California's resilience goals by providing actionable, high-resolution intelligence on wildfire risk under both current and projected future weather conditions. It addresses key vulnerabilities in the state's energy infrastructure by enabling proactive adaptation strategies at multiple scales—from individual utility assets to regional grid systems and especially communities that face acute fire risk. FireGrid-AI will generate future-looking fire risk maps informed by downscaled weather projections, allowing grid operators and planners to anticipate where fire hazards will increase over the next decades. It will enable long-term resilient infrastructure planning, including prioritization of infrastructure upgrades based on where fire exposure is most likely to increase. Supports utilities in integrating wildfire risk into adaptation plans.

viii. Contributors to This Concept Include: Qing Zhu, Robinson Negron-Juarez (EESA)

3. Storm and Seismic Hardening of Assets

i. Description: This concept proposes investing in much needed research to fully characterize how solar racks and modules behave under wind and snow loading. This characterization should encompass load paths through the structure, into fastened joints and into mounted modules. Essentially, research should investigate storm and seismic hardening of solar PV and battery storage assets as well as conduct efforts to mature associated industry engineering consensus standards and complimentary product level certifying tests. The solar PV industry lacks matured voluntary consensus standards and integrated testing procedures and is instead dominated by CAPEX decision making. The structural standards committees lack the data needed in order to create rational design methods, standards and adjoining certifying tests (e.g. UL 2703). While large investment in wind tunnel testing has been made by industry, product engineers still lack full knowledge because of the use of rigid scale models not exhibiting dynamic responses. Further, the investment in wind tunnel testing has been done using ASCE wind tunnel methods which have inadvertently resulted in less rigid design and even higher failures.

ii. Breakthroughs: Structural failures on single axis trackers, fixed ground and elevated canopies are occurring during even routine wind events such as annual Santa Ana winds. This effort would fill in fundamental knowledge gaps and develop low cost tools (CFV modeling, structural health monitoring, lab testing) that will enable rack designers to improve product performance and provide voluntary consensus standards development committees with rational design methodologies.

iii. Outcomes: Many solar PV systems have significantly higher levelised cost of energy (LCOE) due to operational expenses from unplanned repairs. This effort will allow system owners to have more predictable outcomes and more investable assets. For solar structures that are located in pedestrian areas (elevated parking canopies) significant public safety concerns can be addressed by standards development organizations.

iv. Metrics:

a. Reduced actual LCOE stemming from a reduction in unanticipated failures and high OPEX costs. Increased confidence in product performance for financial services firms (insurance and finance).
b. Reduction in failure incidences that present safety concerns.
c. Rack designers have tools that can be used without having to incur large investments in things like wind tunnel testing that cannot provide full knowledge of the structural behavior of rack systems in wind, snow, and seismic loading.
d. Development of industry engineering consensus standards with an associated product level testing for the critical structural joints used to assemble racks and mount modules.
e. Module mounting methods prevent unanticipated loading events resulting in module failures.

v. References:
   a. https://eta-publications.lbl.gov/publications/maturing-rational-design
   b. https://escholarship.org/uc/item/0ps866jg
vi. Strategic Goal: Distributed Energy Resource Integration, Building Decarbonization, Climate Adaptation
vii. Support for Goal: Unqualified rack products that fail at far less than the design wind speeds fail due to lack of fundamental knowledge about the behavior of these lightweight and flexible structures in wind, snow, and seismic loading. This effort seeks to fill knowledge gaps (as defined by industry), which will enable simplified rational design methodologies and the development of industry consensus standards. This effort will develop testing methods that will allow evaluation of new racking concepts and critical structural joint hardware.
viii. Contributors to This Concept Include: Mathew DeJong (UCB), Gerald Robinson

4. Cost Effectiveness of Wildfire Mitigation Measures
   i. Description: Wildfires pose an escalating threat to communities, electric utilities in California, and ultimately ratepayers. The cost of reducing wildfire risk, such as by grid hardening and undergrounding powerlines, can be high. However, the cost of wildfire risk is also high and manifests itself through higher costs of capital and the cost and availability of insurance. There are limited tools and gaps in data for utility planners to use to fully assess cost effectiveness of wildfire mitigation measures.

      This proposal is to have EPIC investigate developing tools to model and improve the cost effectiveness of wildfire mitigation measures. The tools would quantify risk reductions from implementing mitigation measures and model the ratepayer impacts. They would take a broad approach to quantifying benefits, expanding traditional approaches to include:
      a. Cost of debt: lower utility credit ratings from wildfire risk exposure make it more expensive for utilities to borrow money. These increased borrowing costs translate into higher rates for customers.
      b. Cost and availability of insurance: as wildfire losses mount, commercial insurers are reassessing their exposure, leading to some carriers declining to offer wildfire liability policies or increasing premium costs for utilities in wildfire-prone areas.

      This concept would explore the relationship between wildfire risk, wildfire mitigation and affordability and would focus on the benefits to ratepayers of reducing utility risk. The tools would help identify the most cost effective technologies and mitigation strategies for reducing wildfire risk.

ii. Breakthroughs: This concept will lead to tools for assessing cost effectiveness of grid hardening measures. It will investigate the quantitative relationship between mitigation measure effectiveness, wildfire risk reduction, and ratepayer costs. Current barriers are the lack of understanding of utility risk and ratepayer costs–and the understanding of measure effectiveness.

    The concept would improve the risk reduced per dollar of wildfire mitigation spending and the rate impact per dollar of wildfire mitigation spending. Beneficiaries would include utility planners and stakeholders with limited or incomplete data on cost effective mitigation. They would also include municipal utilities throughout the state with limited resources and experience with mitigation measure effectiveness.

iii. Outcomes: The proposed concept would incorporate a broader accounting of wildfire mitigation benefits, including operational savings, the positive impact on insurance costs and the utility's cost of capital. By quantifying these wider benefits of risk reduction, such an effort would provide a stronger justification for wildfire mitigation investments and would foster better understanding among decision makers, state energy officials, stakeholders, and the general public, ultimately leading to more cost-effective outcomes for ratepayers.

iv. Metrics: Wildfire risk reduction per dollar of mitigation spending
    Utility dollars spent per avoided ignition

v. References:
    a. https://www.eei.org/-/media/Project/EEI/Documents/Issues-and-Policy/Assessing-Benefits-of-Investing-in-Wildfire-Mitigation.pdf
    b. https://www.spglobal.com/_assets/documents/ratings/research/101591877.pdf
    c. https://www.fitchratings.com/research/corporate-finance/fitch-rates-pacific-gas-electric-co-first-mortgage-bonds-bbb-rr2-02-06-2025;

vi. Strategic Goal: Climate Adaptation

vii. Support for Goal: This concept supports the CEC's goal and strategic objective (M) of supporting cost-effective decision-making on grid hardening for long-term climate impacts. Developing an accessible tool with a comprehensive framework for assessing the relationship between utility risk, wildfire mitigation measures, and ratepayer impacts enables utilities to improve the cost-effectiveness of their investments.

viii. Contributors to This Concept Include: Myles Collins