Energy Research and Development Division

FINAL PROJECT REPORT

Research Gap Analysis for Zero-Net Energy Buildings

California Energy Commission

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas and Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs which promote greater reliability, lower costs and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Research Gap Analysis for Zero-net Energy Buildings is the final report for the Research Roadmap for Getting to Zero-net energy Buildings project (contract number 300-15-008) conducted by Itron, Inc. (doing business in California as IBS). The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

California has adopted numerous policies to reduce energy use from the building sector including the California Public Utilities Commission (CPUC)’s Long-Term Energy Efficiency Strategic Plan, which calls for all new residential construction and all new commercial construction in California to be zero-net energy (ZNE) by 2020 and 2030, respectively. This project identified high potential technologies along with their research, development, demonstration, and deployment challenges to achieving these ZNE goals with a focus on the commercial and multifamily residential market sector. The team also developed a prioritization framework based on objective factors and weights that help define ZNE scenarios to provide context for assessing technologies. The resulting work includes technology details with research gaps and the prioritization frame, as well as the background of literature reviewed and stakeholder input through surveys and interviews.

Keywords: Zero-net energy (ZNE), Research Priority, Technology, New Construction, Commercial, Multifamily, Residential

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EXECUTIVE SUMMARY

Introduction

California has adopted numerous policies to reduce energy use from the building sector because residential and commercial buildings account for more than 60 percent of California's electricity use and nearly 37 percent of the state's total energy use. The California Public Utilities Commission's (CPUC) *Long-Term Energy Efficiency Strategic Plan* calls for all new homes and business construction in California to be zero-net energy (ZNE) by 2020 and 2030, respectively. The California Energy Commission is creating a roadmap to identify and prioritize the most significant research, development, demonstration and deployment (RDD&D) opportunities to support these ZNE goals.

Project Purpose

This project provided guidance to the Energy Commission on technology research priorities that support California's ZNE targets. The foundation for this project's results consist of consultations with stakeholders and subject matter experts, a technical assessment of the current baseline of best-in-class ZNE building technologies and strategies, and a gaps analysis of key RDD&D needs for achieving the state's goals for ZNE buildings in a safe, equitable, and cost-beneficial.

The gaps analysis synthesizes the input of stakeholders and experts to:

1. Analyze stakeholder recommendations on research most needed to achieve cost-effective ZNE buildings.
2. Provide a detailed description of barriers that hinder adoption of ZNE building technology in the marketplace.
3. Analyze performance and cost targets for promising ZNE technologies.
4. Develop critical indicators of success for ZNE building adoption.

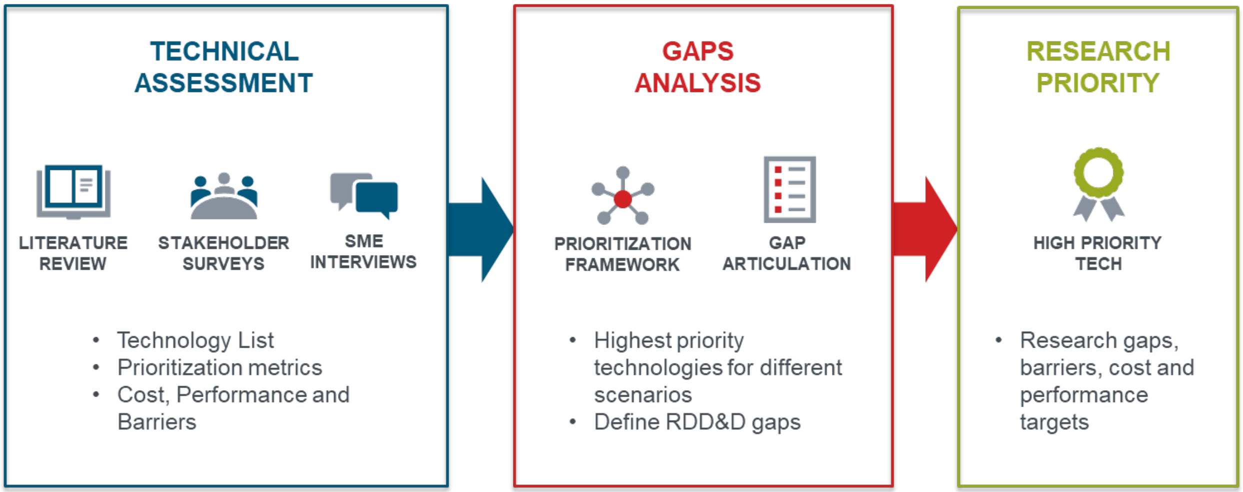
California's 2019 *Building Efficiency Standards* for residential buildings required solar installations, which moved the needle towards the near-term goal for residential ZNE (2020). The project intended to focus the scope on new construction for homes and business structures, but with evidence that residential ZNE is already achievable with off-the shelf-technologies, the scope shifted to technologies relevant in the commercial and multifamily building sectors.

The team defined ZNE in a flexible, inclusive, and future-facing manner. When reviewing project's outcome software product, the user can dynamically choose specific details, such as site-size or energy type, while assigning weights to various attributes valuable to the grid, such as load shaping or the daily power requirements of a customer over time. By not limiting the ZNE definition to the energy code time dependent values (TDV) definition, where the net annual energy are weighted by time dependent values (be it site or source), this project's findings remain valuable as policy evolves. This method also allows a wider net of technologies for consideration that may not be suitable in the current policy definitions.

Project Process

The overall approach consisted of two main parts: compile a technical assessment and research gap analysis with prioritization. The technical assessment identified a list of high priority technologies with the potential to advance ZNE and collected metrics necessary to rank the research priority of each technology within the context of various ZNE goals. The gaps analysis identified the research gaps inhibiting market adoption for each technology and prioritized the technologies based on their impact. The technical assessment combined a review of current ZNE technology literature, two stakeholder surveys, and interviews with subject matter experts. The gaps analysis ascertained research gaps for each technology and ranked the research priority based on various scenarios set up using objective scores on factors with varies weights. Figure ES-1 illustrates the steps in the two areas of the process that culminate a list of highest priority technologies within each scenario.

Figure ES-1: Project Approach



Source: Itron Team Staff

The technical assessment started with an expansive literature search of more than 500 individual reports and articles from credible sources such as state and federally funded research, national lab research, academic journals, and recommendations from industry experts. The team solicited stakeholder input through online surveys to initiate a higher-level assessment of broad ZNE focus areas, priorities, and barriers followed by detailed input for specific technologies. The first higher-level survey received more than 540 responses representing a broad range of occupation in residential and commercial entities within and outside California. The survey asked subject matter experts to volunteer for a follow-on survey to provide details for specific technologies they assessed as being high potential to enable ZNE. A final list of about 150 technologies were constructed with input from subject matter experts. This information, compiled as briefs, summarized each technology by building type and climate, cost and performance status, and targets, critical barriers, and research gaps.

The gaps analysis identified the specific gaps in adoption of each technology that can be addressed with research support. These research gaps ranged from early phase prototype development to demonstrations and pilots, including cost and performance targets with feature enhancements and standards development. The research gaps details the technology applicability and the importance of ZNE in a set of briefs for more than 60 technologies.

Project Results

The project outcomes directly support the Energy Commission in developing future EPIC research funding solicitations towards the state's ZNE goals by first prioritizing the technologies to target, then providing the specific research gaps for each of those technologies.

- The **ZNE Technology Assessment and Prioritization (zTAP)** tool helps determine the priority of technologies in defined ZNE context based on nine factors.
- **Technology briefs** for more than 60 high potential, yet underserved technologies, that identify research gaps, along with barriers, cost and performance targets.

The zTAP tool allows the user to decide which technology should be prioritized based on various criteria such as 'community scale' or 'site-level' or whether the user prefers mixed fuel or full electrification. The assessment evaluates from nine factors that either weighted individually to consider changing priorities by the state or by the user (Figure ES-2). The tool is publicly accessible and can be downloaded at https://efiling.energy.ca.gov/GetDocument.aspx?tn=227407&DocumentContentId=58522

Figure ES-2: Factors for Priority Assessment Framework

Source: Itron Team Staff

- **Energy Impact** - Overall energy benefit based upon reduction in energy use intensity within the respective end use category, scaled by the projected growth for applicable building types in climate zones by 2030 (for new construction); End uses impacted by the tech/strategy; percent of energy benefit; applicable market sectors – new/retrofit; Building types applicable – single family, multifamily, grocery, schools, etc.; applicable climate zones; scaled by California Commercial End Use Survey (CEUS) data on energy use intensity and growth projection for the applicable building types;
- **Load Shaping Potential** - Technologies and strategies with the ability to shape load, such as creating a flattened or predictable load profile or impact permanent load shifting.
- **Greenhouse gas (GHG) Reduction Potential** - The ability of the technology/strategy to reduce GHG emissions.

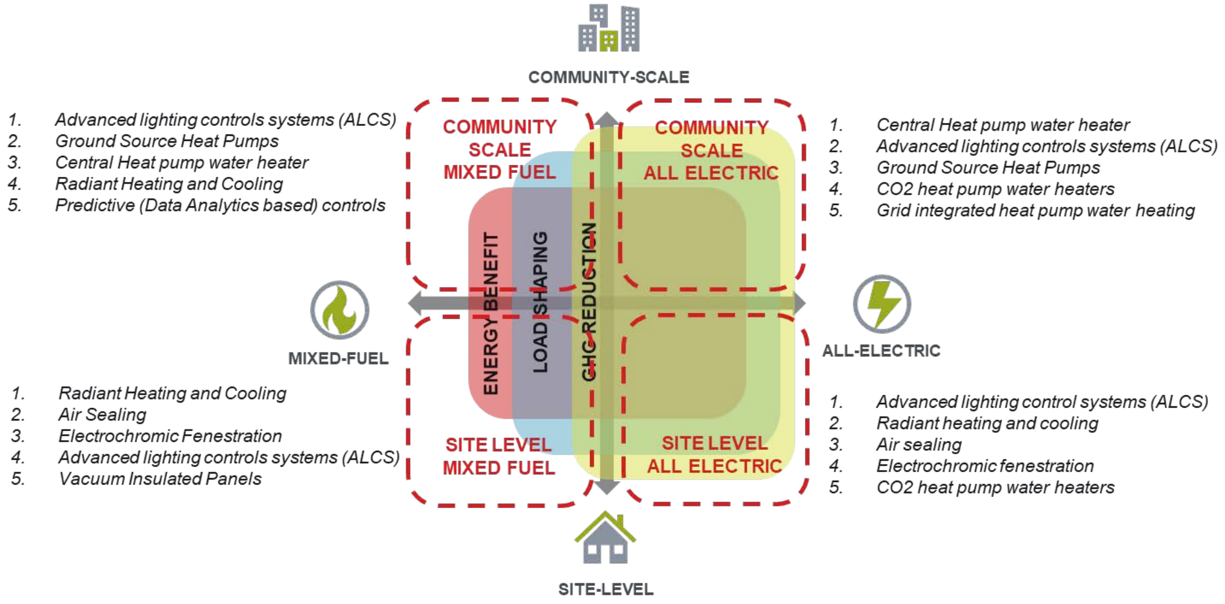
- **Technology Readiness** - Potential for the technology to reach maturity by 2025 for 2030 full market adoption. Qualitative – high medium low. Based on current stage and expected stage in five to seven years as assessed by the stakeholders
- **Context Scenario** - The relevance of a technology is assessed in four contexts of scope and fuel mix that define the ZNE solution space: site level; community scale; mixed fuel; all-electric
- **X-factor** - This is a wild card; an extraneous factor that determine priority in alignment with evolving policy and priorities.

The 150 high potential technologies collected from stakeholders, literature review, and by the subject matter expert (SME) input assessed the priority framework. The scenarios constructed, from defining weights associated with each factor, formed a priority index based on an empirical formula. These weights define the scenario and are customizable to align with policy or preference depicted by a factor.

The basic scenarios on fuel scope and scale are simple examples of some setups. Looking at the site level of mixed fuel within the zTAp tool, the user can see how changing the priorities and weights of the priorities cause different technologies to be suggested. However, custom scenarios that best align with policy and preference can be constructed with the zTAP tool by weighting the factors differently at any time.

The layout of the scenarios in scope and scale quadrants along with the resulting list of technologies that emerge as high priority, shown in Figure ES-3.

Figure ES-3: ZNE Context Scenarios with Examples of High Priority Technologies



1. *Advanced lighting controls systems (ALCS)*
2. *Ground Source Heat Pumps*
3. *Central Heat pump water heater*
4. *Radiant Heating and Cooling*
5. *Predictive (Data Analytics based) controls*

1. *Central Heat pump water heater*
2. *Advanced lighting controls systems (ALCS)*
3. *Ground Source Heat Pumps*
4. *CO2 heat pump water heaters*
5. *Grid integrated heat pump water heating*

1. *Radiant Heating and Cooling*
2. *Air Sealing*
3. *Electrochromic Fenestration*
4. *Advanced lighting controls systems (ALCS)*
5. *Vacuum Insulated Panels*

1. *Advanced lighting control systems (ALCS)*
2. *Radiant heating and cooling*
3. *Air sealing*
4. *Electrochromic fenestration*
5. *CO2 heat pump water heaters*

Source: Itron Team Staff

These details on each technology help focus the research outreach towards the specific gaps and cover the basic information on each technology. They include:

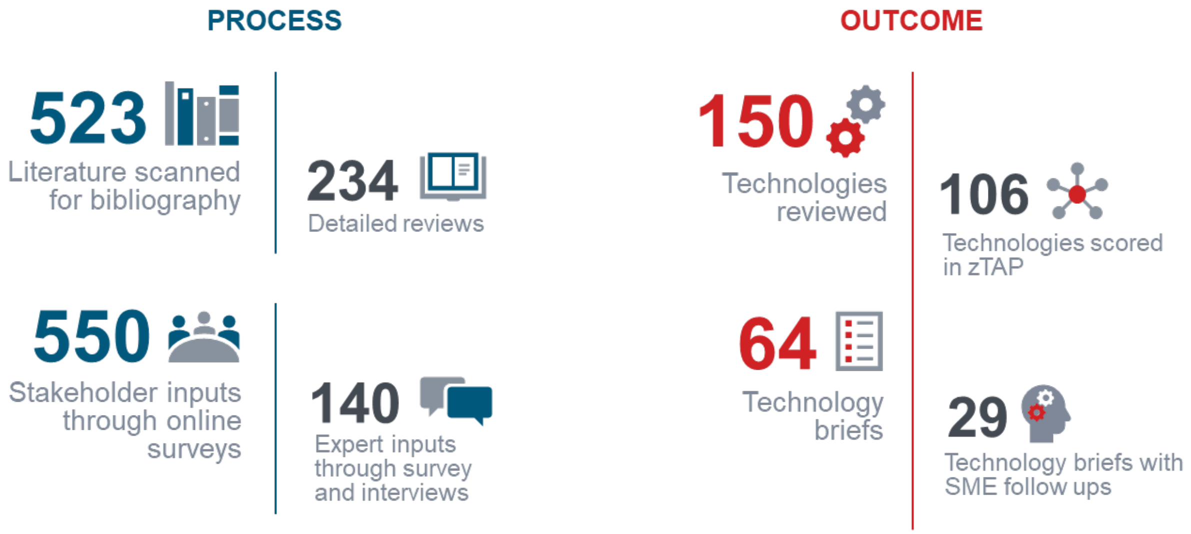
- Energy Impact – Energy benefit, applicable building types and climate zones for the technology
- Technology Readiness – Current state of technology and its potential by 2025, with a view to full market adoption by 2030.
- Cost and Performance – Current cost and performance indicators and targets for 2025, with a view to the 2030 goal for the market.
- Barriers – Technical, market and policy barriers prohibiting the technology from full potential.
- Research Gaps – Prototype development; Performance improvement; Performance testing and validation; Systems integration; Product design evolution or feature enhancement; Cost improvement; Lab testing and simulations; Demonstrations and pilots; Test procedures and protocols for technologies; Standards development
- Key references and Subject matter experts that provided input where relevant.

Additional significant outcomes that provided the foundational support for the primary outcomes are also valuable and include:

- Energy Impact Calculator – The energy impact calculator is the tool that feeds the energy impact score in zTAP. Based on detailed energy end use by building type and climate zones from the California Commercial End Use Survey (CEUS) and Residential Appliance Saturation Study (RASS) data, and projected for the future growth in floor area by building type for potential cumulative impact by 2030. The calculator is available to update for other future uses.
- ZNE Stakeholder Survey Data – The responses from more than 550 ZNE stakeholders is a rich trove of data, which is available for additional useful insights and information.
- Literature review and bibliography – The dataset of more than 500 bibliography entries structured for look-up by key word and technology type is a meaningful source of information for future references. The review of more than 200 reports includes information digested out of these reports relevant to the technology information.

Figure ES-4 provides perspective on the amount of foundational information that shaped the conclusion for this project.

Figure ES-4: Process and Outcomes



Source: Itron Team Staff

Key Findings

1. While **technology does not pose the biggest challenge to achieving ZNE, it is a significant solution**. Even though stakeholders ranked technology as the fourth lowest out of 16 challenge areas, they also ranked it the second-most significant solution in the ‘silver bullet’ tool kit behind government policy and regulation.
2. Decades of energy efficiency as the first energy loading order in California has yielded a high level of development and market adoption. While efficient building technologies remain critical to make ZNE ubiquitous, the focus now extends to **control technologies, renewables, and grid management.** Therefore, the greatest research gaps and market needs are technologies and strategies that support demand response and smart control.
3. The emergence of c**ontrols** with **embedded intelligence and predictive analytics** enable buildings to schedule and balance load to minimize grid impact. Furthermore, renewable generation can align with demand to achieve **grid harmonization** with adoption of both electrical and thermal energy storage technologies.
4. The most prevalent research gap for technologies identified **demonstrations and pilots as the most prevalent**, including market awareness and education and echoed by both experts that provided online input on technologies as well as those the team reached out to specifically.
5. To establish the relative research priority of various technologies, it is critical to evaluate them in their effectiveness at addressing not ZNE by itself, but rather as the **key drivers for ZNE: energy, load shaping, and GHG reduction.** This in turn requires examining the technologies’ potential scale (site versus community) and fuel (mixed versus all electric) implications.

Knowledge Transfer

This project has produced several deliverables to the Energy Commission that are usable even outside the context of this project.

The literature reviewed (more than 500 reports and articles), the individual technology briefs (more than 60), and feedback from more than 550 stakeholders on ZNE technologies are all publicly available online at http://zneroadmap.researchenergy.net/ and will be a valuable asset to those conducting further research to meet California's ZNE goals.

Benefits to California

An important outcome of this project is the zTAP tool, publicly accessible by download at https://efiling.energy.ca.gov/GetDocument.aspx?tn=227407&DocumentContentId=58522. This tool will help guide future technology solicitations by providing necessary cost and energy effective information on gaps in publically funded research, especially from California ratepayers. The technology-level analysis and prioritization details will help guide public research funds and improve the outcomes that fill gaps to providing cost and energy effective solutions to achieve ZNE in California buildings.

The zTAP tool is transparent, scalable and flexible to assist in California's journey to ZNE. The clarity from the zTAP tool provides an unbiased evaluation for the user; this also gives untainted support to drive the right public policy for California. The capacity from the zTAP tool is able to expand the list of technologies to include new and emerging technologies over time as California continues to be the lead the clean energy initiative. The flexibility from the zTAP allows for adaption from the evolving specifics and policy around defining ZNE, all of which keep the results relevant over a much longer period. The tool framework objectively assesses the technologies providing results that minimize bias. This benefits California because it allows energy research to flexibly prioritize based on changes to policy and direction from Legislature.

CHAPTER 1: Introduction

Background

Residential and commercial buildings are the largest users of electricity in California, accounting for more than 60 percent of the state's electricity consumption (Kavalec et al. 2013). California has adopted numerous policies to reduce energy use from the building sector including the California Public Utilities Commission's (CPUC) *Long-Term Energy Efficiency Strategic Plan* which calls for all new residential construction and all new commercial construction in California to be zero net energy (ZNE) by 2020 and 2030, respectively (CPUC 2011). The California Energy Commission (Energy Commission) is developing a roadmap to identify and prioritize the most significant research, development, demonstration and deployment challenges to achieving these ZNE goals.

Objective

This project developed, in consultation with stakeholders and subject matter experts, a technical assessment of the current baseline and best-in-class ZNE building technologies and strategies; and a gaps analysis of key RDD&D needs for achieving the state's goals for ZNE buildings in a safe, equitable, and cost-beneficial manner. Specifically, the gaps analysis must synthesize the input of stakeholders and experts to:

1. Analyze stakeholder recommendations on research most needed to achieve cost-effective ZNE buildings.
2. Provide a detailed description of barriers that hinder the adoption of ZNE building technology in the marketplace.
3. Analyze performance and cost targets for promising ZNE technologies.
4. Develop critical indicators of success for ZNE building adoption.

Scope

The project focused on **new construction** of residential and commercial buildings. However, given the near-term goal for residential ZNE (2020) and anecdotal evidence that residential ZNE is already achievable with off the shelf technologies, the scope of the project shifted to **commercial and multifamily commercial sectors**.

To ensure coverage of all high-potential ZNE technologies and strategies, the technical assessment and gaps analysis categorize technologies within the topic areas shown in Table 1.

Table 1: Technology Categories

Technology Category	Description
Building envelope	Wall, foundation, roof, and attic technologies that improve comfort and reduce the transfer of heat between conditioned and unconditioned spaces.
Fenestration	Windows, curtain walls, glass facades, and other openings that allow and control access to the building, daylight, and ventilation to reduce building energy use and improve comfort.
Heating, ventilation, and air conditioning (HVAC)	Space conditioning, heating and cooling, air and radiant systems, controls, and strategies that improve comfort and energy performance while minimizing waste heat and fan energy use.
Indoor air quality	Ventilation and dehumidification strategies that improve indoor air quality and related energy use technologies.
Lighting	High-efficacy lighting technologies and accompanying controls for indoor and outdoor use.
Plug-loads and equipment	Outlet and plug load related controls, advanced power strips, as well as large equipment and process loads associated with commercial buildings such as elevators and escalators.
Demand response	DR enabling technologies such as controllable thermostats and loads that respond to utility DR signals, as well as technologies that enable auto and/or manual DR for commercial sites.
Occupant behavior focus technology	Home energy management devices and dashboards that provide feedback or automate control that improve occupant behavior.
Other building level controls	Smart building controls, home area networks, and information/action displays that give real-time data and control to the resident and/or building owner.
Water heating and efficiency	Water heating and water reuse technologies that also provide electricity savings.
Whole-building solutions	Passive design, systems interaction, and other integrated design strategies, including DC-DC and appliance electrification.
Distributed generation	On-site and community scale generation, including solar PV, tri/quad gen, CHP, wind, etc.
Energy storage	Thermal and electrical energy storage, site and community scale, customer or utility owned assets
Grid Interaction/Smart grid connectivity	Behind-the-meter device and load controls to enable mutual customer and grid benefit. Smart inverter functionality for grid communication, electric vehicle charging and vehicle-to-grid (V2G), interaction between buildings to electrical grid (B2G), including system capacity.
Technology solutions to address other areas	Energy modeling and design tools to aide planning, permitting, construction and commissioning, GHG modeling and calculation, planning and permitting tools.

Source: Itron Team Staff

Electric vehicles (EVs) straddle a line between the transportation and building sectors. With increased adoption of EVs, which are poised to become the single largest end use in buildings, further research is needed to incorporate, manage, and balance this new load at the individual site level and fleet scale. However, the team did not include research on EV and EV charging as a core part of this work.

Defining ZNE

In California's policy and regulatory environment, there are a few definitions of ZNE. The Energy Commission, in the context of the building energy efficiency code, defines it as zero TDV, where consumption and generation are weighted by time dependent values. The CPUC started out defining it broadly in the Long-term Energy Efficiency Plan (2008) as the amount of energy consumed and offset by renewable generation in a year. However, the more operative definition used by DGS for defining ZNE in State buildings is source energy on an annual basis. The code ZNE definition stops at design and intent, while the actual operation and energy use provides an operational ZNE focus. The annual basis for net zero however, leaves much room for inadvertent behavior that may not result in the true intent behind ZNE, GHG reduction. ZNE is not vision as a goal by itself; it is a strategy with tactical approach towards achieving the GHG reduction goal or a zero carbon.

For this project, ZNE was not defined in a singular or restricted way, but a more expansive, inclusive, and future-facing concept was used. This allowed for casting a wide net for technologies that may not be suitable in the current policy definitions but could be more crucial in the evolving definitions, which are trending towards all electric and community-scale ZNE with a greater emphasis on carbon reduction than energy impact/benefit.

Method

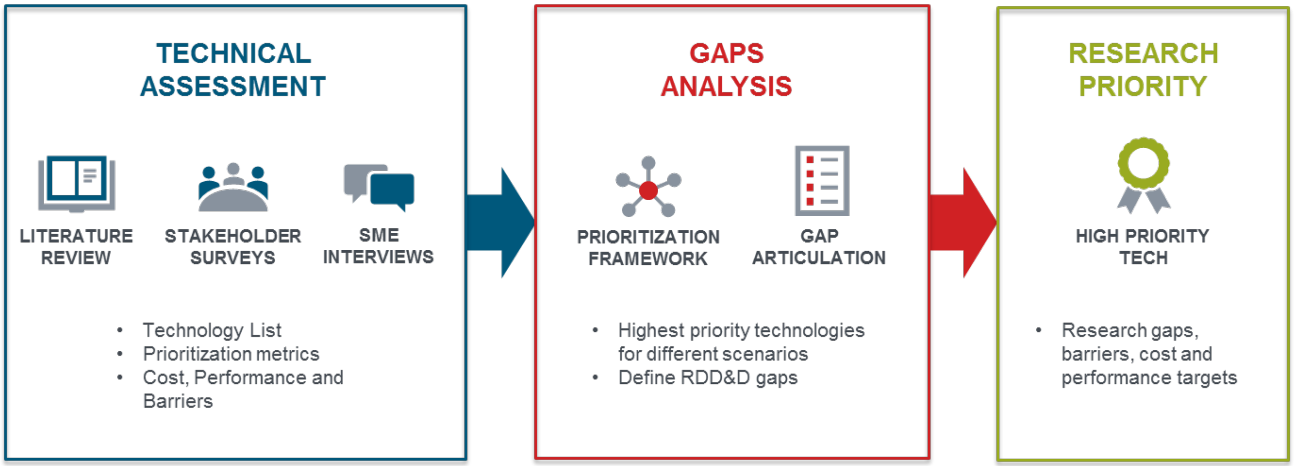
The project split into two essential parts: a technical assessment and research gap analysis with prioritization. The technical assessment was an investigation into high-priority ZNE technologies by means of concurrent literature review, stakeholder surveys, and subject matter expert (SME) interviews. These parallel paths focus on identifying technologies with the potential to help realize the state's ZNE goals and specify the barriers and performance and cost targets necessary for market adoption.

The gaps analysis process identified research gaps inhibiting market adoption and assessed the research priority of each technology using the zTAP tool, incorporating metrics collected in the technology assessment. The overall priority based on how each technology contributes to various ZNE goals, such as energy benefit, load shaping potential, and greenhouse gas emissions reduction. In addition, this analysis articulates research gaps for each technology, highlighting opportunities for funding that could help overcome current cost or performance barriers prohibiting the technology from reaching market maturity. technology researchers and designers to assist in informing and shaping a well-rounded outcome.

Figure 1 illustrates the steps of the process culminating in the list of highest priority technologies. The method was presented and discussed with the Technical Advisory Committee

(TAC) for the project and represented the Energy Commission, IOU ETP and ZNE staff, technology researchers and designers to assist in informing and shaping a well-rounded outcome.

Figure 1: Project Approach



Source: Itron Team Staff

The technical assessment started with an expansive literature search of more than 500 individual reports and articles from credible sources such as state- and federal-funded research, national lab research, academic journals, and recommendations from industry experts. The stakeholder input solicited through online surveys sequenced initially receive a higher-level assessment of broad ZNE focus areas, priorities, and barriers followed by detailed input for specific technologies. The first higher-level survey fielded widely and received over 540 responses representing a broad range of occupations and residential and commercial representation, both within and outside California. The survey asked subject matter experts to volunteer for a follow-on survey to provide details for specific technologies they assessed as being high potential to enable ZNE. The final list of about 150 technologies was constructed from these efforts and rounded out with input and addition from subject matter experts. The information for each technology was compiled as briefs that include applicability of the technology by building type and climate, cost and performance status, and targets, critical barriers, and research gaps (Appendix B).

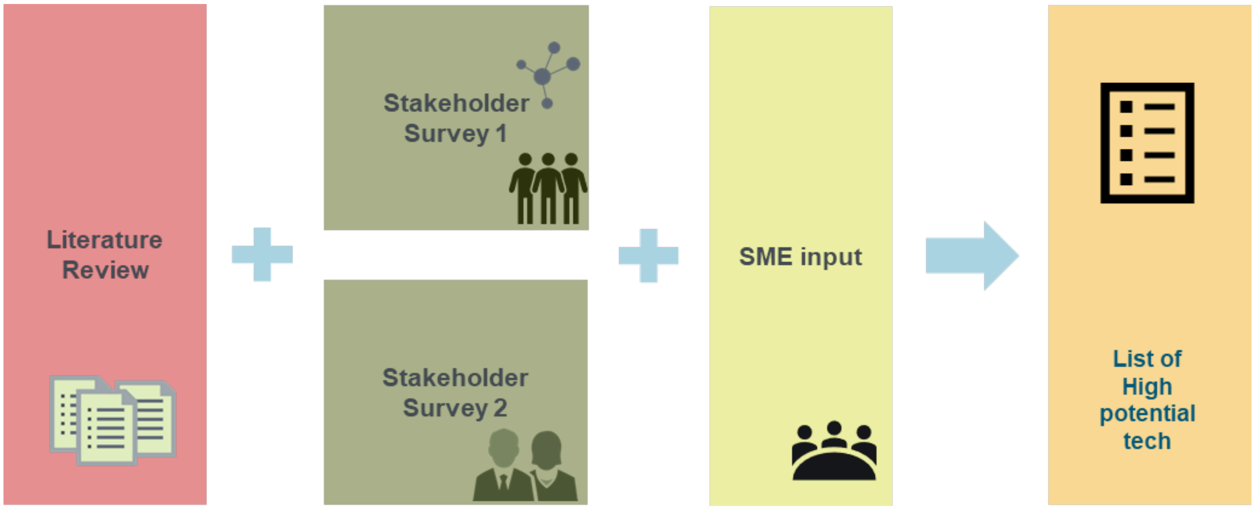
The gaps analysis was a process of identifying the specific gaps in the technology adoption that can be overcome with research support. These research gaps ranged from early phase prototype development to demonstrations and pilots, including cost and performance targets with feature enhancements and standards development. The research gaps and details of technology applicability and importance to ZNE are captured in a set of technology briefs for over 60 technologies. The priority assessment was made thorough the development of a framework based on objective criteria and is described in Chapter 3.

CHAPTER 2:
Technical Assessment

Overview

The goal of this task was to develop a technical assessment of the current baseline, best-in-class, and emerging ZNE building technologies and strategies, including cost and performance attributes that can be used to inform and develop the ZNE Research Roadmap. The technical assessment consisted of literature review, stakeholder surveys, and subject matter expert interviews with the goal of creating a list of high-potential ZNE technologies, each with cost and performance metrics and detailed research gaps necessary to determine the research priority. Figure 2 shows the overall process of the technical assessment, resulting in the list of high potential ZNE technologies.

Figure 2: Overview of Technical Assessment



Source: Itron Team Staff

Literature Review

Process

The team gathered literature on technologies that do not have full market adoption but could play a significant role in advancing ZNE buildings, and ensure that technologies not identified in the stakeholder surveys are not overlooked. The review investigated recent, credible ZNE research, including peer-reviewed technical journals, government reports, trade journals, performance specifications of technology used in current ZNE building installations, and other relevant, high-quality sources. The team specifically avoided vested-interest trade industry information. Key sources included the U.S. Department of Energy Office of Scientific and

Technical Information (OSTI), Emerging Technologies Coordinating Council (ETCC), and research laboratories and institutes such as Lawrence Berkeley National Laboratory (LBNL), National Renewable Energy Laboratory (NREL), and Rocky Mountain Institute (RMI). In addition, the search was limited to articles published within the last 10 years to focus on current building energy technologies and up-to-date performance and cost metrics.

The team conducted in-depth reviews of each relevant research document, collecting characteristics and metrics on each technology, including:

- Normalized energy benefit per unit building floor area (e.g., kWh/ft2, kBtu/ft2) or relative energy benefit (percentage saved in each end-use category)
- Applicability to the 12 commercial building types defined in the California Commercial End-use Survey (CEUS)[1]
- Applicability to single-family, low-rise and high-rise multifamily residential building types
- Applicability to California climate zones
- Current cost per unit energy or capacity (e.g., $/W, $/ton) and energy performance (e.g., Seasonal Energy Efficiency Ratio (SEER), lumens/W)
- Future normalized cost and performance necessary for market adoption
- Current technology maturity on technology readiness level (TRL) scale
- Expected technology maturity (TRL) by 2030
- Technical, market, and policy barriers
- Technical, market, and policy drivers
- Relevance to supporting adoption of ZNE

Summary of Results

In total, 523 research documents on various ZNE technologies and strategies were included in the literature review. Each document reviewed was catalogued in a bibliography database, including the title, author, sponsor, source, publication date, abstract/summary, hyperlink, and key topics (keywords) covered in the document. The literature bibliography has been provided as a complimenting dataset with this report and is available with the Energy Commission.

Figure 3 shows the distribution of research documents across the 15 focus areas identified previously in the project scope section, plus complementary work like research roadmaps and technical assessments. Most of the documents were on energy efficiency and renewable energy generation technologies.

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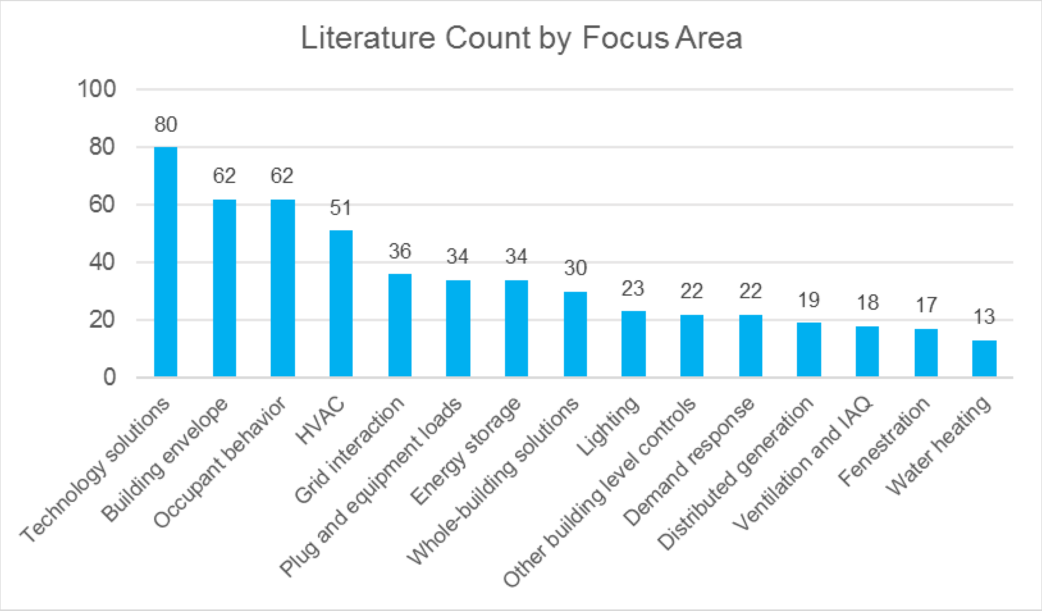
[1] California Commercial End-Use Survey http://www.energy.ca.gov/ceus/

Figure 3: Literature Review



Source: Itron Team Staff

Table 2 shows the most frequently identified technologies, strategies, and concepts found in the literature review in each focus area.

Table 2: Technology Categories Within Topic Areas

Technology Category	Top Keywords
Building envelope	Phase change materials, Trombe wall, thermal mass
Fenestration	High performance glass, dynamic windows, thermochromic glazing
Heating, ventilation, and air conditioning (HVAC)	CO2 heat pump, low ambient radiant convectors, radiant slabs, VRF, VRV
Indoor air quality	Façade-integrated ventilation, natural ventilation
Lighting	Controls, IoT, Li-Fi, DC power, LED
Plug-loads and equipment	Controls, Low energy escalators, elevators, smart/occupancy sensing plug strips
Demand response	OpenADR, load shedding
Occupant behavior focus technology	Feedback, dashboards/displays, education
Other building level controls	Lighting controls, daylighting, model predictive control (MPC), feedback
Water heating and efficiency	CO2 heat pump, low-water irrigation, recirculation controls
Whole-building solutions	Passive design, DC power

Distributed generation	Wind, cost estimation, CHP, fuel cells, BIPV
Energy storage	Storage costs, Li-ion, Redox flow, flywheels
Grid Interaction/Smart grid connectivity	EV charging, load shift-enabling software
Technology solutions to address other areas	Design tools, financing, incentives, GHG

Source: Itron Team Staff

The following sections summarize key findings and high potential technologies collected from the literature review for each technology focus area.

Building Envelope

Numerous building envelope technologies present an excellent opportunity for energy savings and load reduction in California. These technologies vary greatly in their readiness for market adoption. Some promising technologies at an early stage of maturity include Trombe walls and night sky radiative cooling. Some technologies have already entered the market but could use more refinement in their manufacturing processes and product design and require further performance testing. This category includes building integrated heat and moisture panels, in addition to high performance insulation, such as vacuum insulated panels, silica aerogel insulation, and structurally insulated panels. Finally, some technologies have already reached maturity in their development and performance, but demand some additional standards development, demonstration projects, systems integration, and training material. This category includes air sealing, thermal barriers, dynamic building facades, and phase change materials.

Fenestration

Significant window performance improvements made over the past few decades are from past investments in fenestration research. Project scope focuses innovative and leading-edge building fenestration technologies that move towards meeting energy and comfort. This includes technologies such as electrochromic glass that are ready but not in use much and could benefit from more research (DOE, 2014b).

Heating, Ventilation, and Air Conditioning (HVAC)

Several efforts have been made to develop a portfolio of advances to efficiency in HVAC systems have been made, including specification, roadmaps, and other plans. Refrigerants with lower global warming potential are mandated and new refrigerants are being researched. One low global warming potential refrigerant with promise is carbon dioxide (CO2). Significant research has gone into its use in heat pump air-conditioning systems (Nekså 2002), water heaters (Dipartimento di Fisica Tecnica, Universita di Padova 2011; Cecchinato et al. 2005; Oak Ridge National Laboratory 2015; Daim, and Khanam 2015) and combined systems (Eklund and Banks 2016).

Vapor-compression systems have dominated the landscape in recent decades, but other mechanisms are likely to be important to enabling ZNE buildings. These range from traditional system types, such as evaporative cooling and solar heating and cooling, to more technically advanced mechanisms and cycles.

Indoor Air Quality (IAQ)

Indoor air quality is an important feature of ZNE buildings, however, there are only a handful of technologies and strategies that provide an opportunity for energy savings and load reduction in California. Each of these techniques, whether they are a specific technology or a design concept is currently exercised in the building industry, but has not quite achieved full market adoption. These strategies already have adequate performance but could reach their market potential with the help of performance testing, demonstration projects, systems integration, and improved modeling capabilities. The techniques that fall within this category include heat recovery ventilation, natural ventilation, and night flush.

Lighting

Electric lighting in commercial buildings is at a relatively advanced stage of development and as lighting technological efficiency gains are tapering off, the integration of existing lighting technologies with daylighting strategies and smart building controls is an area of increasing importance.

Plug-Loads and Equipment

Exploring plug loads was first documented in 1987 (Meier 1987), with a more detailed examination in 1992 (Meier, Rainer, and Greenberg 1992). The focus on the residential sector is attributed, in part, to the comparatively limited data in the literature for analysis in the commercial sector and a need to measure load profiles of key plug loads for different climate zones and building types to better understand and control their energy consumption (Kamilaris et al. 2014). Even in the residential sector, the development of a bottom-up model of energy consumption using historical shipment data and forecasts was based on estimates from disparate sources and was limited by sparse and non-existent data (Sanchez et al. 1998). Characteristics of plug loads, along with methods for reducing their consumption, have subsequently been examined to the greatest extent possible in applications such as new homes (Brown et al. 2007), hospitals (Christiansen et al. 2015), consumer electronics (Roth et al. 2014), coffee makers (Energy Star 2011), and electric motors in residential and commercial applications (Goetzler, Sutherland, and Reis 2013). However, these characteristics are largely dependent on the type of end-use load or device. Few studies document both energy consumption and load shapes for the selected loads analyzed (Parker 2003). Standby modes were introduced in the last two decades as strategies for improving the efficiency of plug load plug loads (IEA 2001); however, the portion of their energy consumption attributed to “idle” or “sleep” modes is still not fully characterized nor communicated to consumers (Delforge, Schmidt, and Schmidt 2015). Further research and field studies are required to characterize, for example, the impacts of “connected standby” mode and the impact of dynamic power draw and device modifications (Urban et al. 2017). An experimental study of a well-instrumented single building suggests that plug loads require monitoring for at least two months, including half of the floor area and 10-20% of the key device categories, to accurately represent time-resolved energy consumption (Lanzisera et al. 2011).

Demand Response

Demand response (DR) applications for ZNE buildings will not perform the traditional role of reducing electrical load on the grid during peak demand periods and they will not necessarily reduce total energy consumption; however, this approach may facilitate grid harmonization by transmitting PV output to the building end-uses rather the grid. A new paradigm shift is necessary to facilitate integration of automatic demand response (ADR) with building energy efficiency (EE) and end-uses to adapt to increased penetration of rooftop solar by automatically shifting consumption of building electricity loads to times with high solar production. This approach can be thought as reverse DR and the demand signals will likely be sent from the building energy management located on the site in response to environmental conditions or solar output.

Occupant Behavior-focused Technology

Providing feedback on energy consumption is a key factor in decreasing consumption. Numerous studies have suggested the potential for significant electricity reduction due to the use of in-home energy displays. However, controlled usability studies and field studies have also pointed to the challenges and limits of energy use feedback.

Other Building-level Controls

One specific area where residents make choices that influence energy consumption is in controlling the interior environment of their homes or workplaces. Thermostats are undergoing a dramatic increase in capability and features, including control of ventilation, responding to electricity price signals, and interacting with a home area network. However, numerous recent studies have found that homes with programmable thermostats can use more energy than those controlled manually depending on how—or if—they are used. With increased technical complexity has come a corresponding complexity in the user interface.

Contractors are the “tip of the spear” when it comes to HVAC system performance. Therefore, the factors that define their practices are critical to understand, and some of them are behavioral. Similarly, the full potential of appliance and equipment efficiency standards are diminished when noncompliance occurs. The California Statewide Utility Codes and Standards Program focuses on appliance standards compliance improvement, by providing access to tools, training, and resources through EnergyCodeAce.com—a website designed to engage and educate key stakeholders—particularly manufacturers and retailers (Richter et al. 2016).

Another focus area is in building operations, as specific changes can save 5-30% of energy use at low cost. Building operators clearly are an important contributor to savings, and factors that support or form a barrier to their ability to make operational improvements are critical to ensuring ZNE performance over time. Trained and certified building operators can more effectively manage the energy consumed by a medium to large commercial building.

Water Heating and Efficiency

Water heating represents a key end use for the residential market sector as it moves to ZNE Water heating energy use is primarily dictated by the magnitude of the hot water loads and the efficiency of the systems delivering the hot water (Schoenbauer 2017). More efficient water-consuming appliances and California's continual advancement in water efficiency initiatives over the past few years (including aggressive showerhead flow restrictions) has contributed to further reduced hot water loads as showering and clothes washing are the predominant hot water loads in most households.

ZNE water heating strategies focus on efficient gas appliances (condensing tankless and storage technologies), air source heat pump water heaters (HPWHs), and emerging CO2 HPWH heating technologies (Eklund et al 2015). Gas tankless water heating has made significant inroads in the California market, even before the 2013 Title 24 Standards set the technology as the prescriptive standard. Although gas technologies will garner significant market share in the near term due to the broad reach of gas infrastructure in California (and the comparatively low fuel cost), efficient electric technologies offer a new avenue to a low carbon future as the California grid is powered more by renewables.

In addition to efficient thermal generation, delivery of hot water becomes an increasingly important component of future ZNE water heating systems. Lower shower, fixture, and appliance flow rates tend to slow the delivery of hot water to use points resulting in increasing water waste and higher distribution losses. Recirculation systems offer the promise of reduced water waste, but significant improvement in recirculation control strategies are necessary to offset the energy penalties. This is especially true in multifamily central system designs where distribution losses can be significant. New approaches to central designs include a more modular strategy where a smaller cluster of apartments are served by an efficient heat source, coupled with a compact distribution system and potentially drain water heat recovery to further reduce loads. These strategies must be demonstrated in the field to document performance (Weitzel and Hoeschele 2017).

Whole-Building Solutions

Direct current (DC) systems can see anywhere from 2 to 8% savings in electricity consumption due to the lack of conversion losses from DC to AC. These savings, coupled with the increased penetration of renewable generation, battery storage, EV loads, and DC appliances, provide efficiency incentives for DC systems. DC appliances are typically more efficient, smaller, more reliable and easier to control through the Internet of Things (IoT), which leads to increased adoption, providing further incentives to create DC systems.

Although encouraging, transitioning to DC is not plausible for every situation. Smaller buildings, with corresponding smaller alternating current (AC) loads, will have an easier time transitioning since the DC appliances and lighting may be able to run on the same wires, requiring no new wiring. However, the lack of market-ready DC equipment and appliances as well as the legacy of AC power make transitioning burdensome and unattractive. For DC systems that include EVs, charging must be done during the day, otherwise AC still must be rectified to DC, resulting in zero energy savings. Appliance electrification (whether AC or DC) is often cited as a popular method to reach ZNE standards; however, with it comes added costs, a need for more PV to offset the load, and a reluctance from customers to switch to electric appliances.

Distributed Generation

Photovoltaics are the most prolifically used DG technology. They have seen a huge upsurge in natural and incentive driven market capture in the last decade. The cell efficiency and technology are ripe enough and the main barriers lie in the balance of system costs for the most part. However, there are a few applications of PV that deserve focus for research funding, such as BIPV or building integrated PV, Organic PV, plug and play AC PV, bifacial PV, and thin film PV. Traditionally BIPV had mostly been associated with roof tile and shingles, however the vertical and façade integrated PV are now in need of support given the vertical building application with limited roof space and high-density urban settings.

Energy Storage

Behind-the-meter (BTM) energy storage technologies enable residential, commercial, and industrial customers to shift energy consumption from one period to another. Today, electricity and thermal energy storage technologies exist at many levels of development, from the early stages of R&D to mature, deployed technologies. Among electricity energy storage technologies, lithium-ion (Li-ion) battery technologies have dominated the market, followed by flow batteries. Thermal energy storage technologies remain largely in the research, development, and demonstration/deployment stages. The most prominent thermal energy storage technologies are ice storage and residential hot water heaters with storage. Incentive mechanisms like the Self-Generation Incentive Program (SGIP) offer financial incentives for installing BTM electrochemical (battery), thermal, and mechanical (for example, flywheel) energy storage technologies.

Battery energy storage technologies are subject to losses - the amount of energy used to charge a battery is always greater than the amount of energy available to discharge from the battery. Consequently, standalone battery energy storage systems will always increase the overall energy consumption on a premise. However, energy storage can reduce grid-level greenhouse gas emissions by shifting energy consumption from periods of high marginal emissions (e.g., late afternoon and early evening) to periods of lower marginal emissions. Furthermore, by shifting energy to mid-day hours, energy storage can increase demand during hours when solar generation is highest and potentially avoid curtailment of grid-scale renewable assets.

BTM energy storage, like other energy efficiency or demand response technologies, must first and foremost provide benefits to the customers that install them. Otherwise customers will not adopt these technologies. Unless customers have the right incentives to operate energy storage systems in a manner that benefits the overall grid, these technologies can have an adverse impact on greenhouse gas emissions. Tariffs and rates must be designed such that the appropriate signals are provided to storage owner/operators. SGIP impact evaluations have shown that as currently designed, California's rates result in storage dispatch behavior that increases GHG emissions and overall utility marginal costs.

Grid Interaction - Smart Grid Connectivity

Increasing sales of smart thermostats, rooftop PV and electric vehicles reflect the growing desire of utility customers to have more say in their energy choices. Customers also expect that their smart devices will work in concert to provide them with higher comfort, value and savings. Controlling and orchestrating DERs within the premise is the next level up of integrating DERs into the grid. This higher level of DER integration can provide benefits to both customers and the utility. For example, orchestrating DERs in the home allows pre-cooling and load shifting that reduces electricity use during peak demand. DER orchestration also increases the value of the customer's installed PV system by enabling exchange of power between the PV system and any installed battery storage or electric vehicle charging systems. Utilities can benefit from in-premise DER controls that help manage net export, thereby reducing transfer of electricity into the grid during low demand, thereby decreasing the possibility of reverse power flows.

Another strategy to improve the interaction between ZNE buildings and the grid is microgrids. A microgrid consists of facilities and resources typically located in a physically distinct area with geographical boundaries; the facilities have electricity and energy loads (such as heating or cooling) that must be met; the resources consist of generators or other devices (for example storage) that help supply the needed electricity and energy, including the existing grid; a network that connects the loads and supplies; and a control system that manages the network on a dynamic basis including connecting and disconnecting to the existing grid.

Microgrids also range in complexity of components and operations depending on the needs being addressed. Microgrids can be relatively simple systems consisting of a backup generator that can run in parallel to the grid and can automatically island and reconnect to the grid. In contrast, advanced microgrids can control multiple distributed energy resources (DERs) and loads, employing sophisticated analytics and controls including seamlessly moving automatically between island and grid connection; and capable of supplying the grid with ancillary services including black-start, and load, volt-ampere reactive (VAR) and frequency support.

The key technology and strategy around microgrids and ZNE relates to the controls hardware and software including but not limited to communications and controls algorithms.

Current ZNE buildings and communities must also begin to factor in EV charging. Any projects that originally designed without EV charging in mind will likely no longer reach ZNE goals. Since the most feasible energy efficiency measures have already been implemented, the remaining options are to increase PV array size or attempt to reduce the annual vehicle miles traveled (VMT). Again, increasing the amount of solar is not always feasible or physically possible, and while a reduction of VMT would be effective, it is unlikely, as annual VMT is on the rise.

A promising option for reducing the EV charging load is by transitioning from AC to DC circuits. Typical transitions to DC can see anywhere from 2% to 8% electricity savings for all loads, with EV charging seeing up to 4%..This is only effective during daylight hours, however, since any charging done at night will still require rectification of AC to DC from the grid. Battery storage installed to store the excess PV generation to then be used for EV charging, but this brings substantial additional costs. EV charging is not the main motivating factor behind switching to DC circuits, but it will benefit from the transition and could provide enough energy savings to reach ZNE targets.

Other ZNE Implementation

Community-scale ZNE

Within the US, community-scale PV continues to struggle through early adoption. Regulatory delays over incentives and bill-credits, net energy metering capacity limits, slow interconnection approvals and sluggish acquisition of community PV subscribers hinder implementation. Specifically, within California, developers are required to meet a minimum level of subscribers within 60 days of awarded the power purchase agreement (PPA). This condensed acquisition timeline, along with low bill credits, presents a challenge for California developers.

For completed ZNE communities, a clear distinction made between communities that designed to ZNE and those that perform to ZNE. Currently, the only requirement is that communities designed to ZNE, when in reality, those ZNE targets missed due to poor equipment performance or unpredictable occupant behavior. In order to reduce the number of communities that fall short of their ZNE design, incentives or some sort of enforcement measures that ensure optimal occupant behavior, and measurement and verification be explored and considered.

As ZNE targets scale to full communities, the potential impacts on the grid magnified, with distribution systems having to manage for unpredictable load peaks and high penetration PV through demand response and energy storage. Residential energy storage has high potential for benefit but must include integrated load management techniques with optimized platforms and control algorithms, an area that requires further attention and development. Additionally, improving storage permitting, solar/storage interconnection and other construction processes is required to scale ZNE communities. According to EPRI's 2017 report, *Grid Integration of Zero-net energy Communities* (written for the CPUC), "The most reliable path forward in distribution planning is to increase transformer and wire sizing for ZNE and high PV penetration, as this requires a 50-year planning horizon."

Using the *Nishi Zero-net energy Feasibility Study* as a case study for ZNE communities, multiple barriers and opportunities for ZNE communities discovered. A serious limitation on ZNE communities is the availability of enough rooftop solar. As rooftops congested with heat pumps, solar thermal and PV, prioritizing space (often for PV) is key. The unavailability of rooftop space forced the Nishi project to discard solar thermal and instead rely on the purchase of biogas to offset natural gas consumption. Electrification to offset natural gas were explored, but the increased electrical load could not be offset by PV generation. Electrification also encounters market hesitation, as customers are reluctant to switch. Addressing and understanding customer behavior, as well as addressing the increasing issue of plug-loads, is among the identified opportunities to move towards consistency within community-scale ZNE.

Stakeholder Input

Overview

The stakeholder input was collected primarily through large-scale online surveys. They were administered online via the project website, with links distributed widely using a combination of direct email, social media, and industry newsletters.

Key stakeholders initially provided feedback on the survey approach and assisted in shaping the questions.

Survey 1: Challenges and Priorities for ZNE

Key research question: *What priority do stakeholders place on research needs for various technologies and strategies that would increase adoption/implementation of ZNE?*

Objective

The objective of Survey 1 was to identify the priority that stakeholders place on research needs for various technologies and strategies that could advance the development of ZNE buildings. Respondents were asked about their professional experience (occupation, primary building sector, work locations, and familiarity with ZNE technologies) to determine how these variables might influence their view of ZNE challenges. Primarily the goal was to seek input on technology barriers, so the survey began by establishing the stakeholders' views on a broad set of ZNE concerns.

All respondents rated, on a scale of 1-5, the significance of 16 different challenges to ZNE adoption; along with technology limitations, the list included government policies, skill of designers and building trades, and other issues. We also asked respondents to describe the three most significant barriers to ZNE, as well as a single "silver bullet" solution to get buildings to ZNE.

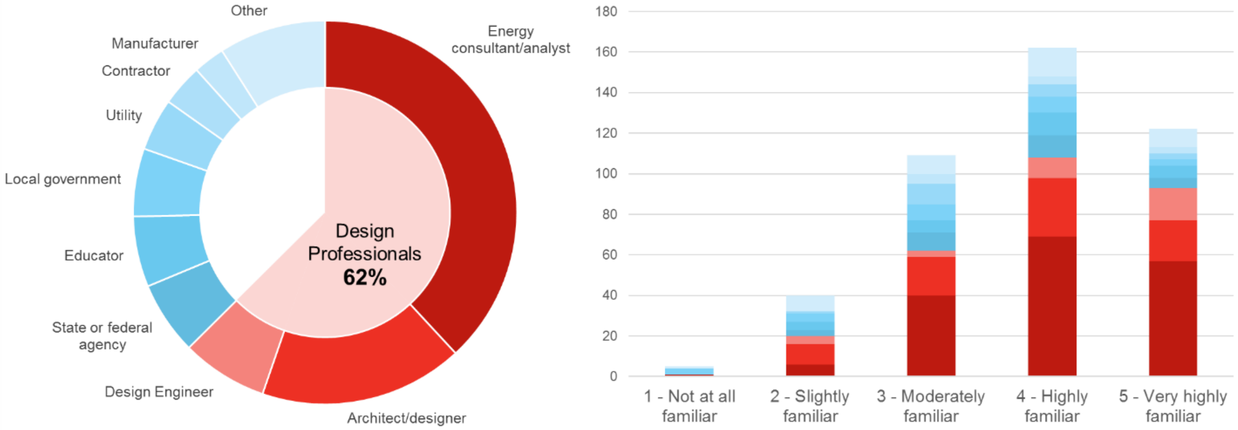
Respondents who said they had little to no familiarity with ZNE technologies were then asked to rate the research priority of 10 broad technology types, including renewable and efficiency technologies, training and certification, and occupant-focused solutions. Respondents who self-identified as being moderately to very highly familiar with ZNE technologies were asked to rate the research priority of 30 individual technology types, such as battery storage, lighting, building envelope, and building management systems. This "technical" group was later invited to participate in Survey 2, to provide more detail on specific technologies and research gaps.

Results

Survey 1 yielded 541 responses – the largest set of responses to a single ZNE survey conducted in the US; of those, 454 (84%) were substantive and formed the basis of analysis. The graphs in Figure 4 shows the breakdown of respondents by profession and their familiarity (on a scale of

1-5) with ZNE technologies. While respondents represented more than 20 unique professions, more than 60% were energy consultants, architects, engineers, and other design professionals. Roughly 90% of respondents identified as having moderate to very high familiarity with technologies, tools, or software used in ZNE projects.

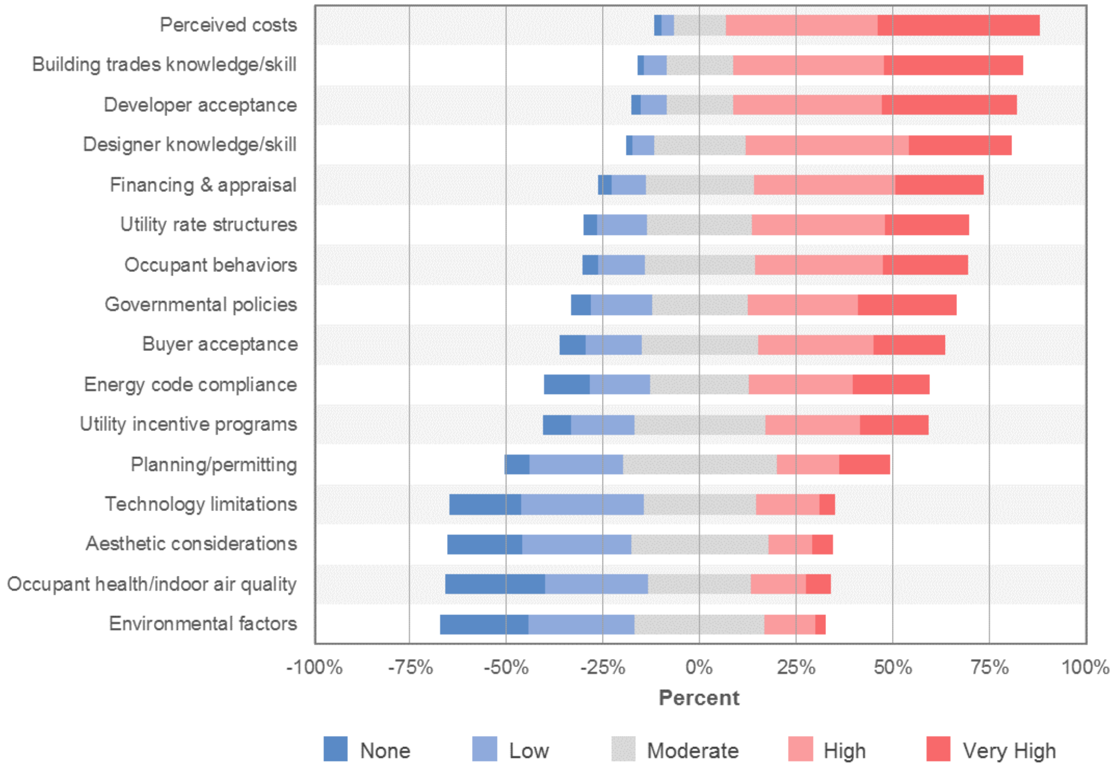
Figure 4: Survey 1 Respondents by Occupation and Familiarity to ZNE



Source: Itron Team Staff

Respondents identified the most significant types of challenges to ZNE adoption. Figure 5 shows the breakdown of responses by degree of significance. Notably, technology (fourth from last) is not perceived to be a very significant barrier to ZNE adoption, whereas perceived costs ranked as the most significant challenge. Technical knowledge of designers and building trades also ranked as highly significant challenges, as did developer acceptance. While these are not technology challenges by themselves, there is the potential for technology solutions to be developed to help address them. For example, designer knowledge gaps might, to some degree, be addressed through innovations in design software.

Figure 5: Survey 1 - Challenges to ZNE Adoption



Source: Itron Team Staff

Respondents were asked to describe the three most significant challenges to achieving ZNE goals. This open-ended question allowed respondents to elaborate on the challenges prompted by the prior question or introduce other challenges. Of the 1,124 responses, 92% were concentrated in nine categories. The top categories and subcategories are shown in Table 3.

Table 3: Survey 1 - Categorization of Challenges

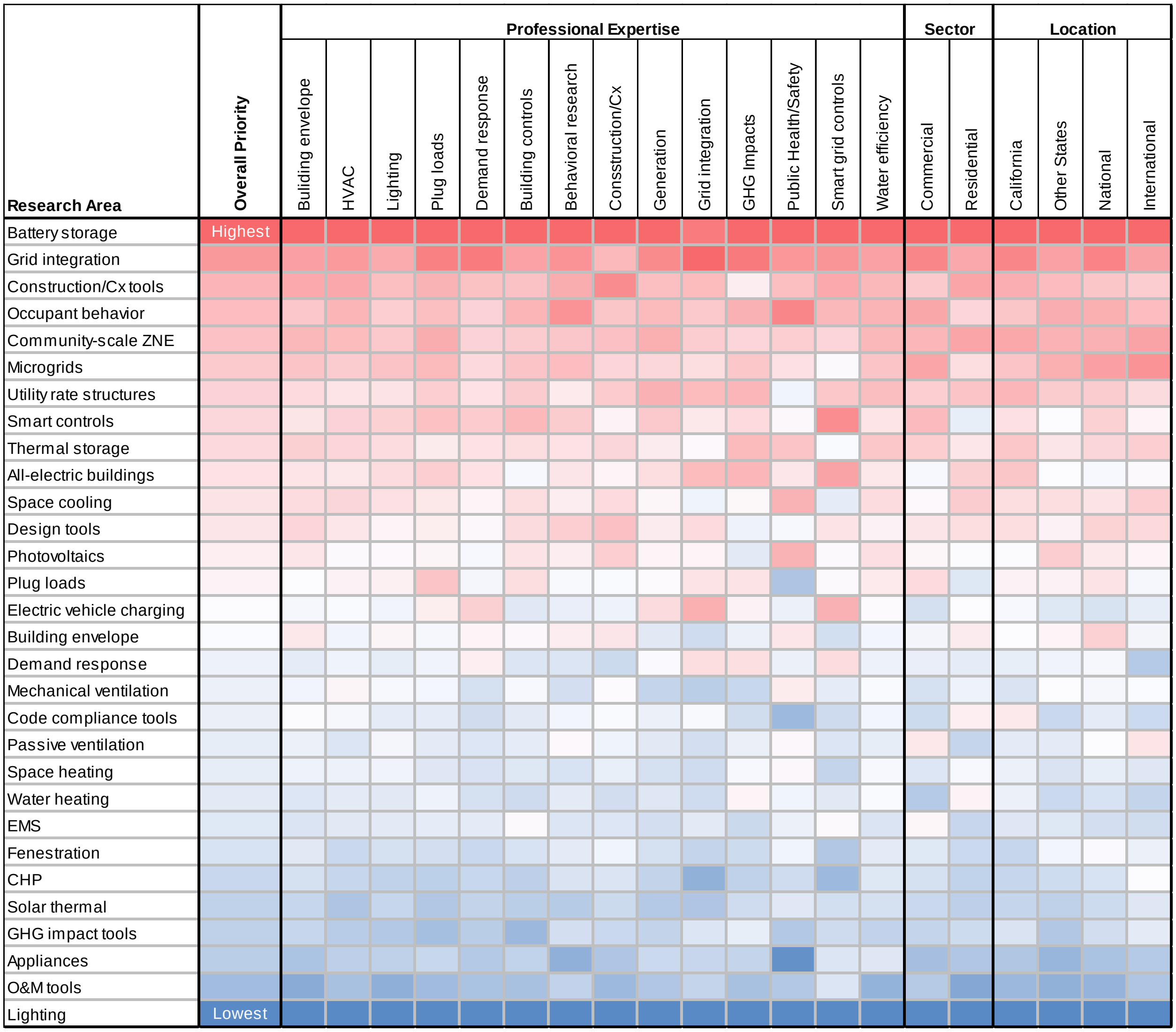
Rank	Category	Subcategory	Subcategory Count	Category Count	% of Total
1	Education	General	59	375	33%
		Building operators	14		
		Design	86		
		Developers	63		
		Finance community	15		
		Local government	2		
		Occupants	40		
		Trades	96		
2	Cost issues	Perceived costs	179	193	17%
		Cost obstacles	14		
3	Government policies	General	90	134	12%
		Energy code	44		
4	Public education/marketing	N/A	111	111	10%
5	Technologies	General	36	65	6%
		Envelope	1		
		HVAC	2		
		PV	2		
		Software	13		
		Energy storage	11		
6	Grid/Utility	General	22	61	5%
		Electrification	10		
		Rates	29		
7	Financing & Appraisal	N/A	42	42	4%
8	Floor Area Ratio	N/A	34	34	3%
9	Incentives	General	9	29	3%
		Government	7		
		Utility	13		

Source: Itron Team Staff

Consistent with the results of the challenge-rating question, respondents identified education and perceived costs as the most significant barriers to ZNE adoption. (Because each respondent provided up to three responses, 33% indicates nearly every respondent provided a response in the education category.) Stakeholder-identified barriers – in addition to those listed in the rating question – included building electrification, policies and leadership, energy codes, and a consistent definition of ZNE.

Respondents were asked to prioritize research needs for various technologies to support ZNE adoption on a scale from 1 (not a priority) to 5 (very high priority). As shown in Figure 6, the prioritizations were relatively consistent independent of respondent expertise, market sector, or work location; occupation also had little effect on responses.

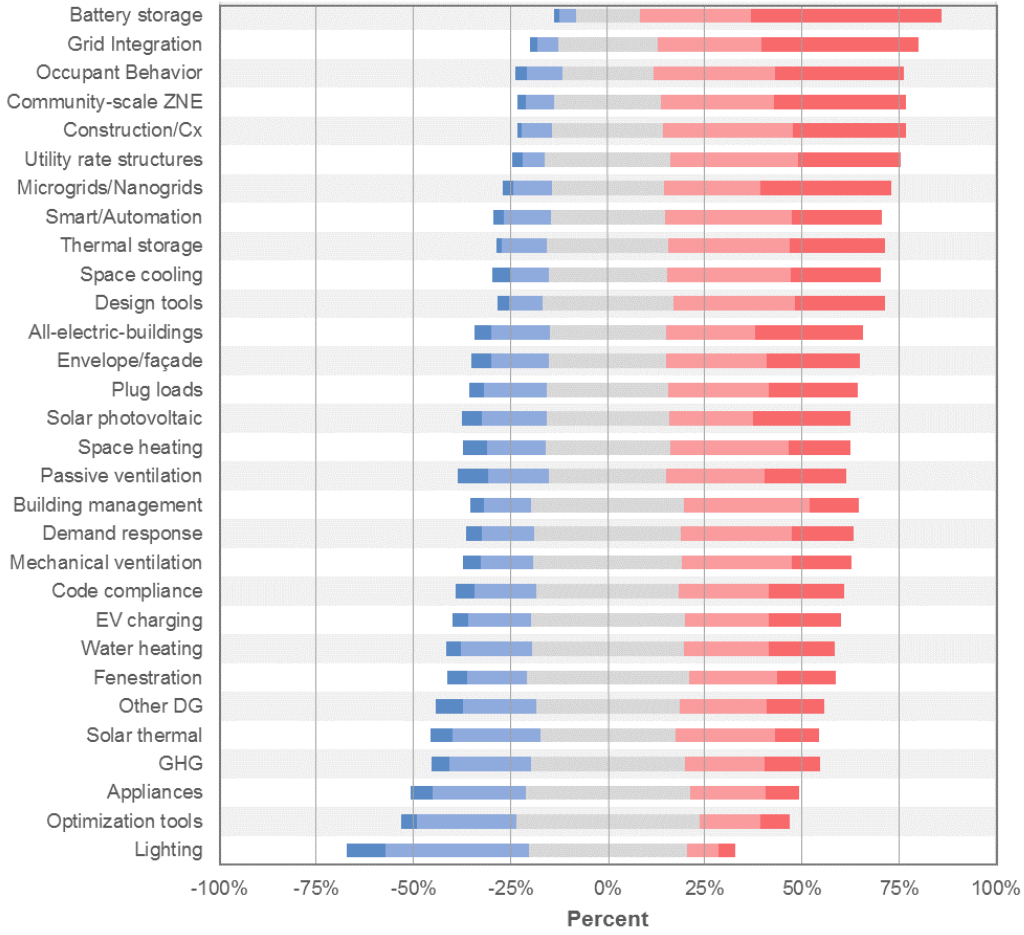
Figure 6: Survey 1 – Research Priority by Occupation, Sector and Location of Respondents



Source: Itron Team Staff

Battery storage and grid integration technologies emerged as the two highest research priorities (Figure 7). These, along with other areas identified by stakeholders as high research priorities, indicate a need for advances in energy load shaping capability. Lighting ranked as the lowest research priority.

Figure 7: Survey 1 – Research Priority (Weighted Ranking)



Source: Itron Team Staff

Survey respondents were queried, “If you could have your wish granted for a single ‘silver bullet’ solution to get buildings to ZNE, what would you ask for?” This question was designed to use the “challenge” mindset established by the preceding questions to prompt free-association ideas for high-priority or high-value solutions (Table 4).

The “silver bullet” solutions were concentrated in eight broad categories comprising 88% of responses. Those categories were divided further into subcategories to allow examination of the solutions at a more granular level; this revealed 10 areas in which there were 10 or more responses. Many of these correlate with stakeholder-identified challenge categories (Table 5).

Table 4: Survey 1 – Categorization of “Silver Bullet” Solutions

Silver Bullet Solution Categories	Rank	n	% of Total
Government policy	1	113	28%
Technology	2	60	15%
Incentives	3	42	11%
Education	4	39	10%
Public education/marketing	5	31	8%
Financing & appraisal	6	25	6%
Community-scale ZNE	7	21	5%
Grid/utility	8	19	5%

Source: Itron Team Staff

Table 5: Survey 1 – Count of “Silver Bullet” Solution Categories

‘Silver Bullet’ Sub-categories	Challenge Subcategory (if applicable)	Response Count	Challenge Category Rank (from Table 1)
Government policy	Energy code	70	3
Public education/marketing	N/A	31	4
Community-scale ZNE	N/A	21	N/A
Government policy	General	21	3
Education	Design	20	1
Incentives	General	14	9
Other	N/A	13	N/A
Technology	Photovoltaics	12	5
Design tools	N/A	11	N/A
Technology	Software	10	5

Source: Itron Team Staff

Survey 2: Detailed Technology Input

Key research question: *What are the most significant innovative or cutting-edge technologies that have unrealized potential to advance ZNE?*

Objective

Survey 2 aimed to identify barriers for emerging technologies with significant unrealized potential to advance ZNE. For a technology of their choice, respondents were asked to provide input regarding its applicability to various building types and climate zones, potential energy benefit compared to currently available alternative technologies, and technology readiness (Table 6). At the end of the survey, each respondent had the option to provide data for one additional technology of their choice.

Table 6: Survey 2 - Questions on Key Technology Attributes

Attribute	Summary of Questions and Range of Response Options
1) Scalability	Applicable building sector – new construction and/or retrofit Climate zones – 5 options, from cold to hot-humid Building types – 3 residential and 13 commercial building types
2) Maturity	Current maturity – 5 options, from theoretical to full market maturity Future maturity (in 5-7 years) – 4 options, from proof of concept to full market maturity
3) Energy Savings	Current savings potential – 4 bins (from 10% or less to 50% or more) and “don’t know” Savings potential at maturity – 4 bins (from 10% or less to 50% or more) and “don’t know”
4) Cost - changes needed to support adoption	Necessary first cost reduction – 5 bins (from 10% or less to 50% or more) and “don’t know” Necessary operating cost reduction – 5 bins (from 10% or less to 50% or more) and “don’t know” Cost factors – multiple-choice selection of potential high cost factors (e.g., relative immaturity)
5) Other – barriers, funding priorities, and area of ZNE contribution	Barriers – multiple-choice selection of potential market barriers (e.g., policy) Funding areas – multiple-choice selection of necessary funding areas (e.g., standards) Contribution areas – multiple-choice selection of ZNE contribution areas (e.g., greenhouse gas reduction)

Source: Itron Team Staff

Results

Survey Part 2 represents the input from 139 respondents, who provided 156 individual responses, with each response focused on a single technology. The respondents were well-distributed by sector, work location(s), and areas of technical expertise. Table 7 shows a breakdown of their responses by broad technology category. Table 8 shows the ten most identified technologies with the current cost and other barriers to adoption and area needing research funding for each technology.

Table 7: Number of Survey Submissions by Primary Technology Category

Broad Technology Categories	Response Count
HVAC	39
Energy storage (thermal and electric)	23
Building envelope	23
Water heating and water reuse related energy use	11
Distributed generation (e.g., solar PV, tri-/quad-gen, CHP, wind)	11
Technology solutions for implementation/operation aspects (e.g., construction/commissioning, energy modeling and design, tools and technologies)	9
Ventilation and indoor air quality	8
Fenestration	8
Plug and equipment loads	6
Occupant behavior focused technology (e.g., controls, dashboards)	6
Grid interaction	5
Other building level controls	4
Lighting	2
Other	1

Source: Itron Team Staff

Table 8: Survey 2 - Top 10 Technologies by Frequency of Response as High Priority

Technology	Response Count	Cost Barriers to Adoption	Other Barriers to Adoption	Research Focus
Lithium-ion batteries	12	Early market phase, Market size, Installation issues	Product availability, Policy, Acceptance/familiarity	Standards development
Air sealing	10	Installation issues, Market size, Early market phase	Acceptance/familiarity, Policy, Institutional	Market awareness campaign, Standards development
Air-to-air heat pumps	7	Installation issues, Market size	Acceptance/familiarity	Market awareness campaign
Thermal energy storage	4	Early market phase, Installation issues, Market size	Product availability, Acceptance/familiarity	Standards development
Structurally insulated panels (SIPs)	3	N/A	Institutional, Policy, Acceptance/familiarity	Market awareness campaign
Air-to-water heat pumps	3	Installation issues, Early market phase, Market size	Acceptance/familiarity, Policy, Product availability	Market awareness campaign, Standards development
Heat recovery ventilators	3	Installation issues, Market size, Other	Acceptance/familiarity	Market awareness campaign, Training materials development, Standards development
Heat pumps with storage tanks	3	Installation issues, Early market phase	Acceptance/familiarity, Product availability, Reliability	Training materials development, Standards development
CO2 heat pumps	3	Early market phase	Acceptance/familiarity	Market awareness campaign, Training materials development, Standards development

Electrochromic glazing/films	2	Early market phase	Product availability	Market awareness campaign

Source: Itron Team Staff

Respondents provided answers to questions regarding their technology's current and future cost and performance, as well as improvements necessary for the technology to be ready for mainstream adoption. They described the factors (if any) responsible for high costs, as well as any other barriers to mainstream adoption, such as institutional, familiarity, or production issues. Finally, they were asked to identify the research activities where funding should be focused to help overcome these barriers, and to describe the technology's overall importance to advancing ZNE.

The responses yielded thousands of subjective data points. The team reviewed the responses, filling in blanks, interpreting narrative responses, and assigned scorings of high, medium, or low to the stakeholder responses. The results, following research team review and refinement, represent the "Stakeholder ZNE List".

The research team did not consider any individual's response as definitive as to the technology potential and/or need for research support. The Part 2 survey responses are by no means a complete list or the final ranking of promising technologies to advance ZNE implementation but do provide valuable insights to the priorities as seen by industry leaders.

Subject Matter Expert Input

After compiling the initial list of technologies by combing the ones from stakeholders and those proposed by the team themselves, the team engaged with subject matter experts (SMEs) and researchers. The input was structured around completing the technology detail briefs included in Appendix B. The SMEs and researchers were contacted based on their ongoing work and research interest in the specific technology areas.

CHAPTER 3:
Research Gap Analysis

Research Gap Analysis

Research gaps for technologies that enable ZNE based on the evolving landscape of increasing distributed energy resources associated with the buildings were identified for each technology. For the most part, the research gap for each technology can be described as one or more of the areas listed below:

1. Prototype development – Basic principles research to make observable properties into something turned into a useful technology. This research gap applies to nascent technologies, so the more developed technologies in the list should not be at this stage of research.
2. Performance improvement - Performance improvements to specific components or the system as a whole. Research needed on aspects of the technology that would improve actual performance and therefore the energy benefit. Further improving a proven technology (e.g., increasing SEER value in HVAC). This would include specifically measurable aspects of improvements that are required in performance to make the technology more market ready.
3. Performance testing and validation – This kind of gap would be to test and validate the performance of a technology. This could be in lab or controlled conditions, or through comparing predicted to actual performance.
4. Systems integration - Proven component but needs integration into a system to make it market viable as a technology product. An example would be Li-ion batteries, where the need is for the system that turns the proven technology into a useable battery unit with charge discharge cycles and capabilities to match the end load profiles. The gap is need for testing and implementation of the component in a usable system. There could examples for other technologies such as variable speed motors that go into HVAC systems.
5. Product design evolution or feature enhancement – Research to enhance and add features to the technology product that are critical to making it usable towards better market adoption. Such things would include
6. Cost improvement – Research to improve the final cost of a technology, which could include:
    a. Production cost – advancements that increase yield or reduce the cost of manufacturing the technology
    b. Supply chain efficiency – cost improvement
    c. Retail or first cost
    d. Installation cost – could include training
    e. O&M - diagnostic cost
7. Testing in controlled lab like conditions or simulated real world
8. Real world demonstrations in small pilot scale that could include specific objectives that listed but not limited to:
    a. Customer acceptance of technology features

    b. Bankability
    c. Performance validation in real world
    d. Installation and commissioning
    e. Occupant behavior impacting energy use
    f. Testing of rate structures for objectives such as mutual customer cost and grid benefits or creating value proposition for a technology
9. Test procedures and protocols for technologies that do not have readily available testing protocols and or modeling procedures. This would be a research gap for new and emerging technologies that do not have existing performance and safety standards or tests to make them ready for market adoption. It could be UL standards for safety or IEEE standards for performance. This could also extend to other testing standards that might be required to get market adoption including:
    a. Communications protocols
    b. Modeling enhancements for the technology in simulation tools for energy assessment

Cost and Performance Targets

The cost and performance, and projected targets collected for each technology to allow for specifying benchmarks in future solicitations for research funding. The metrics for cost and performance are technology specific and the baselines vary.

Prioritization Method

Overall Framework

Our proposed framework embraces and imbibes the following principles:

- **Transparency** of the approach so that the assessment is an objective prioritization and not perceived as rigged process with bias or skew
- **Scalability** to include more technologies in the future as the framework can allow for addition of new and emerging technologies to the mix
- **Flexibility** of adapting the framework to allow alignment with evolving polices and not be stranded in time to get shelved and obsolete easily

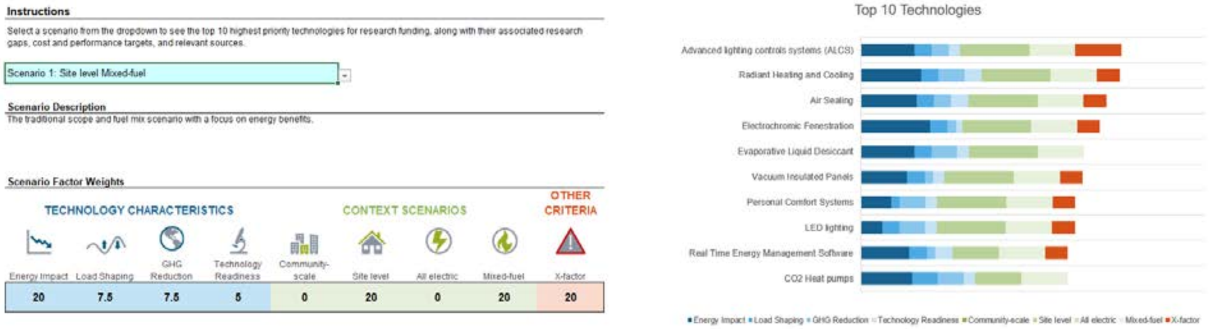
Based on results from the literature review and stakeholder input, the team was able to get a shortlist of the highest priority technologies. To systematically assess the relative prioritization of these technologies, the team normalized them on the factors of energy impact, technology readiness in the timeframe (impact ZNE before 2030), and the addressability of barriers. Technologies assessed based on their relevance in the various contexts for defining ZNE and a placeholder wild card factor, called the X-factor, to align with evolving policy and priorities. The team articulated the disposition of each of these high priority technologies in terms of the specific barriers, cost and performance targets.

The focus has been on technologies with the greatest potential to positively impact adoption of ZNE but have been underserved and need research support towards market adoption. The primary source for technologies on the list is Survey 2, supplemented with gaps evident based on experience from both the project team and TAC, as well as standout technologies and strategies identified in the literature review.

zTAP tool

The **ZNE Technology Assessment and Prioritization (zTAP)** tool helps determine the relative priority of technologies in a defined ZNE context based on nine objective factors (Figure 8). The zTAP tool assesses the relative research prioritization of technologies based on factors that describe various ZNE scenarios that align with policy and preference. The zTAP tool allows multi-factor objective assessment of technologies which otherwise are not intuitive to synthesize in combination. The assessment is based on nine factors that can be individually weighted to consider changing priorities by the state or by the user.

Figure 8: zTAP Tool Screenshot



Instructions

Select a scenario from the dropdown to see the top 10 highest priority technologies for research funding, along with their associated research gaps, cost and performance targets, and relevant sources.

Scenario 1: Site level Mixed-fuel

Scenario Description

The traditional scope and fuel mix scenario with a focus on energy benefits.

Scenario Factor Weights

TECHNOLOGY CHARACTERISTICS				CONTEXT SCENARIOS				OTHER CRITERIA
Energy Impact	Load Shaping	GHG Reduction	Technology Readiness	Community-scale	Site level	All electric	Mixed-fuel	X-factor
20	7.5	7.5	5	0	20	0	20	20

Source: Itron Team Staff

Priority Factors

The factors listed in Figure 9 were assessed for each identified technology to determine the relative priority compared to the rest of the technology list. The numeric and qualitative factors below are not to be assessed as absolute values, but are a relative indicator of research priority across technologies.

Figure 9: Factors for Defining the Priority Framework

Source: Itron Team Staff

Table 9 summarizes the description and scoring metric for each of the priority factors.

Table 9: Description and Scoring for Factors Used to Assess Relative Priority of Technology

Factor	Description	Metric
Energy Impact (EI)	Overall energy benefit based upon reduction in energy use intensity (EUI) within the respective end use category, scaled by the projected growth for applicable building types in climate zones by 2030 (for new construction) End uses impacted by the tech/strategy % of energy benefit Applicable market sectors – new/retrofit Building types applicable – res, MF, schools…. etc. Applicable climate zones Scaled by CEUS data on EUI and growth projection for the applicable building types	Scale: 0-3 0 – No energy benefit 1 – Low energy benefit 2 – Medium energy benefit 3 – High energy benefit The actual score is calculated on a grading scale approach. The technology with maximum benefit is scored 3 and the others are scaled accordingly with scores between 0 and 3 up to 2 decimal places.
Load shaping potential (LSP)	Technologies and strategies with the ability to actively shape load, such as creating a flattened or predictable load profile or impact permanent load shifting.	Scale: 0-3 Objective assessment 0 – No ability to shape load 1 – Low ability to shape load (e.g.: building envelope, static building fenestration, etc.) 2 – Medium ability to shape load (e.g.: thermal mass, pre-cooling measures) 3 – High ability to shape load (very reactive and controllable technologies such as storage, communicable thermostats, lighting or other high impact responsive controls)
GHG reduction potential (GHG)	The ability of the technology/strategy to reduce GHG emissions.	Scale: 0-3 Objective assessment 0 – No GHG reduction 1 – Low GHG reduction 2 – Medium GHG reduction 3 – High GHG reduction
Technology Readiness Level (TRL)	Potential for the technology to reach maturity by 2025 for 2030 full market adoption	Scale: 0 – 3 Scaled based on the actual 1- 9 TRL for the technology

Context Scenario - SL - CS - AE - MF	The relevance of a technology is assessed in four ZNE context settings which combined shape scenarios. Scale - Site level (SL) - Community scale (CS) Fuel - All electric (AE) - Mixed fuel (MF)	Relevance score of the tech in each of the four context settings of scope and fuel Scale: 0-3 Objective assessment 0 – No relevance in the scenario 1 – Low relevance to the specific scenario 2 – Medium relevance to the scenario 3 – High relevance and very applicable in the scenario
X-factor (XF)	This is a wild card or extraneous factor which can be used to determine priority in alignment with evolving policy and priorities.	Scale: -3 through +3

Source: Itron Team Staff

Energy Impact

The potential energy impact for a technology, either electricity or gas use reduction or electricity generation, is a key metric to define a new technology's potential to advance ZNE. Each of the technologies identified were assessed based on their applicability to various commercial and residential building types and California forecasting climate zones. The team assessed an energy benefit percentage to each building end use category (e.g., lighting, cooling, water heating) based on available literature and input from stakeholders and subject matter experts. The electricity and natural gas energy impact is calculated as an energy use intensity (EUI) benefit for each end use category using data from the 2006 California Commercial End-Use Survey (CEUS) and the 2009 Residential Appliance Saturation and Unit Energy Consumption Study (RASS) for the commercial and residential sectors, respectively. The data used in the energy impact calculation came from the 2006 California Commercial End-Use Survey (CEUS) for the commercial sector and the 2009 Residential Appliance Saturation and Unit Energy Consumption Study (RASS) for the residential sector. The CEUS data provides EUI by forecasting climate zone, building type, and end use. RASS provides household annual energy use by climate zone, building type, and end use for weather-sensitive end uses, and provides household annual energy use by building type for the other end uses. The team assumed that the end uses not classified as weather-sensitive would use the same amount of energy in every climate zone. Interior lighting end uses were not provided in RASS data, however, RASS reports interior lighting to be 22% of total energy use, which is the estimate that was used. RASS also provided data on square footage of homes by building type and climate zone. This was used to estimate EUI for residential building types. Projected building growth data for each forecasting climate zone and building type was supplied by the California Energy Commission Demand Analysis Office.

This normalized value is then scaled to the potential new building stock in California by 2030 for each applicable building type and forecasting climate zone.

Once electricity and gas savings have been calculated for all applicable building types and climate zones, the final energy impact score is calculated. Electricity savings are multiplied by a site-to-source conversion factor of 2.401 (CEC 2017, NREL 2007), which was based on statewide electricity fuel mix. The final energy impact score is the savings for the technology, as a ratio of the technology with the maximum savings, scored 0-3, which can be seen in Figure 10.

Figure 10: Energy Benefits

Source: Itron Team Staff

Load Shaping Potential

Technologies and strategies that have the ability to actively shape load, be it to flatten a profile, create a predictable load profile, or impact permanent load shifting.

GHG Reduction Potential

The ability of the technology/strategy to reduce GHG emissions. These could range from technologies that provide load shifting, or directly use a fuel that lead to reduced GHG. Example technologies with high GHG reduction potential would include: CHP that are run on biogas with heat being used to space conditioning, or waste heat recovery processes that utilize energy for space conditioning, solar thermal systems that directly offset a GHG intense fuel.

Technology Readiness Level

Many agencies use a technology readiness level (TRL) scale of 1-9 to represent the maturity level of a technology, enabling a consistent mechanism to compare the stage of development of different types of technology. The following list of TRL levels and descriptions were used to assess each technology in the analysis. Since the existing TRL scale is from 1-9, the level was divided by three to be more consistent with the other factors on a 0-3 scale (for example a TRL of 6 would be represented by a 2 for the TRL factor score).

TRL 1: Scientific research begins translation to applied R&D – Lowest level of technology readiness. Scientific research is translated into applied research and development. Examples might include paper studies of a technology's basic properties.

TRL 2: Invention begins – Once basic principles are observed; practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.

TRL 3: Active R&D is initiated – Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.

TRL 4: Basic technological components are integrated – Basic technological components are integrated to establish that the pieces will work together.

TRL 5: Fidelity of breadboard technology improves significantly – The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.

TRL 6: Model/prototype is tested in relevant environment – Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.

TRL 7: Prototype near or at planned operational system – Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment.

TRL 8: Technology is proven to work – Actual technology completed and qualified through test and demonstration.

TRL 9: Technology proven through successful operations - Actual application of technology is in its final form

Context Scenarios

The context of ZNE is key to defining a successful solution space and therefore the technologies that will be relevant and useful as priority. The current California policy definition is somewhat limiting in the technologies and strategies it is able to address as a TDV metric. The definition has the potential to evolve with the progress of standards and policy changes. Specifying the relevance of a technology each of the four scenarios allows the information to persist and technologies be reassessed for priority in the future. Such changes could come with a renewed focus on GHG reduction and inclusion of community scale definitions along with grid interaction and all electric buildings.

The four distinct factors shaping scenarios to frame solution space are a combination of scope of project (single building or community scale) and the fuel type (all electric or mixed fuel with gas and electric). Most objectives adopt a ZNE policy or mandate mapped back to one or more of these scenarios and the solution space that emerges. The context scenarios provide a framework for assessing the solutions and technologies that meet the objectives while grounded in proper context to ensure realization of the zero net goals.

The idea here will be to assess the applicability of each technology in each of these four context factors. For example, some generation technologies and electric storage may score high in a community scale and all electric scenario while being much lower value in individual building and mixed fuel setting. Similarly, a combined heat and power technology could score high in a community scale mixed fuel scenario versus individual site and all electric.

Community scale– This factor relates to the applicability and relevance of a technology in a community scale setting. A higher score would be for technologies that are better positioned or have higher benefit when installed and operated in a community scale such as district cooling and heating or microgrid type controls which manage the energy flow on large scale. The definition of community used here is operational for all levels of aggregation, be it community campus or district with a central jurisdiction. Technologies with benefits that are limited to a single building are scored lower in this factor such as individual fenestration and building envelope technologies. The GHG reduction potential at community scale is higher as is the energy benefit with added benefit of economies in scale.

Single building– This factor relates to the relevance of technology in a single site level. A higher score in this indicates the larger benefit and applicability of the technology in a single site setting. Such technologies include building envelope and fenestration. The scores in the community and site level are not mutually exclusive but are evaluated for relevance in the particular scale of applicability.

Mixed Fuel – This factor relates to the fuel mix associated with the end use. Technologies that are more applicable when the context is mixed-fuel are scored higher in this factor compared to those that provide benefit in the all-electric realm. Advanced water and space heating technologies that benefit both electric and gas use are favorable over things like electric storage and PV that have more relevance in all electric settings. A mixed-fuel setting always has the inherent combustion of gas, either at site or source, which makes it a less impactful for GHG reduction.

All electric –This factor favors technologies that are applicable in all electric setting. This setting will favor on-site electric generation and complimenting electric storage solutions as an example, to offset most or all the onsite energy uses. Technologies that use gas and provide savings are not applicable. The GHG reduction potential is higher for this setting due to the option of clean and renewable electric generation.

X-factor

This is a wild card or extraneous factor which can be used to determine priority in alignment with evolving policy and priorities. This tipping factor would have a high weight and tip the prioritization due to extraneous factors. Such factors could be technology specific such as the ability of the technology to support resilient communities, or the technology is already well on its way to maturity either from market or other agencies such as DOE supporting the research. Examples of these DOE supported research include research investment in solar and storage or the industry advancements through natural growth.

This factor allows the Energy Commission to accommodate new and evolving policy factors that shape decisions for research funding support.

Negative score would indicate that the technology must be severely down-scored from extraneous factors that are not suitable for EPIC funding support. All negative scores are based on the spectrum of how much the extraneous factors negatively make a case against supporting research funding for the tech/strategy that are not already captured by the other static factors. A zero score implies no extraneous factors that either support or negate the case for research funding. All positive scores indicate the compelling reasons to support research funding for the tech/strategy that are not already captured by the other factors. These could include new and evolving policy and executive decisions that shape funding priority.

Priority Index

Scenarios are created based on defining weights associated with each factor to come up with a priority index based on the empirical formula seen below. These weights define the scenario and can be customized to align with policy or preference that is depicted by a factor.

The priority index is a sum product of the weight defined by the scenario setup applied to the individual score of the technology for that factor.

$$RPI = a\,(EI) + b\,(LSP) + c(GHG) + d(TR) + e(CS) + f(SL) + g(AE) + h\,(MF) + i(XF)$$

Where: RPI = Research Priority Index

EI = Energy Impact; cumulative energy benefit

LSP = Load Shaping Potential

GHG = GHG reduction potential

TR = Technology Readiness

CS = Community-scale

SL = Site-level

AE = All-electric

MF = Mixed-fuel

XF = X-factorCoefficients a through i are the weights that total 100 to imply a % allocation to each factor

The basic scenarios on fuel scope and scale described in Table 10 as examples of some setups. However, custom scenarios that best align with policy and preference can be created in the zTAP tool by weighting the factors differently at any time.

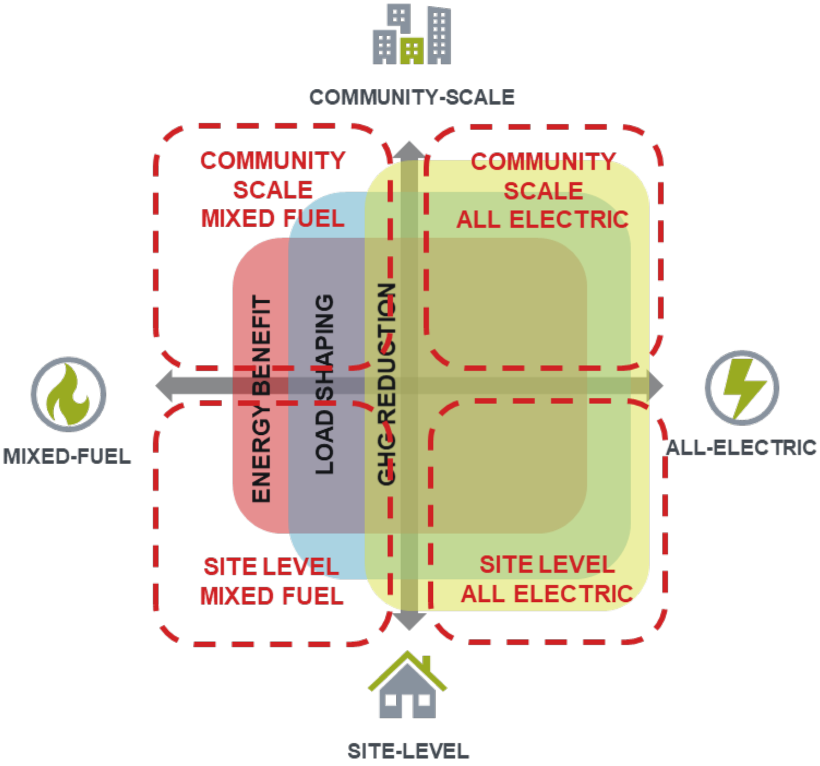
Table 10: Examples of Scenarios with Suggested Factor Weights

<table>
<tr><th>Scenario</th><th>Energy Impact</th><th>Load Shaping</th><th>GHG Reduction</th><th>Technology Readiness</th><th>Community-scale</th><th>Site level</th><th>All electric</th><th>Mixed-fuel</th><th>X-factor</th><th>Total</th></tr>
<tr><td rowspan="2">Site level Mixed-fuel</td><td colspan="10">The traditional scope and fuel mix scenario with a focus on energy benefits. This scenario places higher weight on the relevance of site specific and mixed fuel factors and does not apply to the community scale and all electric relevance.</td></tr>
<tr><td>20</td><td>7.5</td><td>7.5</td><td>5</td><td>0</td><td>20</td><td>0</td><td>20</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Site-level All-electric</td><td colspan="10">The site level scope but all electric fuel switch benefit, which includes the GHG reduction and load shaping potential along with overall energy benefits as important criteria.</td></tr>
<tr><td>20</td><td>7.5</td><td>7.5</td><td>5</td><td>0</td><td>20</td><td>20</td><td>0</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Community-scale Mixed-fuel</td><td colspan="10">Defining the scope of ZNE as a community/ campus/ district rather than an individual building but in the mixed fuel realm, where overall energy benefit is the primarily focus.</td></tr>
<tr><td>20</td><td>7.5</td><td>7.5</td><td>5</td><td>20</td><td>0</td><td>0</td><td>20</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Community-scale All-electric</td><td colspan="10">Defining the scope of ZNE as a community/ campus/ district rather than an individual building but in the all-electric mode. This scenario values, GHG reduction and load shaping potential along with energy benefits.</td></tr>
<tr><td>20</td><td>7.5</td><td>7.5</td><td>5</td><td>20</td><td>0</td><td>20</td><td>0</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">GHG Reduction</td><td colspan="10">The primary focus is on technologies that have the highest GHG reduction potential, and agnostic about applicability to scope and fuel type.</td></tr>
<tr><td>20</td><td>10</td><td>40</td><td>5</td><td>0</td><td>0</td><td>5</td><td>0</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Grid focus</td><td colspan="10">The primary focus here is on the load shaping potential of technologies, along with energy benefit. All other criteria are somewhat equitable.</td></tr>
<tr><td>20</td><td>40</td><td>10</td><td>5</td><td>0</td><td>0</td><td>5</td><td>0</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Early stage research priority</td><td colspan="10">Focus on funding early-stage technology readiness level (TRL) technologies, agnostic to scope and scale of applicability. Primarily driven by supporting research to further nascent technologies with high potential across, energy, load shaping and GHG reduction criteria.</td></tr>
<tr><td>20</td><td>7.5</td><td>7.5</td><td>-45</td><td>0</td><td>0</td><td>0</td><td>0</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Market facilitation focused research priority</td><td colspan="10">Focus on funding market ready technologies with high potential across, energy, loading shaping and GHG reduction criteria.</td></tr>
<tr><td>20</td><td>7.5</td><td>7.5</td><td>45</td><td>0</td><td>0</td><td>0</td><td>0</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Custom</td><td colspan="10">This scenario can be anything based on policy alignment and focus on any of the factors</td></tr>
<tr><td>?</td><td>?</td><td>?</td><td>?</td><td>?</td><td>?</td><td>?</td><td>?</td><td>?</td><td>100</td></tr>
</table>

Source: Itron Team Staff

The spatial layout of the scenarios in terms of scope and scale quadrants along with the resulting list of technologies that emerge as high priority are shown in Figure 11.

Figure 11: ZNE Context Scenarios



Source: Itron Team Staff

CHAPTER 4: Conclusions

Key Findings

The project through technical assess and gap analysis provides insight into several technologies and strategies with the ZNE perspective. The key takeaways based on information collected and synthesized through the literature review, stakeholder and SME input, and gap analysis leading to prioritization framework are listed as:

1. While technology does not pose the biggest challenge to achieving ZNE, it is a significant solution. While stakeholders ranked technology as the fourth lowest out of 16 challenge areas, they also ranked it the second-most significant solution in the 'silver bullet' tool kit behind government policy and regulation.
2. Decades of energy efficiency as the first energy loading order in California has yielded a high level of development and market adoption. While efficient building technologies remain critical to make ZNE ubiquitous, the focus now extends to control technologies, renewables, and grid management. Hence, the greatest research gaps and market needs are technologies and strategies that support demand response and smart control.
3. The emergence of controls with embedded intelligence and predictive analytics enable buildings to schedule and balance load to minimize grid impact. Furthermore, renewable generation can align with demand to achieve grid harmonization with adoption of both electrical and thermal energy storage technologies.
4. The most prevalent research gap for technologies was identified as demonstrations and pilots, including market awareness and education. Both experts who provided online input on technologies and those specifically contacted echoed this research gap.
5. To establish the relative research priority of various technologies, it is critical to evaluate them in terms of their effectiveness at addressing not ZNE per se, but rather the key drivers for ZNE: energy, load shaping, and GHG reduction. This in turn requires examining the technologies' potential scale (site versus community) and fuel (mixed versus all-electric) implications.

Overarching Research Gaps

Research gaps associated with ZNE are often not limited to one technology or for that matter technology at all. As the primary objective of this work was to focus on technology specific research gaps with a focus on cost and performance targets, the following research gaps are barriers to ZNE adoption at large and can be applicable across multiple technology and research areas.

1. System integration – This is a gap not specific to a technology or one end use, but an approach that considers the interplay between measures as a system. Controls and related algorithms are a good example of such a research gap. The systems approach is coordinating the specific technologies such lighting, HVAC, storage, pool pumps and

water heating to operate in coordination and provide the maximum benefit to both energy and grid operations.

2. Demonstrations and pilots are another area transcending most specific technology types. Demonstrations typically allow for actual field placement of technology out of the laboratory realm to prove performance and longevity in real world conditions. Such demonstrations and pilots serve to prove the reliability and bankability of technology and unearth hidden nuances of the interface of technology with other systems in the real world.
3. Alignment of policy and utility rates towards goals such as ZNE is an important aspect to realize value proposition for technology implementation. This plays out especially where GHG reduction is a policy, but the utility rates may not be aligned to reflect the on-peak energy reduction which translates to GHG reduction. Such misalignment can often misinform the decision makers that apply technologies to solve problems for building owners. The research gap lies in aligning the intent of policy with the reflection in utility rate structure for enablement. An example of such a misalignment is the value proposition for customer owned behind the meter storage. While as a technology storage coupled with solar is well-aligned with GHG reduction, however due to lack of appropriate rate structure there is little monitory incentive for owners which limits and affects market pricing and adopting the technology.
4. ZNE is fast coming of age in the design realm, where projects and buildings are designed to be ZNE. However, the operational aspect is the frontier, which is even more important with its far-reaching impact on GHG reduction. However, making buildings more reliable, more controllable by grid operators and building operators, and able to cheaply provide the expected services to the occupants is not yet a possibility and needs more research.
5. Electric vehicles straddle a line between the transportation and building sectors. With increased adoption of EVs, further research is necessary to incorporate, manage and balance this new load at the individual site level and fleet scale.
6. Research, industry development and in-field use of building technologies is extensive and rapidly changing. Continual collaboration with leading design firms offers the greatest access to current trends affecting the path to ZNE.

Research Gaps for Specific Technology Types

The summary of research gaps along with cost and performance targets for a few handpicked technologies under each category are described in the next section. The details for each technology are listed in the individual technology briefs in Appendix B.

Building Envelope

Traditional developments in building envelope technologies have focused primarily on increasing the R-value of the building facade. Modern technologies, such as phase change materials and BIHME (Building Integrated Heat and Moisture Exchange) panels, are integrated into the building’s space conditioning controls. This gives the building envelope a dynamic role in energy management, improving load shaping and minimizing grid impact.

The building envelope technologies highlighted below are mostly all related to the thermal property of the vertical façade.

Air Sealing

Real world demonstrations. Conduct demonstrations to achieve customer acceptance and understand the actual leakiness of well-sealed buildings and poorly sealed buildings.

Standards development. Develop simplified infiltration measurement protocols. Because guarded blower door testing is so time-consuming and difficult, a simpler measurement protocol is necessary. To create such a protocol, guarded blower door testing would need to be conducted on different room configurations in different types of construction to develop factors for different configurations.

Breathing Wall

Prototype development. Develop prototypes to fully understand technology and its potential.

Product enhancement. Address areas of improvement specifically proper weatherproofing, air filtration, vapor transfer and latent heat exchange, transient heat transfer, buoyancy driven ventilation, heat recovery.

Systems integration. Connect breathing wall technology with low-grade heating and cooling systems.

Building Integrated Heat and Moisture Exchange Panels (BIHME)

Real world demonstrations. Conduct field demonstrations to determine how BIHME panels compare to traditional DOAS and ERV designs, to understand and validate long-term performance, acquire occupant feedback regarding the BIHME panels, and showcase projects to major market players.

Dynamic Building Envelopes

Standards development. Develop standardized testing procedures, better design support tools so the technology can be evaluated during design, and methods for assessing the operational performance and occupant interactions of buildings with adaptive building envelope components.

Systems integration. Develop shading products fully integrated with appropriate controls sequences, to be more easily installed and operated.

Phase Change Materials (PCM)

Performance testing. Test products to understand how placement of PCM affects performance. Collect real building data in different climates to see how PCM performs. Validate performance of existing PCM products in the market.

Product enhancement. Improve the durability, fire resistance and long term thermal behavior of PCM enhanced wallboards.

Systems integration. Integrate PCM products with passive cooling techniques and conventional cooling systems, to increase efficiency and explore different applications.

Standards development. Develop metrics to effectively assess PCM technologies by their effectiveness to dampen air temperature.

Vacuum Insulated Panels

Performance testing. Test products to better predict product lifetime and acoustical properties.

Product enhancement. Enhance product to better maintain vacuum and be less vulnerable to perforation.

Cost reduction. Reduce production cost of nano-porous materials.

Standards development. Develop standards on how to handle VIPs during construction.

Thermal Barriers

Standards development. The most significant area of research falls within training materials development. Much research has been done on different technologies and strategies to minimize thermal bridging and effectively design thermally sealed envelope, but this information has not been disseminated in an organized and easy to use fashion. It is now time to compile the research into an envelope design guide specifically for California. The research conducted must be organized in a systematic manner. This should include decision trees and selection tools for architects on batt insulation, rigid insulation, and attachment methods. This guide should also include example section drawings and detail drawings and information from practitioners on how to communicate with clients on envelope systems. Table 11 summarizes the key research gaps and cost and performance targets for some of the highest priority building envelope technologies.

Table 11: Building Envelope Technology Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
Air Sealing	Real world demonstrations. Standards development.	**Cost Target:** Current cost is $0.75/sq ft façade → Future cost of $0.5/sq ft façade. **Performance Target:** Current and future performance is 0.25 cfm/sf façade
Breathing Wall	Prototype development. Product enhancement. Systems integration.	**Cost Target:** Comparable upfront cost when including; equipment downsizing but requires building envelope redesign. **Performance Target:** 35% energy savings, system downsizing by 7-10%
Building Integrated Heat and Moisture Exchange Panels	Real world demonstrations.	**Cost Target:** Comparable upfront cost when including; equipment downsizing but requires building envelope redesign. **Performance Target:** 35% energy savings, system downsizing by 7-10%
Dynamic Building Envelopes	Standards development. Systems integration.	**Cost Target:** Current cost is $50-60/sq ft glazing → future cost is $25/sq ft glazing. **Performance Target:** Improvement needed in ease of implementation/integration
Phase Change Materials	Performance testing. Product enhancement. Systems integration. Standards development.	**Cost Target:** Current performance is $1.50-$7.50/lb PCM product →Future performance is $2.00/lb organic PCM product and $3.50-$4.00/lb inorganic PCM product **Performance Target:** Current performance is 52 Btu/lb enthalpy → Future performance is 82-95 Btu/lb enthalpy
Vacuum Insulated Panels	Performance testing Product enhancement. Cost reduction. Standards development.	**Cost Target:** Current cost is $0.50/sq ft → future cost is $0.25/sq ft **Performance Target:** Current and future performance is 0.0011 W/mK (R-12/in)

Source: Itron Team Staff

Fenestration

Fenestration products are a key element in protecting building occupants from undesirable external environmental conditions while simultaneously providing natural light and connection to the outside. In ZNE buildings, fenestration performance can have a large impact on building heating and cooling loads, as well as lighting energy use. Heat transfer through windows (both conduction and solar heat gain), can be the largest component of energy lost through the building, and in cooling-dominated climates, solar heat gain from windows has a significant energy impact in commercial and residential buildings. In commercial buildings, visible light transmittance through windows can reduce lighting loads.

Improvements in fenestration and next-generation windows have significant potential to reduce energy consumption in buildings. However, to make substantial progress toward additional performance improvements, next-generation technologies must be developed with specific emphasis on achieving market-acceptable products with installed costs that facilitate mass-market adoption. Energy savings potential is climate dependent with lower impact in mild climates.

Because of prior research funding and changes in building code requirements, window performance has made dramatic improvements over the past few decades, where low-E dual pane windows are now common with R-values ≥ 3 (U-factors ≤ 0.32) and solar heat gain coefficients (SHGC) ≤ 0.25. Nevertheless, further performance improvements, getting from R-4 to R-8, are possible.

General Research Gaps

Additional research should focus on further improvements in window performance and controls. In general, the two main areas where fenestration improvements could be achieved include:

1. Next generation windows with higher R-values and solar heat gain coefficients appropriate for the climate. Triple-pane windows with R-values ≥ 7 exist but cost reductions and more product options are necessary to make them a viable option in new buildings.
2. Better options for dynamic windows that can independently control solar heat gain and visible transmittance into buildings, integrate with indoor lighting to maintain lighting levels within the buildings without disrupting occupants, and reduce glare.

Technology-specific Research Gaps

Some technology-specific gaps deserve special attention. Table 12 summarizes these key research gaps and cost and performance targets for the highest priority fenestration technologies.

1. Dynamic fenestration: Windows which have the potential to change performance properties including U-factor, solar heat gain coefficient (SHGC), or visible transmittance (VT). Due to better potential for controllability, the largest potential is with electrochromic fenestration, which actively change the transmission of light when energized by an electrical current. Further development needed to improve and simplify

switching controls and switching times, as well as ability to significantly adjust SHGC while maintaining VT.

2. Highly insulating windows: Further development of triple-pane windows and thermally broken frames and glazing assemblies needed to bring cost of high R-value windows down, including low-cost inert gases, improved durability of frame assemblies and glazing seals, and thin triple-pane windows which have the potential for lower manufacturing costs and wider applicability. Current research is being done on thin triple-pane windows by LBNL to validate the technology.

Table 12: Fenestration Technology Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
Electrochromic fenestration	Performance improvement Performance testing and validation Cost improvement	**Cost Target:** Current installed cost with sensors and controls is \$22/ft2. Cost target is \$8/ft2. **Performance Target:** Δ SHGC ~ 0.4 (SHGCbleached = 0.46 to 0.47 and SHGCtinted = 0.09) plus VT in the bleached state > 0.6 for the residential sector and > 0.4 for the commercial sector.
Highly insulating windows	Prototype development Product design evolution or feature enhancement Systems integration Performance testing and validation Cost improvements	**Cost Target:** Cost premium should be \$5/ft2 for premium market, or \$3/ft2 for broader production market. **Performance Target:** R-7 to R-10.

Source: zTAP tool

Heating, Ventilation, and Air Conditioning (HVAC)

Space heating and space cooling (HVAC) energy use accounts for 35% of residential energy consumption and 40% of commercial energy consumption. Addressing research gaps in promising HVAC technologies is key to achieving the state’s ZNE goals.

Although electric vapor-compression technologies are common for space cooling applications, there has been slower adoption of vapor-compression heat pumps for space heating. The most commonly used refrigerant in HVAC equipment are hydrofluorocarbons (HFCs), which contributed to the phase-out of chlorofluorcarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). This is because CFCs and HCFCs significantly contribute to the depletion of the ozone layer, while HFCs having zero ozone-depletion potential. However, HFCs unfortunately have a large global warming potential, and recently proposed US energy legislation commits to reducing the consumption of HFCs. This has spurred interest in the development and use of alternative refrigerants with low GWP, including carbon dioxide.

Many alternative refrigerants come with tradeoffs, including increased cost, reduced efficiency, and safety concerns. Hence, there are also non-vapor-compression technologies currently in the research and development phase that do not suffer from the same technical barriers of alternative refrigerants.

Air Source Heat Pumps

Performance improvement. Research ways to better deal with defrost during cold and moist hours. Often, to deal with defrost cycles, an additional 30% of capacity is required.

Standards development. Develop better standards for how defrost is accounted for and how heating output is documented to the defrost. It is challenging to have overseas vendors bring products to the US because of the difficulty in attaining a Underwriters laboratory (UL) listing. The average time to get a new product UL tested and listed is 1 year to 3 years.

Real world demonstrations in small pilot scale. There must be real world demonstration projects that show that the air source heat pumps work well in cold temperatures. Real world demonstration projects would also help fight the perception that air source heat pumps are primarily for small buildings.

Cost improvement and having additional manufacturers. There is a lack of local vendors selling air source heat pumps. This results in a lack of “or equal” vendors, making it difficult to spec air source heat pumps on public bid projects. The manufacturers are primarily located in southern Europe.

CO_2 Heat Pumps

Standards development. It is challenging to have overseas vendors bring products to the US because of the difficulty in attaining a UL listing. The average time to get a new product UL tested and listed is one year to three years.

Performance improvement. Although CO2 heat pumps compete well in heating mode, they have low cooling coefficient of performance (COP) when ambient temperatures are above 30 degrees Celsius. Research is required on thermodynamic cycle improvements so CO2 heat pumps can provide hot and chilled water.

Performance improvement. Research improved insulation materials.

Real world demonstrations. It is necessary to have multiple manufacturers' products in existing buildings to validate performance.

Magnetocaloric Technology

Prototype development. Continue to develop laboratory prototypes of magnetic cooling systems for A/C applications.

Performance improvement. Continue research into higher efficiency magnets and magnetocaloric materials with a larger paramagnetic effect for use in future magnetic cooling systems.

Performance testing and validation. Conduct laboratory and field-testing with available prototypes to understand their performance for building air conditioning systems.

Personal Comfort Systems (PCS)

Systems integration is the most crucial area of research. Currently, it is difficult to connect personal comfort systems to conventional building HVAC controls; the software systems to perform integration between personal comfort systems and building management systems are just beginning to appear in the marketplace, but they still require work to ensure that HVAC does not conflict with the PCS. For PCS be successful, they must interact as a network to communicate with the building's HVAC controls.

More performance testing is necessary in laboratory and field research to help quantify comfort and energy savings.

Product enhancement recommended to improve performance, aesthetics, and usability of the products.

Cost improvement research is necessary as the cost of PCS is typically borne by the tenant while the energy savings accrue to the landlord.

Radiant Heating and Cooling

The most significant area of research falls within standards development. EPIC grants have funded a lot of research in the last few years on the performance and design of radiant systems. It is now time to compile all of that research into a radiant design guide specifically for California. Organized the research conducted in a systematic manner. This should include a rigorous definition of radiant system, decision trees and selection tools for architects and mechanical designers, information from practitioners on how to communicate with clients on radiant systems, and a set of sequence of operations based on real projects.

Although there have already been many real-world demonstration projects of radiant systems, there should be more demonstration projects focusing on compressor-less cooling designs. In addition, there should be focus on data from distributing loads in real buildings accurately quantify loads in the design stage, since incorrect load design lead to over-sized systems.

Finally, there should be additional performance testing and systems integration for weather based predictive control.

Thermoelastic/Elastocaloric Cooling

Prototype development. Continue to investigate and develop different thermoelastic materials that meet necessary heat transfer and material properties. Continue to develop laboratory prototypes to understand the performance and efficiency of current materials and system designs. Develop next-generation prototypes that can more closely mimic the form factor and operating parameters of conventional air conditioning systems.

Table 13 summarizes these key research gaps and cost and performance targets for the highest priority HVAC technologies.

Table 13: HVAC Technology Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
Air Source heat pumps	Performance Improvement Standards Development Real world demonstrations in small-scale pilots. Cost improvements	**Performance Target:** Ability to maintain performance in cold climates. Coefficient of performance should have a 30% to 50% improvement by 2030 (IEA, 2011). **Cost Target:** Installed cost should decrease by 20% to 30% by 2030 (IEA, 2011)
CO2 Heat pumps	Standards development Performance improvements Real world demonstrations	**Performance Target:** CO2 heat pumps should achieve an energy factor of 2.5 by 2020 (US DOE, 2014) **Cost Target:** CO2 heat pumps have an installed cost target of $800 by 2020, assuming $600 installed cost of electric resistance storage model as baseline (US DOE, 2014).
Magnetocaloric Technology	Prototype development Performance improvement Performance testing and validation	**Performance Target:** Ahmad Abu-Heiba of Oak Ridge National Laboratory is working on a research that forecasts energy savings of 20% higher COP than vapor compression counterparts (US DOE, 2017) **Cost Target:** Costs are largely unknown since prototypes are still under development, but this technology uses advanced materials that are likely to have high incremental cost until volumes reach a high level (US DOE, 2017)

Personal Comfort Systems	Systems integration Performance testing Product enhancement Cost improvements	**Performance Target:** By relaxing temperature setpoints by 4 deg F, 15% energy savings are possible; this should be the target (US DOE, 2017) **Cost Target:** Incremental costs of dynamic clothing technologies are currently unknown. However, since high performance clothing for athletics usually carry a price premium, a cost target for PCS could be the costs of current high-end athletic clothing.
Radiant Heating and Cooling	Standards development Performance testing	**Cost Target:** Current cost is $9/sf premium for radiant → future cost is no premium for radiant Performance Target: No improvement needed in performance
Thermoelastic / Elastocaloric cooling	Prototype development	**Performance Target:** Ichiro Takeuchi of Maryland Energy and Sensor Technologies has a project objective of demonstrating a thermoelastic cooling system with COP > 4 (US DOE, 2017) **Cost Target:** Ichiro Takeuchi of Maryland Energy and Sensor Technologies has a project objective of achieving a cost target of $98/kBtu (US DOE, 2017)

Source: Itron Team Staff

Lighting

Electric lighting remains an important component of building energy use even with the approaching ZNE goal, especially in commercial buildings where daytime lighting is more commonplace, and the internal gains from lighting constitute a large fraction of the cooling load. Lighting in the residential sector is less critical because the operation of household lights does not typically align with peak loads on the grid, and the energy savings partially offset by increased space heating loads.

Recent advances in LEDs have greatly reduced the per lumen electricity use for lighting in all sectors, and full market penetration appears to be inevitable with time due to its long-term cost-effectiveness compared to other lighting options. Although LEDs are a point-source technology, developments in luminaire design have paved the way for inroads into nearly all lighting applications. Federal and industry investments have contributed greatly to advancements in LED technology.

Lighting controls have also evolved over the past few decades. Electric timers have been available for many years. Occupancy and vacancy sensors can reliably turn off lights when nobody is present in the lighting zone. Photosensors used to dim electric lights when sufficient daylight is present. Controls used to reduce lighting use during peak demand periods, and to adjust color temperature to better align with desired biological preferences during different times of day.

Advanced lighting control systems (ALCS) and organic LEDs (OLEDs) are two of the more promising technologies reducing lighting energy use. An ALCS uses sensors and controls to optimize the balance between natural daylighting and electric lighting to minimize energy use and react to demand response signals while maintaining high lighting quality in occupied spaces. This technology used with dynamic window coatings, electronically controlled shading, dimmable light fixtures, vacancy sensors, and other advanced lighting technologies. An ALCS often tracks lighting performance and the control strategy adjusted based on performance or changing conditions. OLED technology is a form of solid-state lighting that has comparable efficiency to LEDs but produce diffuse light over a broader spectrum, and manufactured in flat, flexible sheets. The result is better quality ambient light with less glare and greater application flexibility than standard LEDs.

General Research Gaps

Future research in lighting should emphasize networked controls that can leverage internal and external signals to provide high quality light, and LED technologies such as OLEDs that can provide excellent low-glare lighting with high efficiency in an aesthetic fashion. These technologies require greater investments in demonstration projects to develop best practices, verify energy savings, and demand stimulation efforts to help reduce manufacturing costs through higher volume.

Technology-specific Research Gaps

Key technology gaps include:

1. ALCS: Large-scale demonstrations and evaluations are necessary to develop best practices for installers, and an objective calculation method is required to increase confidence in the cost-effectiveness of the technology.
2. OLEDs: Manufacturing costs and limited product availability are the largest barriers for OLEDs. Federal and manufacturer investments best overcome these challenges. However, technology demonstrations and occupant response studies for currently available products could help stimulate investment and demand by increasing customer awareness and interest in the technology.

Advanced Lighting Controls

Cost: OLED technology is still in its early stages, and manufacturing cost is high. The 2025 target is $100/meter square (m2), but the current cost is about $1000/m2. There is some hope that Korean investment in OLED displays will have a trickle-down effect on OLED lighting costs. The largest specific cost-related challenges are improving yield, reducing costs for materials (substrates, electrodes, encapsulants), and reducing fabrication costs (patterning, printing).

Higher efficacy would also have a beneficial effect on cost by reducing the number of panels necessary for the same light output.

Efficacy: The efficacy of OLEDs is currently about 60 lumens per watt (lm/W) for commercially available products, and 80 lm/W for some high-end products. Efficacy increased to about 100 lm/W to be viable in niche applications and 150 lm/W is necessary for broad use in buildings. The greatest challenge for efficacy is not converting electricity to light, which is nearly at 100% efficiency for OLEDs, but extracting the light from the OLED. Light extraction is currently at about 40-50% and increased to about 70%.

Limited availability: There appears to be only one U.S. manufacturer of OLED panels at this time. Greater investment has been occurring in Korea, focused on OLED displays, and there is some European manufacturing activity. There are several U.S. luminaire manufacturers interested in using OLEDs if there is demand, but currently there are very few lighting products available. Investment is needed for development and testing of prototype OLED applications to help stimulate markets. Support is also required for companies to be OLED luminaire suppliers.

Product reliability: Performance consistency and degradation in the field is a challenge that overcomes through better manufacturing techniques, quality control, and designs that better protect OLEDs from environmental pollutants. At times, stability must be traded off against efficacy, such as for blue emitters, which operate at higher energy levels. The power draw of OLEDs typically increases by about 25% over the life of the product, but recent advancements are moving this closer to 10-15%. Lifetime (calculated based on lumen output) is currently about 10,000 hours, and must be increased to about 50,000 hours.

Low brightness: Lighting intensity is lower than LEDs and other lighting technologies, so a higher surface area must be used for OLED lighting. Because this is an inherent characteristic of OLED, offering certain aesthetic and visual benefits, it is not viewed as a weakness that should be addressed through research. However, it does limit the number of viable market applications, especially for retrofits, where existing fixtures would have to be replaced. It is expected that market penetration may be capped at 10-20% of the overall lighting market due to this limitation.

Customer awareness: OLEDs are an unfamiliar technology that may require greater education and early adopters to spur market acceptance. Finding an ideal near-term application is key to getting a foothold in the market, reducing cost and generating interest, which will lead to further R&D investment. Customer responsiveness to OLED lighting is not well understood, and studies of occupant reactions to OLEDs would be valuable.

Advanced Solid-State Lighting

Knowledge and Experience: 83% of commercial buildings have no automated controls beyond occupancy sensors. Only 2% of commercial buildings use daylight harvesting. As a result, there is very limited experience with advanced controls in the existing building stock. Increased training is necessary to educate the labor force about how to install, program, and interact with the technology. Investment is needed to scale the delivery of training for this technology, especially for designers/specifiers and contractors/installers. The curricula exists, it's a matter of developing delivery methods and providing incentives for participating.

Complexity: For the more advanced ALCS systems, the range of lighting system designs and control types can make it difficult to develop optimal control algorithms appropriate for multiple applications. Specialized expertise may be required to interact with the system and make adjustments. However, there are many simpler networked systems on the market that achieve most of the savings with a much simpler interface and basic feature set. An additional challenge is architectural lighting, which may require a different approach to optimal control logic because of safety and aesthetic requirements.

Lack of Standardization: Communication among sensors and controllers from different manufacturers is challenging without further standardization of communication protocols that will allow an integrated lighting system control strategy. There is a danger that building owners will be locked into obsolete fixtures unable communicate with newer equipment that complies with standard communication protocols developed in the future. Standardized data collection guidelines and consistent methodologies for predicting energy savings are also required.

High Costs: The cost of ALCS remains high from the lack of volume production of standard products, along with design complexity, communication challenges, and high installation costs driven by lack of familiarity and standardization. Hardware costs are higher because the technology is manufactured in low volume; installation costs are higher because contractors do few projects with them and are unfamiliar with the systems. Costs should come down over time with sufficient adoption in the market. The current cost-effectiveness of the technology is not where it needs to be to support mass adoption. Most projects with advanced controls provide a payback in the 7-15 year. range whereas LEDs by themselves provide a payback of 2-5 yrs. As a result, most customers install LEDs without advanced controls to achieve a shorter payback. This creates a lost opportunity for savings that will not be available again until the lighting is replaced in the future, often in 10-15 years. It is crucial to get the advanced controls installed at the time of the LED retrofit.

Value Proposition: Cost effectiveness has not been demonstrated in a sufficient number of buildings. It is especially difficult to identify the characteristics of commercial buildings that will achieve the greatest savings, or best practices for ALCS design and control logic, because calculation methods have not been standardized, ALCS designs have a broad range of control capabilities, and building features and occupant behavior are very diverse. Much larger validation studies (1000s of applications) are necessary to address these questions.

EE Program Designs: ALCS is generally not adequately promoted, targeted, or properly credited by energy efficiency programs due to uncertainty in savings estimates and using baselines that assume controls are installed. Utility incentives are very effective at overcoming cost barriers, however California IOU program offerings and incentives for this technology are currently very limited. This is probably due in part to limitations placed on the IOUs by regulators that require them to use a Title 24 baseline for all projects, which, in turn, has limited the energy savings IOUs can claim for projects using advanced controls, and thereby limited the programs and incentives they can offer for the technology. Another concern is that some programs properly credit ALCS, but are overly complex and cumbersome, discouraging broad participation. Other ALCS technologies in the pipeline will run into the same commercialization barriers faced by market-ready ALCS products now, which makes those barriers the highest priority.

Table 14 summarizes the key research gaps and cost and performance targets for the highest priority lighting technologies.

Table 14: Lighting Technology Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
Advanced lighting controls systems (ALCS)	Real world demonstration Standards development Cost improvement	**Cost Target:** 25% or greater reduction from current cost. The technology is cost-effective in many applications, but the payback period is often over 10 years, and the uncertainty in energy savings makes the cost seem prohibitive. Reduction in first cost, or financial incentives, could help stimulate demand and reduce uncertainty by increasing the number of applications. **Performance Target:** 50-75% reduction in lighting energy use
Advanced Solid-State Lighting	Cost improvement Performance improvement Real world demonstration	**Cost Target:** The 2025 target is $100/m2, but the current cost is about $1000/m2. **Performance Target:** Panel cost is about 60 lm/W for commercially available products, and 80 lm/W for some high-end products. Efficacy must be increased to about 100 lm/W to be viable in niche applications. 150 lm/W would be needed for broad usage in buildings.

Source: Itron Team Staff

Plug-Loads and Equipment

The plug loads end use refer to the energy consumption of products powered by an ordinary AC 120 V connection. This end use generally excludes energy use associated with HVAC, lighting, water heating and other major end uses. Plug loads exist in residential and commercial buildings. In ZNE buildings, plug loads can be the largest end use, reflecting the greatly reduced contribution from traditional end uses and rising contributions of plug loads. In modern California buildings, plug loads are responsible for roughly a quarter of total electricity use.

Dozens – sometimes hundreds – of individual plug loads devices will be present in a building and no specific device is likely to dominate energy consumption. Indeed, the defining features of plug loads are their large number, their diversity, and their low electricity consumption per device. They also exhibit rapid turnover and are often linked to behavior and social trends. For example, home medical equipment is a rapidly-growing component of plug loads. These characteristics make reducing plug load energy use particularly difficult from a policy perspective because minimum efficiency regulations, incentive programs, and other policies have high transactions costs compared to the value of the energy savings. Identifying productive research opportunities is equally difficult because even a technical breakthrough in a single product is likely to result in small aggregate energy savings.

General Research Gaps

Since energy consumption among plug loads is so diffuse, the most fruitful areas of research are those that apply "horizontally" across a wide spectrum of products. Horizontal research might focus on specific components or systems present in many products. These components may consume energy directly or influence energy consumption of other components. Some horizontal research topics are:

1. Technologies to facilitate power-scaling in electronic and mechanical systems. Many products draw about the same power regardless of the actual need for their services. For example, Wi-Fi routers and ethernet switches use almost the same amount of power when idle or transferring data. Inexpensive solutions are necessary to detect loads and adjust behavior of the Wi-Fi.
2. High-efficiency power conversion. Power supplies have made dramatic improvements in efficiency in the past 20 years; nevertheless, further savings are possible. Nearly all plug loads have a power supply, so a modest efficiency improvement still translates into substantial energy savings. This covers conversions from AC to DC and DC to AC.
3. Energy storage. A growing fraction of plug loads rely on batteries for operation while away from an outlet. Battery-powered competitors are gradually replacing ever-larger corded models. For example, battery-powered vacuum cleaners will soon grab the majority of the full-size vacuum market. The energy losses of charging (and discharging) are still high, so innovations can still achieve significant energy savings. (Note: this research should focus on batteries considerably smaller than those paired with PV systems.)
4. Network connectivity. Plug loads and the Internet of Things strongly overlap. These devices must remain continuously connected to a network and, as a result, draw more power than otherwise. New technologies and protocols are necessary to reduce the power penalty introduced by connectivity.
5. Zero-standby solutions. There has been tremendous progress in reducing the standby power use of residential and commercial plug loads. Unfortunately, these reductions have been offset by a huge increase in the number of products continuously drawing power. As a result, even more ingenious – and cheap – methods of further reducing standby power are necessary.
6. More effective power management. An important means of reducing energy consumption of plug loads is to shorten the times in which they are in the "active" modes and extend the times they are in "idle" or "sleep" modes, which have lower power

consumptions. These strategies involve giving the products greater awareness of current conditions (through more sensors) and more capability to predict future conditions (through learning algorithms). Power management is mostly associated with electronics; however, it can apply to electromechanical equipment, too.

7. User interfaces. Every plug load has some sort of control, whose settings affect the product's energy consumption. A poorly designed interface confuses the user and often leads to unnecessary energy consumption. The best example is the programmable thermostat, where user-unfriendly controls contributed to a 50% disabling of energy-saving features. An important research gaps exists in evaluating user interfaces and developing guidelines for improving them.
8. Technical standards to enable compatibility of communications protocols, definitions, and procedures to ensure low-energy operations. Many technical standards are created without considering energy efficiency, forcing products to remain in higher-power modes because of incompatibilities with coordinated products. Recognizing these gaps – and then bridging them – is a unique form of research. It also includes long-term interaction with, and participation in, technical standards committees to ensure that the energy-saving opportunities are not precluded. Important standards affecting plug loads include communications, power delivery (hardware and software), energy price information, and product taxonomy.

Technology-Specific Research Gaps

As indicated, bridging one specific research gap will not result in large energy savings in the plug loads end use. However, some technology-specific gaps deserve special attention. These include:

1. ZNE appliances. "ZNE appliances" has been proposed by combining extremely high efficiency and harvesting ambient energy. This goes beyond the "zero standby" solutions described. Research is required to demonstrate feasibility (or not).
2. Energy-efficient food preparation. The food preparation end uses—cooking and refrigeration—are fragmenting into many, smaller plug loads. Each device offers unique benefits but there is little research into appropriate, energy-efficient technologies to serve the whole ecosystem. This research strongly overlaps with behavior.

Demand Response

Automated Demand Response

Automated DR refers to automated control of individual or aggregated loads in response to utility pricing signals or demand response events. Controls include lighting reduction, HVAC set-point control, electric water heater set-point control, on/off control, and thermal storage. Auto demand response strategies are typically pre-programmed responses to utility signals. Current standards have helped to define hardware and communication requirements to enable off the shelf, DR ready products.

1. **Reliability:** Need for increased reliability of system response, especially from possible customer Wi-Fi connectivity issues. Currently, upkeep of aggregation software platforms or hubs is necessary to ensure that each energy management system remains connected

and functional. Off the shelf products still experience connectivity or data issues due to outdated software, poor site maintenance, and Wi-Fi issues.

2. **Data Security:** As more customer end use data becomes available, extra care must be taken to securely transmit and store the personally identifiable information (PII).
3. **Site Demonstrations:** There is a need for expanded demonstrations to include data centers, different types of residential sites and smaller commercial buildings to understand better the impact potential as well as the most fluid path to integrating auto DR into these buildings.
4. **Performance testing of off the shelf products:** Further research is necessary to understand the capabilities and functionality of off-the-shelf demand response enabling technology (DER aggregation hubs)
5. **Demonstrations of auto DR value:** Need demonstration projects to quantify impact and to determine if there are other value streams in which demand response can be valuable (i.e. ancillary services)

Dispatchable Storage for Peak Load Management

Dispatchable storage refers to controllable, fast acting, distributed storage systems at the commercial level or aggregated at the residential level to provide grid and customer services including backup power, peak load reduction, and other ancillary services, while also deferring system upgrades. This requires established communication between the utility and the distributed battery systems for direct control.

To improve the value proposition of storage technology (battery and thermal storage), utility controls must be created and adopted to shift load to off-peak times and increase load during periods of excess generation. With adequate control strategies and technology, rapid response could allow for frequency regulation as well, adding to the value of fast-acting dispatchable storage. Prior to implementation, the following challenges and gaps must be addressed:

1. DER communication: There is currently a lack of standard communication protocols that would enable products to easily communicate to other products and utilities. This limits projects to pilot programs since there is little to no ability to scale.
2. How do the architecture and interfaces for communication engineered, especially at a retrofit level? The software architecture must be able to support and interface with existing systems.
3. Determining and creating algorithms that should be on the system including self-supply, TOU, and utility set-point command control.
4. There is a demand for consistent, guaranteed response times for utility needs. For customer convenience and comfort, fast, consistent response time is not necessary. From a utility perspective, response times need to be quick (under four seconds) and guaranteed.
5. High upfront cost remains a barrier to distributed storage, but as more value streams surface, distributed battery storage nears economic viability.

Table 15 summarizes the key research gaps and cost and performance targets for some of the highest priority demand response technologies.

Table 15: Demand Response Technology Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
Automated Demand Response	Reliability Data Security Site Demonstrations Performance testing of off the shelf products Demonstration of Auto DR value	**Cost Target**: Current costs of auto demand response implementation are cost competitive, especially with incentives from utility partners. Current addition of connected devices (for residential/small commercial) come at a ~$100-$200 premium per device, plus, typically, the addition of a ~$50-$100 hub. As standardization improves, those costs will reduce and payback periods should expect to be 5-10 years. **Performance Target:** Reliable control over loads at a commercial, residential and industrial level with response times of less than 4 seconds. A kWh reduction number or percentage is difficult to determine due the variability and uniqueness of every application and the feasibility for only a certain amount of reduction at different sites.
Dispatchable storage for peak load management	**Controls:** Controls for value stacking (TOU management, backup power, ISO response, distribution support, etc.)	**Cost Target:** While not necessarily a 2025 target, battery storage needs to hit $125-$165/kWh (a significant reduction from the current ~$500/kWh price point) for increased market penetration**.** **Performance Target:** Ability to reduce peak demand, provide voltage support and frequency regulation, participate in demand response, etc. Need to target a battery lifetime of 15-20 years for competitive levelized cost of energy.

Source: Itron Team Staff

Technologies Related to Occupant Behavior

Designing for ZNE requires assumptions about occupant behavior, such as occupancy schedules, temperature preferences, ability to correctly control equipment, and other practices, in order to estimate the requirements for on-site energy production. Actual energy performance of ZNE buildings is then influenced by occupant behavior (Zhao et al. 2016; Gil, Tierney, Pegg, and Allan 2010; Karlsson, Rohdin, and Persson 2007). Although a majority of ZNE-designed buildings have not provided actual performance data to verify ZNE status (New Buildings Institute 2016), anecdotal evidence suggests that many have not achieved their goal. Occupant behavior is often cited as the reason.

While occupants of ZNE buildings are assumed to have adopted the goal to achieve ZNE, that may not always be the case. For example, a study by Cardwell (2016) found that ZNE homebuyers assume that they do not have to change their behavior to save energy. Moreover, Berry et. al. (2014) found that near-zero energy households reacted negatively when urged to adopt energy saving strategies that required too much effort on their part. The result is that electricity consumption varies widely across households within the same ZNE community, and often exceeds predicted levels (Brown et al. 2016; Outcault et al. 2016). As ZNE construction expands, and adoption broadens beyond early adopters to the wider population (Rogers 2010), occupants will be even less likely to value the energy goals of the building design. This makes it imperative to understand how occupants use energy in a ZNE building, and how their behavior can be influenced, if necessary to achieve ZNE as a *performance* target.

Fundamental Research Gaps

To lay the foundation behavior-focus technology, fundamental research is necessary to understand better the drivers of energy saving behavior irrespective of any particular application. Key topics are:

1. **Motivation**
    a. Altruism: Do (some) occupants have an altruistic motive to save energy? If so, how can it be harnessed? How much information is the right amount to motivate people?
    b. Financial: For whom are financial incentives appealing, and at what level are they effective?
2. **Information**
    a. Does providing better information (alone) stimulate persistent behavior change? If so, what are the nature of those changes, and the relative effectiveness of various feedback mechanisms?
3. **Addressing the principal-agent problems -** Fundamental research on occupant behavior within organizations is necessary to understand how to engage occupants beyond the facilities department, particularly to address the principal-agent problem in commercial settings.
    a. Owner/tenant. To what degree is it possible to get tenants to use energy according to the modeled behavior? What types of interventions assist in that effort?
    b. Company/employee. The same questions must be answered for workers within a building, since they do not face energy costs.
    c. Facilities vs. operations. To what degree are there barriers to adopting or deploying certain technologies because of principal-agent problems within a firm's organizational structure (such as when capital expenditures vs. operational costs vs. operating responsibilities are all handled by different departments)?
4. **Persistence**

    a. How can technologies stimulate and prolong behavior change?
    b. How can leaders promote a culture of sustainability that minimizes the cost of re-educating new entrants (such as employees, tenants, students) when there is turnover? Are champions/ambassadors an effective approach?

Technology-Specific Research Gaps

Answering the fundamental research questions outlined provides a solid foundation for more specific questions that relate to the various technologies that can be used to influence (or predict) occupant behavior.

This section briefly describes several promising technologies or strategies that may be incorporated into ZNE construction to save energy by influencing occupant behavior, as well as the critical research gaps associated with each technology.

1. **Gamification**

   Description: Energy-themed games aimed at informing and shaping occupant behavior and energy use.

   Research Gaps:
    a. Research is necessary to test and measure energy games' impact on behavior over the long-term, across various user groups and relative to the cost of game development. User groups differences may be defined by readily observable characteristics (such as business type) or more hidden ones (for example internal vs. external locus of control).
    b. Research is required to test how the length of time between engaging with energy games and engaging with energy-consuming technologies impacts behavior.
2. **Occupant Level Controls**

   Description: Controls for HVAC, lighting, etc. that promote and attempt to influence occupant engagement with technology.

   Research Gaps:
    a. Research is necessary to evaluate forms of intervention not yet investigated in a rigorous manner, including: coercion, restriction, training and enforcement of rules on energy consumption, in the context of the workplace and beyond.
3. **Predictive Building Controls**

   Description: "Smart" controls of HVAC, plug load, lighting, etc. that utilize data on occupant and technology "behavior" to save energy by anticipating the occupants' needs and reducing waste.

   Research Gaps:
    a. Research is needed on how to: 1) collect data from building owners, users, and operators (especially during the design process) to understand objectives for the building and occupant behavior, and 2) use those as inputs to refine the building energy model to better reflect the energy usage of the building.
    b. Research is required to advance building information systems that integrate an early warning system to identify meaningful deviations from predicted and actual energy consumption.

   c. Research is necessary to better understand the impact of occupant behavior (including conservation efforts) on building energy performance, to better enable Predictive Building Controls (PBC) to anticipate the impacts of behavior change campaigns. Human-in-the-loop (HIL) interaction technologies (sensing/controls) is a promising area of inquiry that should continue to be explored.
   d. Research is needed to improve technologies and algorithms that can accurately sense and quantify occupants and provide inputs to the ventilation control system. Research in this area would need to address concerns about privacy and data security.
   e. Research is needed to determine the cost effectiveness for PBC for various building types.

4. **Dashboards/Displays**

   Description: Digital displays for conveying energy-related information to building occupants such as energy consumption, PV generation, and energy storage, as well as trying to influence occupant behavior to save energy.

   Research Gaps:
   a. Research is needed to better understand the interactions between feedback, energy pricing and control technology. Such work could further develop on-demand energy savings platforms/programs that use dashboards/displays to provide information on real-time energy use, strategies for curtailing demand, and available financial incentives, and measure the impact on peak demand and energy consumption.
   b. Research is necessary to understand how to engage building occupants to use energy dashboards, promote active participation, and retain dashboard users. Research is also needed to understand how the optimal techniques may vary by building or organization type, demographic or other factors.

5. **Social Media Platforms**

   Description: Web-based social media platforms to convey information to and engage one or more groups of occupants around energy-related issues in buildings.

   Research Gaps:
   a. Research is needed to determine how best to adjust occupant engagement strategies across multiple social media applications (i.e., web vs. mobile) and ensure interoperability.
   b. Research is needed to determine how best to leverage storytelling and the use of compelling narratives in social marketing campaigns launched on social media platforms.

Other Building Level Controls

Predictive (Data Analytics-based) Controls

Predictive, or data analytics-based controls, use collected historical data (occupancy, weather, consumption patterns, etc.) to anticipate future energy needs and respond accordingly including set-point control, on/off control, and system alerts. The control systems in residential and commercial buildings are categorized in two groups:

- Networked Controls: Traditional building energy management systems which operate with a central controller or a hub, usually connected to the internet. These systems control multiple loads including HVAC, lighting, plug loads, and safety systems.
- Distributed Intelligence: These systems usually control one end use load such as HVAC or lighting, with built in performance optimization for that particular end use system. These units have individual connection to the internet (cloud connected) but can also be locally networked in some cases with the right hardware combination.

Both systems are suitable for retrofit of existing buildings or new constructions. Controls of the systems are to meet four objectives: comfort, convenience, security and savings.

Research Gaps

1. Lack of clear interface/interoperability between systems: Current solutions require integration of many different pieces with different with many different interfaces and communication protocols. Standardized protocols and interfaces would lead to more easily installed systems and increased market penetration.
2. Integration of existing control loops with artificial intelligence:
3. Research into the most effective way to integrate AI into existing control loops. Demonstration projects would be useful to determine actual impact of analytics-based controls.
4. Mitigation of system oscillation: As system sensitivity increases, the possibility of system oscillation (in which the system reacts to a stimulus, which then creates some change which the system then reacts to again, essentially creating a continuous loop) becomes an issue. Research is needed to create a balance of artificial intelligence in order to keep controllability within certain bounds.
5. Data Storage: The critical question of what will be done with the mass amounts of data (circuit level, sensor, AMI data, etc.) required for predictive controls must be answered.
6. Security: Research is needed to encrypt, store and analyze data to prevent unwanted dissemination of data. Need to develop processes to de-identify data from all personally identifiable information.
    a. Within security, there exists a realistic potential to incorporate block chain technology for secure data storage and transfer.

Table 16 summarizes the key research gaps and cost and performance targets for some of the highest priority building level control technologies.

Table 16: Building Level Controls Technology Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
Predictive (Data Analytics based) controls	Lack of clear interface/interoperability between systems Integration of existing control loops with artificial intelligence	**Performance Target:** Ability to reduce load peaks at a premise level. **Cost Target:** Provision of easily attainable ROI (<5 years) for the added system cost.

	Mitigation of system oscillation Data Storage Security	Suggested $1-2/sf cost target for a model-based building controls

Source: Itron Team Staff

Water Heating and Efficiency

Water heating contributes to 6% of total primary energy use in the commercial buildings sector and 20% of primary energy use in the residential building sector (Itron, Inc. 2006, Palmgren et al. 2010). While the split between natural gas and electric water heating is relatively even nationwide, approximately 88% of residential water heating is provided by natural gas, with approximately 7% and 5% is electricity and propane, respectively. With the push to meet the statewide carbon reduction goals, there is increased interest in to electrify water heating in the state, especially using heat pump technology. Prior water heating research funding nationally and in California, as well improvements in appliance and building code requirements has led to reductions in water heating energy use. Nevertheless, further performance improvements are possible. DOE's Building Technologies Office (BTO) identified primary energy savings targets of 19% and 37% for 2020 and 2030, respectively (Goetzler et al. 2014).

General Research Gaps

Additional research might focus on further improvements in the following areas:

1. Heat pump technologies: There are several potential areas for improvement with heat pump water heaters (HPWHs), including improved COPs, performance validation and field testing, further development of CO2 refrigerant technologies, and improved operational performance and capabilities for central and commercial applications. With increased electrification of water heating to meet carbon reduction goals, it is essential to understand better the capabilities and opportunities for grid-integrated HPWHs to minimize potential for negative impacts on local grid and utility distribution systems and maximize reliance on renewable energy when available.
2. Solar thermal: While there have been significant improvements in the technology over the years, prior investment has not transformed the market place and solar thermal is still much more expensive in most applications than photovoltaics. Further reductions in first cost and maintenance costs are required for solar thermal to become more successful in the marketplace.
3. Hot water distribution: Improved controls and design of hot water distribution systems is necessary. Demand recirculation controls are available for single family residential buildings but have limited market acceptance. Demand controls in multifamily and commercial buildings need careful attention to piping design to be effective. Further research into predictive controls can also minimize wasted heat from hot water recirculation systems.

4. Wastewater Heat Recovery: Single-use applications of hot water (such as commercial laundries, dishwashing, and residential hot water use) results in wastewater being dumped into the municipal waste stream. There are opportunities, where there is still valuable heat in the wastewater, to extract the heat and minimize the energy required to heat cold water. There is a need to identify key markets and design strategies for cost-effective implementation of wastewater heat recovery. Drain water heat recovery products exist but there are no U.S. manufacturers. Focus has been on DWHR systems installed in shower drains in multifamily buildings, but effective application requires incorporation early in building design.

Table 17 summarizes the key research gaps and cost and performance targets for some of the highest priority water heating technologies.

Table 17: Water Heating and Efficiency Technology Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
Central heat pump water heater	Systems integration Cost improvement Real world demonstrations Test procedures and protocols	**Cost Target:** Costs need to be comparable to central gas boiler and storage for cost competitiveness. Current cost premium is about $4,000 - 5,000 per apartment. **Performance Target:** 3.5 - 4.5 COPs at minimum 160F delivery temp and low ambient temperatures.
Grid-integrated heat pump water heater	Performance testing and validation Systems integration Real world demonstrations Test procedures and protocols	**Cost Target:** Incremental cost over base water heater should be less than $50 to be cost competitive. **Performance Target:** Peak reduction of up to 4.5 kW per residential HPWH and 20% total energy use savings.

Source: zTAP tool

Whole-building Solutions

3D Printed Buildings

3D printing of buildings has gained experimental traction as a viable but relatively unproven option for single-family residential and small commercial sites. Continuing research explores the optimal material composition (whether a carbon-fiber polymer, modified concrete or an undiscovered composition), as well as various strategies for construction of 3D buildings, including on-site 3D printing of the entire building or mass printing of modular components off-site to then be assembled efficiently on-site. While unsure costs and technical applicability remain barriers, the reduction of site waste, reduced labor costs, comparable performance, and the opportunity for scaled implementation are attractive benefits to justify further research.

The main research needs to improve the market-readiness of 3D printed buildings include:

1. **Material Composition:** One key research gap is the identification of the most effective 3D printing material to optimize envelope performance (R-value, sealing, high thermal mass) while maintaining structural integrity and minimizing total material use and waste (specifically. is there a material that provides the same performance values but uses only say ~80% as much material as the other).
2. **Insulation Integration:** Since 3D printing only prints the façade, research is needed in how to go about efficiently integrating insulation (whether during the print process or after). Are there materials that are structural and can simultaneously provide high R-values?
3. **Optimal Design:** 3D printing is not as effective when building using typical existing building designs meant for more standard framing techniques. For example, typical stress points (corners, etc.) require added material when 3D printing. Research required to identify the best design elements (natural curves) to reduce material use and maximize interior space.
4. **Application Expansion:** The capability of 3D printing allows for thinking outside of the box in terms of building design and functionality. What functionality can be explored that typical construction practices cannot provide?
5. **Demonstration Projects:** Necessary to better understand actual performance of air sealing and thermal efficiency.

Pre-designed Buildings Assembled On-Site

This research area includes the assembly of sustainable, pre-fabricated components (wall panels, steel beams, etc.) on-site to create energy efficient, zero net ready homes or buildings. The off-site fabrication of components allows for quicker build times, reduced site waste and labor costs, and scalability. Included are modular, replicable buildings ranging from single family residential to larger multi-story office buildings. These advanced buildings are designed for HERS 0 assembly using advanced sealing techniques and reduction of thermal bridging through advanced assembly. Although a number of products are already on the market, further research is necessary to improve market penetration:

1. **Product Improvement:** Continued product testing and development to reduce amount of materials required for the product and during construction. Can the same structural integrity and energy efficiency exist while reducing the amount of materials consumed?
2. **Scaled Demonstrations:** Need for scaled demonstrations in order to prove viability of construction methods. Single projects do not make sense when dealing with a new building technology that the trades and builders will likely be unwilling to accept. Demonstrations will also help to better understand the associated costs with changing construction techniques. Typical quotes for buildings using these advanced technologies are based on square-footage quotes of standard stick framing, incorrectly valuing the technology.

3. **Development of ancillary products:** Research into other products that can be integrated with the technology and within the construction timeline to add value to the nascent highly energy efficient design. For instance, creating a technology/material to replace stucco on one of the existing manufactured walls in order to further reduce build times and improve product performance.
4. **Education of Trades:** It is necessary to educate the trades on new technologies and processes for them to accept these new technologies and the new construction practices that accompany them. There must be enough incentive for them to change their practices. Initial implementations have seen earnest push back from builders and trades due to the added necessary training and a lack of value to the builder.

Table 18 summarizes the key research gaps and cost and performance targets for some of the highest priority whole building technologies.

Table 18: Whole Building Technology Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
3D Printed Buildings	Material Composition Insulation Integration Optimal Design Application Expansion Demonstration Projects	**Cost Target:** 3D printing is best for building a limited number of products. Early demonstrations claim costs as low as $17 per square foot for complete wall installation. Due to reduced construction time and waste, the cost is competitive with regular stick framing. However, this is for small scale residential (<1000 square feet). As building sizes increase and floors are added, per square foot material and labor costs may rise due to the increased need of materials per square foot and increased human interaction with the 3D printers (labor). **Performance Target:** Expansion to new building types with larger, more building inclusive 3D printers. Integration of insulation as well as plumbing and electrical chassis into the product.
Pre-designed buildings assembled on site	Product Improvement Scaled Demonstrations Development of ancillary products	**Performance Target:** “Zero Energy Ready” construction. Build to a point in which only renewable energy resources are needed to reach a zero net energy target. Much of this field is close to this target due to the highly efficient envelope and air sealing provided by

	Education of Trades	the manufacturers. Reduction of site construction waste. **Cost Target:** Reach level of cost associated with typical T24 shell/envelope construction. Depending on the technology, some are already cost competitive when comparing to California's T24 requirements, but for others, reductions of over 50% are still needed to be cost competitive.

Source: Itron Team Staff

Distributed Generation

Community Scale Solar (Virtual Net Metering)

Community scale solar (CSS) refers to projects under 10 MW that are interconnected to the grid (as defined by RMI). Systems are typically situated near or within the communities, helping to drive down transmission losses. The critical item with CSS is understanding how to implement and finance virtual net metering for the community, in which each household receives a portion of the benefit while typically providing a portion of the financing. The following research areas will help to improve implementation of community scale solar and virtual net metering:

1. **Unified virtual net metering framework:** There is currently no unified regulatory framework to support virtual net metering for community scale solar. Proper valuation of CSS (and other DERs), is critical to market adoption and effective operation.
2. **Packaging of CSS with other distributed energy resources:** There is ongoing research to identify packages that pair CSS with other DERs (storage, energy efficiency, etc.) to provide increased value to the customer and the grid. As system complexity increases, the compensation framework will be forced to evolve.
3. **Real world demonstrations:** Once the virtual net metering framework has been established, demonstration projects will be needed to evaluate performance and acceptance of the framework. Real world demonstrations will also be key in evaluating and optimizing the packaging of CSS with other DERs.
4. **Innovative financial models:** There is a need for innovative financial models to finance CSS, especially in disadvantaged communities.
5. **Impact Assessment**: There is a need for the assessment of the impact of virtual net metering on community level energy consumption.

PV coupled Storage

The integration of PV + Storage onto the grid at a community or premise level has garnered much attention due to the possibility for it to provide customer benefit through energy and cost savings (with quick ROI) and grid benefit through load shifting, demand response, voltage regulation etc., assuming the proper rate structures and value propositions are implemented. Research needs prior to increased market penetration include:

1. **System management and integration:** As utility rate structures adapt to incentivize PV + storage systems, there is a need for easily integrated, localized storage management for optimal performance and cost savings.
2. **System availability for small commercial sizes:** Battery system sizes have tended to be designed for residential or larger commercial applications, with little focus on small commercial with battery sizes of 10-100kW. There are few storage systems that supply 3-phase power at ~10kW range, which meet both the needs for small commercial applications (3-phase power with 10-100kW storage).
3. **Standardized communication and controls:** There is a research need for development of one, standard communication protocol that can communicate with and control all different distributed energy storage types and manufacturers.
4. **Interconnection issues for battery storage:** Process and rule constraints for interconnection of batteries are complex and expensive. There is a need for a streamlined process.
5. **Further project demonstrations:** As solar + storage proves its capabilities, further demonstrations at both a community level and a premise level are needed to quantify the actual value (both monetary and synergistic) of the controllability and grid applications that battery storage paired with PV can have. Which value streams and control strategies make the most sense in practice (highest ROI) and are most utilized? Varying rate structures and market signals (TOU, DR, ancillary services etc.) need to be tested and their impact quantified. At the right rates and with the right value streams, PV + storage makes financial sense.

Thin Film PV

Thin film PV refers to PV technology with active layers nearly 100 times thinner than typical c-Si panels, allowing for reduced material consumption, flexibility, building integration and transparency. Current technologies include Cadmium telluride, amorphous silicon, and copper indium gallium selenide, with emerging technologies including perovskites. Although adaptable for many applications, thin film PV requires more space due to lower efficiencies, which can be a limiting factor for applications with finite area constraints. Research in the following areas is needed for increased product deployment:

1. **Increase in Efficiency:** Research in improved design and composition of thin film PV in order to increase efficiency and reduce cost and space requirements. Reduction of production costs for Copper Indium Gallium Selenide (CIGS) and Gallium Arsenide panels in order to provide higher efficiency panels (20-25 percent) at a comparable cost.
2. **Project demonstrations:** Various demonstrations to identify optimal building types to benefit from thin film while also testing panel durability. Would be useful to look at a cost and energy impact assessment of thin film building integrated PV.
3. **Emerging thin film technologies:** There is a need for proven product performance since many emerging PV absorbers lose power at a fast rate and are considered unreliable.

Emerging thin-film technologies (i.e., perovskites) have seen high power at low cost, but reliability remains an issue. Field testing through project deployment and analysis is needed to quantify reliability and field performance.

Higher Efficiency PV Integrated Electrochromic Windows

While electrochromic (EC) technology has been developed for some time, the integration with photovoltaic (PV) and electrochromic (EC) devices provides better efficiency in energy saving without additional power sources. Researchers that integrate photovoltaic technology have provided diverse application of electrochromic devices, for instance, building integrated photovoltaic (BIPV) solar cells may be incorporated with the electrochromic technology to automatically adjust the colors of electrochromic windows to reduce indoor heat. (Source: NREL)

Fully integrated electrochromic PV includes PV throughout the entire panel, taking advantage of both PV as a distributed generation resource for the building as well as powering the small draw for the electrochromic changes. The fully integrated panel produces energy while reducing building cooling or heating loads through the electrochromic response. Typical applications have utilized PV and electrochromic windows as separate assets or integrating only small PV cells in the windows to produce enough energy for the electrochromic response. Full integration of the two products is ideal for space limited applications, but must be further researched in the following areas:

1. **Product Improvement**: Research into the integration of PV and electrochromic windows to provide a single product that produces energy and reduces overall building HVAC use by shading and reducing internal heat gain. The technology is still very new and mostly only laboratory tested.
2. **Building integration for retrofit applications:** Demonstration retrofit projects to identify feasibility of integrating BIPV into existing buildings.
3. **Increase in efficiency of PV generation:** Research into increased efficiency from the PV cells in order to reduce percentage of glazing that must be PV integrated.
4. **Pilot Projects:** Need for new construction pilot demonstration projects to properly quantify impact of BIPV on PV generation as well as the impact of the electrochromic technology on reducing building consumption. Side by side comparisons of PV integrated electrochromic and typical electrochromic would be useful to compare performance and cost tradeoffs.

Table 19 summarizes the key research gaps and cost and performance targets for some of the highest priority distributed generation technologies.

Table 19: Distributed Generation Technology Shortlist

Technology	Key Research Gaps	Cost and Performance targets for 2025
Community Scale Solar (Virtual Net Metering)	Impact Assessment Unified virtual net metering framework Packaging of CSS with other distributed energy resources Real world demonstrations Innovative financial models	**Cost Target:** Current levelized costs: $50/MWh Current costs for CSS are competitive with central generation and distribution. A monetary target will be to have appropriate compensation through virtual net metering. **Performance Target:** Efficiency performance will match that of PV panel improvements, but otherwise it is difficult to quantify a direct performance target. The main target is to have a standard framework for virtual net metering that will help to incentivize further CSS.
PV coupled Storage	System Management System availability for small commercial sizes Standardized Communication and controls Interconnection issues for battery storage Project demonstrations	**Cost Target:** Battery storage needs to hit $125-$165/kWh with solar deployed at $1/W. At these costs, the total levelized system cost would be ~$0.11/kWh (GTM) to ~$0.14/kWh (EPRI). **Performance Target:** Further integration and control of PV + storage to tap into varying value streams. PV efficiencies: • Single-crystalline: 25% • Multi-crystalline: 21% • Thin film Si: 15% • CIGS: 18% • CdTe: 15% Si consumption of less than 2g/W (data from IEA)

Thin film PV	Increase in Efficiency Project demonstrations Emerging thin film technology evaluation	**Cost Target:** Residential goal for 2030: \$0.05/kWh Commercial goal for 2030: \$0.04/kWh These numbers are for PV in general, not specifically thin-film. Currently thin-film and c-Si are comparable in cost. **Performance Target:** 15-20% efficient PV module with a 30-year lifetime
Higher efficiency PV integrated electrochromic windows	Product Improvement Building integration for retrofit applications Increase in efficiency of PV generation Pilot Projects	**Cost Target:** For electrochromic technology (not PV integrated): current costs are \$8/square foot with \$2/square foot install premium; payback period of 7-21 years. Installed cost premium <\$5/square foot. For PV integrated electrochromic technology, costs need to reach targets for the standalone electrochromic tech (above) while also matching the installed cost of a separate PV system (\$2.5-\$4/watt) **Performance Target:** Integration of electrochromic windows with storage, generation and control. • actively controlled windows with a visible transmittance (Vt) of >0.6 for bleached state in residential and >0.4 in the commercial sector. • PV generation needs to hit 10% efficiency (lab), 8% for full window • 50% potential reduction from lighting consumption • 10 yr. lifetime

Source: Itron Team Staff

Energy Storage

Solid-State Batteries

Solid-state batteries use a solid electrolyte layer instead of a liquid electrolyte. The costlier solid electrolyte layer allows for longer lifetimes, increased safety and higher energy density. There is still much work needed before market adoption, especially with a timeline of around five years to there being a market-ready solid-state battery. Research requirements include:

1. **Improvement of lithium-ion mobility**: Continued research in improving the mobility of lithium ions through materials and across interfaces is necessary, as well as research into ideal material and interface configuration.
2. **Pilot Projects:** Testing outside of lab environments is required to understand in field performance of solid state (includes EVs since EVs drive the market and the battery technology will then trickle down to residential/commercial storage applications).
3. **Cost reduction:** Cost is a big deal breaker for solid-state battery technology. Costs can be driven down through research into inexpensive chemicals to replace the semiconductor grade chemicals, as well as development of high throughput manufacturing processes once scale is achieved.
4. **End of life disposal:** As the technology evolves, the end of life disposal must always be considered from a cost and sustainability perspective. Steps should be taken to understand what the recycling/decommissioning of the battery units will look like.

Lithium-Ion Batteries

Implementation of lithium-ion batteries for residential and commercial storage applications gains traction as the opportunity for added value through utility incentives (rate structures, reduction of demand charges, etc.). From a ZNE (net kWh) perspective, storage is not necessary, but it is essential to mitigating the negative impact that ZNE has on the grid (the duck curve) and can provide other ancillary services. Driving lithium-ion costs down and improving performance and life cycle will be crucial to increasing adoption; alongside the following research opportunities:

1. Combination of improved cathodes and electrolytes without sacrificing cycle life. Although the performance characteristics of cathodes, anodes, electrolytes and separators continue to improve, the low number of cycles, along with safety and capacity degradation remain as concerns.
2. Research is required to understand the expected life cycle cost through the disposal and recycling of batteries. Research into the design of better systems to prepare for ease of disposal and recycling.
3. Focus areas include new chemistry blends, resilient electrolytes, material and system design for better thermal management, and battery energy and power density improvements (EPRI 2018).
4. From a system perspective, research into the value of stacked benefits of storage is crucial to improving adoption. Not to mention, this is a more feasible research opportunity for the Energy Commission as much of the performance and technology research is performed at a product manufacturer level.

Table 20 summarizes the key research gaps and cost and performance targets for some of the highest priority energy storage technologies.

Table 20: Energy Storage Technology Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
Solid-state batteries	Improvement of Lithium Ion mobility Pilot Projects Cost reduction End of life disposal	**Cost Target**: ~$0.20/kWh life cycle cost. Comparable to lithium ion and lead acid. More typical metric is to look at upfront cost: Will need to reduce to $100-$200/kWh to compete with lead acid. Projected 2030 cost of lithium ion is $73/kWh. **Performance Target:** 80-90% depth of discharge, 10,000 cycles • 200-250 Wh/kg • 300-400 W/kg
Lithium-ion Batteries	Technology improvement Life cycle cost analysis Performance improvements Value stacking testing	**Cost Target:** Cell level: • DOE: Cost target of $125/kWh by 2022 • Bloomberg New Energy Finance: Target of $70/kWh by 2030, ~$96/kWh by 2025 System level: • By 2020: $500-600/kWh **Performance Target:** 95% round trip efficiency, 20 yr. battery life, 7000 cycles (consistent), equivalent to natural gas turbine in terms of safety and performance

Source: Itron Team Staff

Grid Interaction/Smart Grid Connectivity

DC Microgrids/Buildings

Introducing DC electric distribution and appliances inside buildings to reduce conversion losses could be a promising energy efficiency measure for new construction. The DC current produced from a PV panel (and stored in a DC battery) is typically converted to AC, then converted to DC at the appliance/product level and results in efficiency losses. A DC system will reduce system complexity and losses but added grid infrastructure may be needed for DC grid connectivity. Exploration of hybrid AC/DC systems in which a building is simultaneously using DC and AC could help transition from purely AC to DC. Other research questions or gaps include:

1. How can DC arcing be prevented, detected and extinguished effectively at a low cost? DC arcing can be stable and prolonged which tends to cause more damage and is harder to detect with protection equipment like AFCIs due to the different signature frequencies. This characteristic is not desired or safe in homes and buildings.
2. Higher efficiency DC: DC conversion for maximum power point tracker and charge control, as well as for utilization equipment. Efficient DC: DC conversion is possible, however many of the existing charge controllers are less efficient than available inverters. Utilization equipment also still needs another DC: DC conversion stage to get from the battery voltage to the voltage needed by the connected equipment. So, the expected efficiency gain may not be there with current technology.
3. Is installing high voltage DC distribution in buildings safe or, if not, can it be made safe? Low voltage distribution is less efficient and would require impractically thick copper cable size, but can high voltage DC be installed safely?
4. How can small, inexpensive, consumer grade VFDs be created and embedded in products designed for direct DC input to run motors in common applications such as air conditioners, dryers, pool pumps, ceiling fans, garage door openers, etc.?
5. What are the real benefits of DC utilization, and how can they be clarified to consumers? Selection of consumer devices that will run from higher voltage DC without modification is quite limited to non-existent. Materials for creating DC utilization infrastructure (breakers, outlets, switches, boxes, and wiring) that are designed and listed for DC are either expensive or non-existent. The apparent benefit to consumers of having a DC bus are minimal, perhaps a small efficiency gain. So, the benefits need to be maximized and clarified in order to generate consumer interest. If no consumer interest is generated companies will not enter this market to fill the niche.

DER Integration Controls

This area includes utility level controls of distributed energy resources (PV, battery storage, thermal storage, controllable loads, etc.) to balance the “duck curve” load shape. Controls include optimization algorithms to translate and appropriately respond to rate signals and other utility signals. Used at the appropriate times and appropriate capacities, DERs can help unload the distribution system during peak hours. Similarly, thoughtful use of smart inverter controls can help utilities better manage voltage at transformers and distribution feeder segments. Conversely, discharge of net electricity onto the grid at times of low demand can lead to increased reliability and system protection issues. Implemented appropriately, integrating combinations of DERs across the distribution system level can provide significant benefits to utilities and their customers. Current research needs include:

1. Software required to enable device data exchange between different DER elements and utility portals.
2. Standardization of impact analysis and baselining as well as a common controls platform for all DERs. There is a necessity for cohesive controls that are compatible with all DERs (existing and future).
3. Field implementations to better understand operational performance of controls and the feasibility of DER controls.

4. Need for a controls platform and algorithm to optimize DERs according to pricing signals, GHG reduction goals, and grid needs while maintaining customer comfort.
5. Must resolve interoperability issues through standards and protocols in order to reduce barriers to an open market place.
6. DOE Recommendations:
    - "Additional R&D on methods and tools to ensure appropriate time, location, and product-specific valuation of DER, efficient integration of DERs into power system planning and operations, and improved market models for more efficient pricing of the electric products and services that DERs provide."
    - "Continuing R&D on tools, including computational methods for managing operations with more dynamic and distributed grid, simulation tools to understand system behavior in high DER environment, and research on the interactions and balance in markets with DER." (Centolella 2017).

Table 21 summarizes the key research gaps and cost and performance targets for some of the highest priority grid interaction technologies.

Table 21: Grid Interaction Technology Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
DC Microgrids/Buildings	Demonstration Projects Evaluation of Grid Impact Standards Evaluation of construction and permitting process for DC systems. Safety evaluation	**Cost Target:** If creating a DC microgrid, costs decline due to the less amount of equipment needed (i.e. inverter), but the appliances and DC products within the building have an added cost. Need for DC appliances and equipment costs to decline to AC product levels. **Performance Target:** Systems that are as safe as AC systems. Hybrid AC/DC systems that run both AC and DC at the same time.
DER Integration Controls	Software Standardization of controls platforms Field implementation Optimized control platforms and algorithms	**Cost Target:** There is a need for a utility TOU rate to encourage adoption of DER controls which would result in product manufacturers to innovate and build to interoperability specifications. The rate needs to understand societal cost and must reflect decarbonization goals. ROI from implementing controls must be greater than the ROI of infrastructure upgrades to deal with high fluctuations in load shapes (especially as a push for electrification increases overall demand). The added cost from a product perspective is minimal (i.e.

		controllable smart thermostats are cost competitive). Cost of data access and storage will be substantial, but it is difficult to quantify. **Performance Target:** Ability to control at a premise or community level as opposed to individual widget-based controls. Ability to optimize storage assets (thermal and battery) by controlling responses to varying signals.

Source: Itron Team Staff

Technology Solutions to Address Other Areas

While energy use cannot be directly attributed to technology solutions, the potential energy reduction and market impact for these software-based tools may be significant. Nearly all areas of building energy use may be supported by these technology solutions or tools, including HVAC, plug loads, lighting, and others. These tools may also influence new construction building design toward improved energy performance as they provide feedback for building designers about the anticipated outcomes of their designs. The focus of this category is on building design tools (greenhouse gas modeling, occupant behavior modeling) and building operational tools (real time energy management, commissioning tools for residential connected devices).

Technology Research Gaps

Most of these technologies or tools have informational research gaps. The tools are performing as intended but could use some improvements to their inputs and assumptions for their accuracy and reliability which will ultimately drive design and operational performance improvements.

1. Carbon footprint analysis tool (GHG modeling): New developments in the private sector are coming up with a more complete understanding of the grid impact of building energy use with sophisticated time-of-use models. The current practice for building design is to use state-by-state inputs for carbon and pollution impacts of a building's energy use. While this is acceptable as a means to improve building design from the status quo of not considering pollution from buildings at design, future improvements to the model's assumptions would be beneficial with the approach a low-carbon grid and time-of-use becomes more significant for targeting carbon emissions.
2. Real time energy management: There are many existing tools on the market for real time energy management, ranging from automated energy and load shape reporting to automated fault detection and diagnostics. The tools within this scope are highly developed and do not have general research gaps. More sophisticated versions of real time energy management would include model-based building controls and optimization, which have opportunities for technical improvement and development (See: Predictive (data analytics based) Controls). These sophisticated next-generation tools still need work on automated model development and calibration algorithms in order to bring down costs and improve scalability. The goal for this tool is to have an

automatically calibrating and improving real time model of the building in order to optimize performance for energy, costs, and other user-defined metrics (e.g. carbon or grid harmonization).

3. Commissioning app for residential connected devices: This tool is in the proof of concept stage. The primary research areas would include device connectivity solutions (Wi-Fi, radio, etc.), algorithms to identify optimization and faults for these devices, and a compelling user interface that incorporated occupant behavior strategies to incentivize action from building occupants or homeowners.
4. Occupant behavior modeling: The technical aspects of occupant behavior modeling are resolved. The main shortfall of this tool is the lack of feedback from the field on how occupants are behaving and to what degree various factors are influencing the behavior. Developing a standard methodology to study occupant behavior with building design in mind would be a good start to allow researchers to conduct field studies to improve model assumptions and properly account for variations in age, gender, region, building type, occupant type, industry, culture, etc. and determine which of these variables affects occupant behavior and how. From there, building designers could use that feedback to design buildings that encourage occupants to use less energy with both passive (i.e. building design) and active (for example dashboards) solutions.

Table 22 summarizes the key research gaps and cost and performance targets for some of the highest priority technology solutions to other ZNE barriers.

Table 22: Other Technology Solutions Shortlist

Technology	Key Research Gaps	Cost and Performance Targets for 2025
Carbon Footprint Analysis tool (GHG modeling tools for building design)	Standard methodology for studying and reporting occupant behavior in a way that can meaningfully provide feedback to building energy models and designers Improvements to the granularity of carbon emission assumptions (both spatial and temporal)	**Cost Target:** This tool is available for free in EnergyPlus **Performance Target:** Performance is not easily quantifiable or measurable and will rely on the accuracy of the model's inputs
Real Time Energy Management Software	Under the current scope of this tool, there are no gaps. The future potential for this tool would need development of self-calibrating and self-developing real-time building and control models	**Cost Target:** \$1-2/ft² of building area **Performance Target:** Performance will depend on baseline, but should target 10-20% energy savings
Commissioning app for residential connected devices	Universal device connectivity or translator to ensure full incorporation of residential devices	**Cost Target:** Unknown at the moment. Will likely need to be below \$100 but should be tied to

	Development of mobile app and computer software Development of rule-based or other solution to flag devices that need adjustments	eventual value proposition of the tool. **Performance Target:** Performance will be measured in accurately identifying issues with connected devices, which should be targeting 100% accuracy.
Occupant behavior modeling	No technical gaps but understanding of drivers of occupant behavior and outcomes of building designs in the field are largely unknown. Need to understand and quantify factors that affect occupant behavior and their energy use.	**Cost Target:** EnergyPlus is available for free. **Performance Target:** The tool’s performance will depend on the inputs developed from further research in the field. Given the stochastic nature of human behavior, performance will be difficult to pin down.

Source: Itron Team Staff

Research Priority Recommendations

The priority frame is a flexible tool which can help the Energy Commission assess the relative priority of funding research for a particular technology or set of technologies based on the preferences and alignment with policy directives. While the Energy Commission can set weights to each of the criteria to make that assessment, a few scenarios were presented that could be considered as examples for defining the priority weights. The tool returns a priority index for each of the 150 technologies that are provided. However, additional technologies can always be added to the list along with their scores for each factor to make them a part of the assessment framework. It is important to remember that the absolute value of the index is not crucial, but it is more important as a comparison with other technologies.

Table 23 provides a description and example list of high priority technologies for an example set of scenarios.

Table 23: Examples of Scenarios with Suggested Factor Weights and High Priority Technology

<table>
<tr><th>Scenario</th><th>Energy Impact</th><th>Load Shaping</th><th>GHG Reduction</th><th>Technology Readiness</th><th>Community-scale</th><th>Site level</th><th>All electric</th><th>Mixed-fuel</th><th>X-factor</th><th>Total</th><th>High Priority Technologies</th></tr>
<tr><td rowspan="2">Site level
Mixed-fuel</td><td colspan="10">The traditional scope and fuel mix scenario with a focus on energy benefits. This scenario places higher weight on the relevance of site specific and mixed fuel factors and does not apply to the community scale and all electric relevance.</td><td rowspan="2">• Radiant Heating and Cooling
• Air Sealing
• Electrochromic Fenestration
• Advanced lighting controls systems (ALCS)
• Vacuum Insulated Panels</td></tr>
<tr><td>20</td><td>7.5</td><td>7.5</td><td>5</td><td>0</td><td>20</td><td>0</td><td>20</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Site-level
All-electric</td><td colspan="10">The site level scope but all electric fuel switch benefit, which includes the GHG reduction and load shaping potential along with overall energy benefits as important criteria.</td><td rowspan="2">• Radiant Heating and Cooling
• Air Sealing
• Electrochromic Fenestration
• Advanced lighting controls systems (ALCS)
• CO2 heat pump water heaters</td></tr>
<tr><td>20</td><td>7.5</td><td>7.5</td><td>5</td><td>0</td><td>20</td><td>20</td><td>0</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Community-scale
Mixed-fuel</td><td colspan="10">Defining the scope of ZNE as a community/ campus/ district rather than an individual building but in the mixed fuel realm, where overall energy benefit is the primarily focus.</td><td rowspan="2">• Advanced lighting controls systems (ALCS)
• Ground Source Heat Pumps
• Central Heat pump water heater
• Radiant Heating and Cooling
• Predictive (Data Analytics based) controls</td></tr>
<tr><td>20</td><td>7.5</td><td>7.5</td><td>5</td><td>20</td><td>0</td><td>0</td><td>20</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Community-scale All-electric</td><td colspan="10">Defining the scope of ZNE as a community/ campus/ district rather than an individual building but in the all-electric mode. This scenario values, GHG reduction and load shaping potential along with energy benefits.</td><td rowspan="2">• Central Heat pump water heater
• Advanced lighting controls systems (ALCS)
• Ground Source Heat Pumps
• CO2 heat pump water heaters
• Grid integrated heat pump water heating</td></tr>
<tr><td>20</td><td>7.5</td><td>7.5</td><td>5</td><td>20</td><td>0</td><td>20</td><td>0</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">GHG
Reduction</td><td colspan="10">The primary focus is on technologies that have the highest GHG reduction potential, and agnostic about applicability to scope and fuel type.</td><td rowspan="2">• Radiant Heating and Cooling
• Higher efficiency PV integrated electrochromic windows
• CO2 Heat pumps
• Ground Source Heat Pumps
• PV coupled Storage</td></tr>
<tr><td>20</td><td>10</td><td>40</td><td>5</td><td>0</td><td>0</td><td>5</td><td>0</td><td>20</td><td>100</td></tr>
<tr><td rowspan="2">Grid focus</td><td colspan="10">The primary focus here is on the load shaping potential of technologies, along with energy benefit. All other criteria are somewhat equitable.</td><td rowspan="2">• Predictive (Data Analytics based) controls
• CO2 heat pump water heaters
• Grid integrated heat pump water heating
• CO2 Heat pumps
• PV coupled Storage</td></tr>
<tr><td>20</td><td>40</td><td>10</td><td>5</td><td>0</td><td>0</td><td>5</td><td>0</td><td>20</td><td>100</td></tr>
</table>

Early stage research priority	Focus on funding early-stage technology readiness level (TRL) technologies, agnostic to scope and scale of applicability. Primarily driven by supporting research to further nascent technologies with high potential across, energy, load shaping and GHG reduction criteria.										• Higher efficiency PV integrated electrochromic windows • Electrochromic Fenestration • Building Integrated PV (BIPV) • Membrane heat pump • Thermoelastic / Elastocaloric cooling
	20	7.5	7.5	-45	0	0	0	0	20	100	
Market facilitation focused research priority	Focus on funding market ready technologies with high potential across, energy, loading shaping and GHG reduction criteria.										• Radiant Heating and Cooling • Predictive (Data Analytics based) controls • Air Sealing • Central Heat pump water heater • Air-to-water heat pumps
	20	7.5	7.5	45	0	0	0	0	20	100	
Custom	This scenario can be anything based on policy alignment and focus on any of the factors										
	?	?	?	?	?	?	?	?	?	100	

Source: Itron Team Staff

Recommendations for Future Work and Updates

The project kept a focus on the primary objective of providing the Energy Commission information for targeting and shaping future EPIC solicitations to support the State's ZNE goals. The background work conducted was primarily conducted in 2017, and any technology assessment, if based in this time and can date itself by the time the Energy Commission wants to act on it. Therefore, the approach of providing the due diligence of information along with the framework is best served if kept updated and enhanced with evolving research, policy and markets. Enhancements and updates to the prioritization framework zTAP tool:

1. The technology list of 106 should be expanded as more are considered and must be part of the relative priority assessment mix. The framework provides the structure to collect and input a technology.
2. The background assumptions and actual scores in the framework should be reviewed and updated at the time of near term use to be more relevant.
3. The energy impact calculator is a core part of the objective assessment and is based on the currently available data for CEUS 2005 and RASS. However, this should be updated when newer values for these data are available through other parallel work. Especially the end use proportions could be changing since the last update and impact the energy benefits assessment for technologies applicable in an end use.
4. The GHG impacts are currently scored on judgement and can be better served when associated with a GHG impact calculator, similar to the energy impact calculator. Making the scores more objective where possible.
5. Similarly, the load shaping potential factor can also be further enhanced with more objective calculations-based assessment.
6. The TRL for technologies should also be updated over time to keep it more relevant when assessments based on stage of development are made.
7. The X-factor is custom factor and should also be carefully reviewed and updated at the time of use. The X-factor currently is a wild card externality that would encourage or discourage the Energy Commission for supporting research funding for a technology. Such as funding by another agency. However, in the future this factor can be morphed to best fit the use by the Energy Commission.

8. The prioritization framework, while developed for the primary use by the Energy Commission, can lend itself to expanded use cases and extend to the coordinating agencies and efforts such as the CPUC and IOU Emerging Technology Programs. Additionally, other jurisdictions and agencies such as CCAs and local governments can use it to drive technology focus based on their policy objectives. The framework can be tweaked to accommodate and address the needs and wants of agencies with purposes to ease through weights and scenario setups that best match their respective needs.

ABBREVIATIONS AND ACRONYMS

Term	Definition
AC	Alternating current
ADR	Automated demand response
ALCS	Advanced lighting control systems
B2G	Building-to-grid
BIPV	Building-integrated photovoltaics; solar cells or modules that are incorporated into the roof, windows, or facades, replacing conventional building materials.
BTM	Behind-the-meter
CPUC	California Public Utilities Commission
CSI	California Solar Initiative
DC	Direct current
DHW	Domestic hot water; water that is heated for household purposes, such as drinking, food preparation, sanitation, and personal hygiene.
DR	Demand response, a change in power consumption to better align with utility supply.
EE	Energy efficiency, reducing the amount of energy required to perform the same service; energy waste reduction
Energy Commission	California Energy Commission
EPRI	Electric Power Research Institute
HPWH	Heat pump water heater
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality

M&V	Measurement and verification
PEV	Plug-in electric vehicle
PPA	Power purchase agreement; a contract for the purchase of electricity
RDD&D	Research, Development, Demonstration and Deployment
SEER	Seasonal energy efficiency ratio, used to measure the energy performance of air conditioners
State	State of California
TAC	Technical Advisory Committee; a group of qualified professionals in the ZNE building sector selected to provide guidance on project direction.
TDV	Time Dependent Valuation; an energy code for modeling energy based on the utility cost value of energy.
Title 24	California Building Energy Efficiency Standards
TRL	Technology readiness level
V2G	Vehicle-to-grid; communication between electric vehicles and the grid to return electricity or throttle charging rate when needed.
ZNE	zero net energy

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International Energy Agency, "Technology Roadmap – Energy-Efficient Building Envelopes" (2013)

US Department of Energy, Building Technologies Office, "Research & Development Roadmap for Emerging HVAC Technologies" (2014)

US Department of Energy, Building Technologies Office, "Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies" (2014)

Northwest Energy Efficiency Alliance, "NEEA Emerging Technology Report" (2017)

Bonneville Power Administration, "National Energy Efficiency Technology Roadmap Portfolio" (2014)

APPENDIX A: Stakeholder Survey Questions

Survey 1

Introduction

The State of California has "big, bold" energy goals for the building design and construction industry:

- All new residential construction should be zero-net energy (ZNE) by 2020
- All new nonresidential construction should be ZNE by 2030

Our team is working on a California Energy Commission project to identify research gaps in technologies and tools needed to meet these goals. The traditional definition of ZNE or zero-net energy implies buildings, or portfolio of buildings, that are designed to produce onsite renewable energy that equals or exceeds their annual energy use. However, for the purpose of this survey, a wider perspective was used that includes but is not limited to; very high energy performance buildings with renewable generation, nearly zero energy buildings, carbon neutral buildings and campuses, limited or very low peak energy use, flat load profiles, and other similar definitions. We understand that it is difficult to provide simple answers on such complex topics, but please provide your best current perspective. We are seeking relative importance, not precise responses. The survey should take approximately 10-15 minutes.

Thank you for helping inform the State's research agenda through your expertise and insight. Your response to the survey will be kept anonymous and only used in aggregate to inform the project. We really appreciate and value your time and input on this survey.

THANK YOU!

For more information on the project please visit the website:

http://zneroadmap.researchenergy.net/

If you have any questions about this survey please email: smita.gupta@itron.com.

Role and Relationship to ZNE

1. What is the geographic scope of your work? Check all that apply.
    - Within California
    - Other State(s)/province(s)
    - National
    - International

2. In which sector(s) do you work? Pick the one that most represents your current work and perspective for the responses that follow.
   - Residential (single family and/or low rise multifamily)
   - Commercial and/or high-rise multifamily residential

3. What is your primary occupation? Pick the one that most represents your current work and perspective for the responses that follow.
   - Appraiser
   - Architect/designer
   - Building official
   - Building owner
   - Contractor (general, HVAC, electrician, etc.)
   - Educator
   - Energy consultant/analyst
   - Facility manager
   - Financier/lender
   - HERS rater
   - Land use planner
   - Local government
   - State or federal agency
   - Manufacturer
   - Real estate agent
   - Real estate developer
   - Solar industry
   - Student
   - Utility
   - Design Engineer
   - Add comment to explain if needed

Challenges to ZNE

4. Please rate your familiarity with technologies, tools, equipment, and/or software used in ZNE* projects. *Rate high even if you are familiar only with a specialized area, such as mechanical equipment.*
   ** The traditional definition of ZNE or zero net energy implies buildings, or portfolio of buildings, that are designed to produce onsite renewable energy that equals or exceeds their annual energy use. However, for the purpose of this survey a wider perspective was used that includes but is not limited to; very high energy performance buildings with renewable generation, nearly zero energy buildings, carbon neutral buildings and campuses, limited or very low peak energy use, flat load profiles, and other similar definitions.*
   - 1 - Not at all familiar
   - 2 - Slightly familiar

- 3 - Moderately familiar
- 4 - Highly familiar
- 5 - Very highly familiar

5. How significant a challenge does each of the areas below pose to adoption of ZNE and high-performance buildings in general? *Rate on a score of 1-5. (1 – Not significant, 2 – Slightly significant, 3 – Moderately significant, 4 – Highly significant, 5 – Very highly significant).*
   - Technology limitations
   - Designer knowledge/skill
   - Building trades knowledge/skill
   - Perceived costs
   - Financing & appraisal
   - Occupant health/indoor air quality
   - Occupant behaviors
   - Planning/permitting
   - Governmental policies
   - Buyer acceptance
   - Developer acceptance
   - Environmental factors (environmental impact reports (EIR), etc.)
   - Utility rate structures, service connection costs and rules
   - Utility incentive programs
   - Energy code compliance
   - Aesthetic considerations

6. Describe the three most significant challenges/barriers to achieving the ZNE goals. *Open-ended response.*

7. If you could have your wish granted for a single "silver bullet" solution to get buildings to ZNE, what would you ask for? *Open-ended response.*

General Input (for respondents answering 2 or lower on Q4)

8. In your view, what priority should be placed on research for the areas listed below? Please indicate the level required to support ZNE adoption. For example, the areas that need more research will get high priority rating versus areas that are fully mature and don't need more research and get a low or no priority rating. That does not mean they are not significant, but just more mature as a technology that doesn't need more research focus. *Rate on a score of 1-5. (1 – Not a priority, 2 – Low priority, 3 – Moderate priority, 4 – High priority, 5 – Very high priority).*
   - Renewable energy (solar, wind, etc.) & storage technologies
   - Building energy efficiency & energy conservation
   - Design tools (e.g., software)

- Contractor training and certification
- Smart operations & building controls
- Occupant-focused solutions – e.g., influence occupant behavior
- Electric distribution system improvements, e.g., grid reliability
- Building-to-grid integration solutions
- Utility rate structures
- Others (please specify)

Technology Input (for respondents answering 3 or higher on Q4)

In your view, what priority should be placed on research for the areas listed below? Please indicate the level required to support ZNE adoption. For example, the areas that need more research will get high priority rating versus areas that are fully mature and don't need more research and get a low or no priority rating. That does not mean they are not significant, but just more mature as a technology that doesn't need more research focus. *Rate on a score of 1-5. (1 – Not a priority, 2 – Low priority, 3 – Moderate priority, 4 – High priority, 5 – Very high priority).*

9. Building Envelope and Equipment
   - Lighting
   - Space heating
   - Space cooling
   - Mechanical ventilation
   - Natural or passive ventilation
   - Windows/fenestration
   - Envelope/façade (wall, roof, attic)
   - Water heating (distribution and use)
   - Appliances
   - Plug loads
   - Other; describe and give a numeric priority value (1-5) for research

10. Controls
    - Smart/integrated systems, automation, and controls
    - Tools to facilitate optimized operations/management (e.g., glass
    - cleaning)
    - Building management systems
    - Occupant/behavior-focused solutions
    - Demand Response
    - Other; describe and give a numeric priority value (1-5) for research

11. Renewable Energy, Storage & Electric Grid
    - Solar photovoltaic
    - Solar Thermal (hot water, including PVT and tri-generation)

- Other distributed generation/renewables (CHP, wind,
- geothermal, et al)
- Battery storage
- Thermal storage
- Building to grid integration (grid harmonization)
- Microgrids and Nanogrids (campus and building level distribution
- systems)
- Electric vehicle charging
- Other; describe and give a numeric priority value (1-5) for research

12. Other/Miscellaneous
    - Utility rate structures
    - Community-scale ZNE
    - Code compliance modeling software
    - Design tools (e.g. to support integrated building design, design-bid-build,
    - etc.)
    - Construction/commissioning tools (e.g., best practices,
    - protocols, diagnostics, training/certification)
    - Greenhouse gas (GHG) impact calculation tools and
    - methodology
    - All-electric-buildings
    - Other; describe and give a numeric priority value (1-5) for research

13. Please let us know your areas of technical expertise. *Check all that apply.*
    - Building Envelope (roof, wall, attic,
    - windows)
    - HVAC
    - Lighting
    - Plug Loads
    - Demand Response
    - Building Controls
    - Behavioral Research
    - Construction/Commissioning
    - Distributed Generation (Solar, wind,
    - CHP et al)
    - Grid Integration
    - GHG Impacts
    - Public Health/Safety
    - Smart Grid Controls
    - Water Efficiency
    - Other (please specify)

14. Would you be willing to respond to a follow-up survey in a few weeks from now about specific technologies within your area(s) of expertise? We would really appreciate your input.
    - Yes
    - No

Email for follow up survey (for respondents answering Yes on Q14)

15. Please provide your email address. *This will not be used or shared for any purpose other than to provide the follow-up survey.*

Thank You

Thank you for completing this survey! We really value your input and appreciate your time and effort.

Survey 2

Introduction

This is a follow-up survey to an earlier one which asked about research priorities for ZNE at a high level. This survey focuses on specific technologies with the potential to advance ZNE and barriers to their adoption. Your input will help California prioritize its research investments.

You will be asked initially about one technology (of your choice), after which you may opt to respond about one additional technology (for a total of two technologies). The responses for each technology should take approximately 5 minutes. For each technology you choose, you will be asked about its:

- Energy impact
- Applicability to climate and building types
- Cost and performance
- Technology maturity and market adoption

If you would like to respond about more than two technologies, you will be given the option at the end to take the survey again. Thank you for your time and valuable input.

For more information, please visit the project website: zneroadmap.researchenergy.net or contact Smita.Gupta@itron.com.

Technology 1

- Please name an innovative or cutting-edge technology that you think has high unrealized potential to advance ZNE. *Open-ended response.*

- Please select the most appropriate technology category for {{Q1 response}}.
  - Building envelope
  - Fenestration
  - HVAC
  - Ventilation and indoor air quality
  - Lighting
  - Plug and equipment loads
  - Demand response
  - Occupant behavior focused technology (e.g., controls, dashboards)
  - Other building level controls
  - Water heating and water reuse related energy use
  - Distributed generation (e.g., solar PV, tri-/quad-gen, CHP, wind)
  - Energy storage (thermal and electric)
  - Grid interaction
  - Technology solutions for implementation/operation aspects

  (e.g., construction/commissioning, energy modeling and design, tools and technologies)
- Any other category not already covered in the list above (please specify)

Building Envelope (for respondents answering Building Envelope on Q2).

All building technologies that relate to walls, roofs and attics.

- Please select the option below that best describes {{Q1 response}}.
  - Phase change material
  - Thermal mass walls
  - Thermal bridging
  - Double-skin facades
  - Ducts in conditioned space
  - Façade-integrated ventilation
  - Insulation
  - Air sealing
  - Roof or attic product/system
  - Other (please specify)

Fenestration (for respondents answering Fenestration on Q2).

- Please select the option below that best describes {{Q1 response}}.
  - Electrochromic glazing/films
  - Thermochromic glazing/films
  - Advanced coatings
  - Thermally broken frames & glazing assemblies
  - Solar (PV) glazing systems
  - Daylight redirecting window films
  - Triple-pane windows
  - Other (please specify)

HVAC

- Please select the option below that best describes {{Q1 response}}.
  - Low ambient radiant convectors
  - Low ambient radiant panels
  - Radiant slabs
  - Variable refrigerant flow (VRF)
  - Variable refrigerant volume (VRV)
  - Air-to-water heat pumps
  - Air-to-air heat pumps

- Heat pumps with storage tanks
- Thermal energy storage
- Liquid desiccant systems
- Energy borefield piles
- Low approach cooling towers
- Brushless DC fan coils (electronically commutated motors,
- ECM)
- Dedicated outside air systems
- Heat recovery chillers
- Heat recovery ventilators
- Heat recovery from exhaust air
- CO2 heat pumps
- Combined heat and power (CHP)
- Chilled beams
- Evaporative cooling
- Indirect evaporative cooling
- High-efficiency air-cooled chillers
- Night flush
- Natural ventilation
- Ceiling fans
- Ventilation cooling
- Cooling tower blowdown water
- Other (please specify)

Ventilation and Indoor Air Quality

- Please select the option below that best describes {{Q1 response}}.
  - Façade-integrated ventilation
  - Night flush
  - Natural ventilation
  - Ceiling fans
  - Heat recovery ventilators
  - Air filters
  - Dedicated outside air system
  - Heat recovery chillers
  - Heat recovery ventilators
  - Heat recovery from exhaust air
  - Dedicated outside air system
  - Ventilation cooling
  - Air quality sensors, etc.
  - Other (please specify)

Lighting

- Please select the option below that best describes {{Q1 response}}.
  - LED
  - OLED
  - High efficacy LED
  - DC powered lighting
  - Light tubes
  - Fiber optics
  - Solar tubes
  - Photosensors
  - Daylighting
  - Light shelves
  - Highly reflective surfaces for daylight optimization
  - Daylight redirecting window films
  - Lighting smart controls
  - Connected lighting systems
  - Advanced lighting controls systems (ALCS)
  - Luminaire level lighting controls (LLLC)
  - Task lighting
  - Lighting controls
  - Other (please specify)

Plug and Equipment Loads

- Please select the option below that best describes {{Q1 response}}.
  - Advanced power strips (e.g., occupancy, activity, remote, Wi-Fi
  - enabled)
  - Power-sensing plug strips
  - Occupant-level control technology
  - Occupancy sensing outlets
  - Wi-Fi enabled outlets and loads for cloud-based computing
  - and control
  - Building-level control technology (Wi-Fi and cloud-enabled)
  - Integrated energy feedback (dashboard/display)
  - Task lighting
  - Security system integrated controls
  - Controllable breakers
  - Energy budget-based controls and optimization
  - Plug load accounting
  - Electric induction cooking ranges
  - Other (please specify)

Demand Response

- Please select the option below that best describes {{Q1 response}}.
  - Automated DR
  - Smart controls and storage for DR
  - Signal response
  - Thermostats
  - Occupant/operator communication
  - Opt-in/opt-out
  - Load disaggregation
  - Other (please specify)

Occupant Behavior-Focused Solutions

- Please select the option below that best describes {{Q1 response}}.
  - Energy dashboards
  - Occupant engagement
  - Integrated energy feedback
  - Occupancy-sensing plug strips
  - Occupancy-sensing outlets
  - Power-sensing plug strips
  - Occupant-level control technology
  - Other (please specify)

Building Controls

- Please select the option below that best describes {{Q1 response}}.
  - Lighting controls
  - Thermostats
  - Open source controls
  - Smart sensors
  - BMS / EMS (building/energy management systems)
  - Fault detection and diagnostics
  - Model predictive control
  - Learning algorithms
  - Fuzzy logic controllers
  - Integrated controls
  - Energy models
  - User friendly controls
  - Smart controls and storage for DR
  - Thermostats
  - Other (please specify)

APPENDIX B: Technology Briefs

This appendix includes details of the high potential and cutting-edge technologies which could be considered for research funding support. They are listed under each of the high-level categories. The details were assembled by the team using literature review, input from stakeholder Survey 2 and subject matter experts, along with the team's own experience and expertise. The technology briefs are typically arranged as consistent fields in three pages for each technology. The briefs include key information on each technology including but not limited to:

- Applicability of the technology to ZNE and in terms of climate and building type
- Cost and performance targets to be met by 2025, where applicable
- Key research gaps
- References and sources for the information

Building Envelope

T001	Air Sealing
T002	Breathing Wall
T003	Building Integrated Heat and Moisture Exchange Panels
T006	Dynamic Building Envelopes
T010	Phase Change Materials
T016	Vacuum Insulated Panels
T004	Building Integrated PV (BIPV)
T005	Double Skin Facades
T009	Night Sky Radiant Cooling (NSRC)
T011	Silica Aerogel Insulation
T012	Structurally Insulated Panels (SIPs)
T013	Straw Bale Wall Insulation/Construction
T015	Trombe Wall

Fenestration

T040	Electrochromic Fenestration
T043	Highly Insulating Windows

T039	Thermochromic Fenestration
T041	Insulation Glass Coating

Heating, Ventilation, and Air Conditioning (HVAC)

T051	Air Source Heat Pumps
T054	CO_2 Heat Pumps
T073	Magnetocaloric Technology
T075	Personal Comfort Systems
T078	Radiant Heating and Cooling
T059	Electrochemical Compression Systems
T062	Ground Source Heat Pumps
T066	Hybrid Heat Pumps (Duel Fuel)
T067	Ice Energy Storage
T068	Indirect Evaporative Cooling
T074	Membrane Heat Pump
T080	Solar + DC Air Conditioners
T082	Thermoelastic / Elastocaloric Cooling

Indoor Air Quality

T124	Heat Recovery - Ventilation

Lighting

T085	Advanced Lighting Controls Systems (ALCS)
T086	Advanced Solid-State Lighting
T087	Direct DC Lighting
T088	Enhanced Daylighting
T089	Fiber-Optic Daylighting
T090	LED Lighting

Demand Response

T160	Dispatchable Storage for Peak Load Management
T151	Automated Demand Response

Other Building Level Controls

T167 Predictive (Data Analytics Based) Controls

Water Heating and Efficiency

T129 Central Heat Pump Water Heater

T132 Grid Integrated Heat Pump Water Heating

T128 Air-to-Water Heat Pumps

T130 CO_2 Heat Pump Water Heaters

Whole-Building Solutions

T168 3D Printing

T169 Predesign Buildings Assembled Onsite

Distributed Generation

T161 Community Scale Solar (Virtual Net Metering)

T162 PV Integrated Electrochromic Windows

T163 PV + Storage

T153 Fuel Cells

T154 Micro CHP

T155 Piezoelectric Flooring

T156 Thin Film PV

T157 Tri-Gen and Quad Gen

Energy Storage

T164 Solid State Batteries

T158 Lithium-Ion Batteries

T159 Redox Flow Batteries

Grid Interaction/Smart Grid Connectivity

T165 DC Microgrid

T166 DER Integration Controls

Other Technology Solutions

T116	Real Time Energy Management Software
T120	Occupant Behavior Modeling
T091	Fault Detection and Diagnostics
T113	Carbon Footprint Analysis Tool (GHG Modeling Tools for Building Design)
T114	Building Design Tool Integrator
T119	Commissioning App for Residential Connected Devices

Plug and Equipment Loads

T091	Fault Detection and Diagnostics
T092	Gamification as a Strategy to Reduce Energy Use
T093	Occupant Level Controls
T094	Predictive Building Controls
T095	Dashboard/Display for Shaping Occupant Behavior
T096	Social Media Platforms
T097	Software & Platforms for Behavior Change Programs
T105	Efficient Cooking Appliances
T106	Efficient Cookware
T107	Efficient GFCIs
T108	Efficient Residential and Small-Commercial Security Systems
T109	Non-Intrusive Load Monitoring and Accounting
T110	Variable Power Wi-Fi Router
T111	Zero Standby Power Remote Control System

Occupant Behavior Focused Technology

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APPENDICES C-Q

These appendices are published in a separate report at CEC-500-2019-031-AP

Appendix C: Building Envelope

Appendix D: Fenestration

Appendix E: Heating, Ventilation and Air Conditioning

Appendix F: Indoor Air Quality

Appendix G: Lighting

Appendix H: Demand Response

Appendix I: Other Building Level Controls

Appendix J: Water Heating and Efficiency

Appendix K: Whole House Building Solutions

Appendix L: Distributed Generation

Appendix M: Energy Storage

Appendix N: Grid Interaction – Smart Grid Connections

Appendix O: Other Technology Solution

Appendix P: Plugloads

Appendix Q: Behavior