California Energy Commission

CONSULTANT REPORT

# Phase 2 Research, Instrumentation, and Monitoring Plan

Lead Locally, EPIC Grant EPC-17-041

Prepared for: **California Energy Commission**
Prepared by: **Sonoma Clean Power Authority**

Sonoma Clean Power

**California Energy Commission**
Edmund G. Brown Jr., Governor

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# California Energy Commission

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# PREFACE

## Project Overview

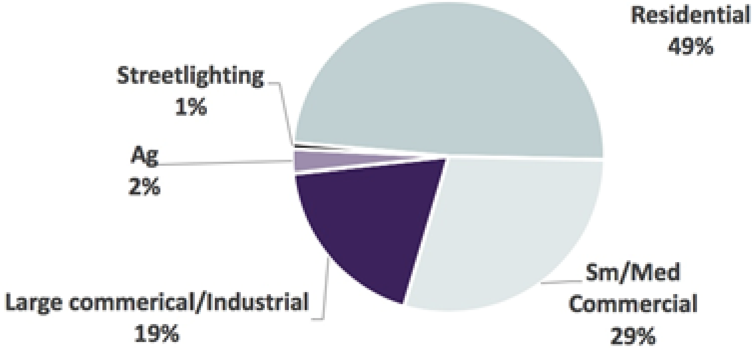
Sonoma Clean Power's (SCP) "Lead Locally" project (Project), funded through the California Energy Commission's (CEC) GFO-17-304 aims to identify strategies and technologies that can assist with the State's goals of doubling the efficiency of existing buildings by 2030. The Project will include applied research and technology deployment activities, each of which will propose innovations that could stimulate the energy efficiency market. With the applied research work, the team will investigate a series of innovative technologies that have the potential to be integrated into existing program models. Lessons learned from the applied research projects will be funneled directly to consumers, contractors, real estate professionals, and building officials through SCP and its local partner organizations. The technology deployment work will be driven in part through the SCP "Energy Marketplace", a physical storefront where consumers can directly procure energy efficient products and services. The Energy Marketplace has the potential to speed deployment of energy efficiency, make energy efficiency programs more accessible to all customers, and increase customer knowledge of energy efficiency and energy code requirements.

## About Sonoma Clean Power and its Customers

SCP is a public power provider operating as a Community Choice Aggregator (CCA) and the default electricity provider for Sonoma and Mendocino Counties. SCP exists to provide broad public benefits relating to affordability, reliability, climate change and sustainability, coordination with local agencies, customer programs, and to support the local economy. The default service for SCP customers is CleanStart, which provides customer with 45% renewable power and 87% carbon free power (2017 Climate Registry certified values). SCP customers also have the option to select EverGreen service, which is 100% renewable power produced entirely within the SCP service area.

SCP serves just over 220,000 accounts, of which 86% are residential accounts. On an annual basis, SCP's load is comprised of about 50% residential energy use as shown in Figure P-1.

**Fig P-1. SCP Customer Load for 2017**



Sonoma Clean Power Authority (SCP), its employees, agents, contractors, and affiliates shall maintain the confidentiality of individual customers' names, service addresses, billing addresses, telephone numbers, email addresses, account numbers, and electricity consumption, except where reasonably necessary to conduct SCP's business or to provide services to customers as required by the California Public Utilities Commission (CPUC). SCP shall not, under any circumstance, disclose customer information for third-party telemarketing, e-mail, or direct mail solicitation. Aggregated data that cannot be traced to specific customers may be released at SCP's discretion.

Any questions or concerns regarding the collection, storage, use, or distribution of customer information, or those who wish to view, inquire about, or dispute any customer information held by SCP or limit the collection, use, or disclosure of such information, may contact Erica Torgerson, Director of Customer Service, via email at etorgerson@sonomacleanpower.org.

## Project Team, Roles and Responsibilities

The applied research team is comprised of the following parties (referenced in this document as the Team), with roles and responsibilities outlined below.

**Sonoma Clean Power** serves as the prime coordinator with the CEC, and will be responsible for identifying project sites, initial outreach to customers, and reporting Project progress to the CEC.

**Frontier Energy**'s lead roles are management of the applied research activities and associated subcontractors, execution of laboratory testing, installation of instrumentation at test sites, analysis of monitored data, energy modeling, and technical reporting.

**DNV GL** will provide independent Evaluation, Measurement, and Verification (EM&V) for the Project, specify required measurement points and accuracy levels for the instrumentation package, and evaluate performance relative to the metrics for success.

**California Lighting Technology Center** will manage the commercial daylighting project, select and evaluate daylighting technologies in both laboratory and field test settings, and assist in extrapolating field performance to estimate energy savings and peak electricity demand reduction for other space types and locations across California.

**Winwerks** will serve as the vendor for phase change materials and provide informal design guidance and field test support throughout the project.

**PLT Multipoint** and **Huvco** will serve as vendors for daylight harvesting sensors and daylight enhancement technologies, respectively, and provide informal design guidance and field test support throughout the project. Additional product vendors may join the Team and provide support as the Project proceeds.

# ABSTRACT

The purpose of this Phase 2 Research, Instrumentation, and Monitoring Plan (Plan) is to document the methodology that will be used by the project team to select, refine, characterize, and evaluate specific retrofit measures involving innovative building technologies or applications that present some level of performance or economic risk to building owners and occupants. Phase 2 technologies are not on the critical path for Lead Locally but must still meet challenging schedules to achieve program targets for deployment and technology transfer within the 3½ year timeframe of the grant. This Plan addresses three Phase 2 technologies: Efficiency optimizing control strategies for grid interactive heat pump water heaters, attic-mounted phase change materials for residential buildings, and daylighting retrofits for commercial buildings.

The Plan also addresses proposed steps in the applied research process tailored to the specific technology and retrofit application, culminating in decision criteria for whether the technology is a suitable candidate for large-scale deployment in Sonoma and Mendocino Counties, or elsewhere in Northern California.

The applied research stage of the project will quantify actual technology energy savings using monitoring equipment for the specific installation context, supported by building simulations to normalize and extrapolate the results to additional applications and climates. The EM&V efforts will ensure that these activities are conducted in a technically sound and objective manner, leading to reliable conclusions that can be trusted and acted upon by SCP and other program implementers.

**Keywords:** California Energy Commission, energy, phase change materials, buildings, research, measurement, verification, EM&V, heat pump water heaters, energy efficiency, lighting, daylighting

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# EXECUTIVE SUMMARY

This *Phase 2 Research, Instrumentation, and Monitoring Plan* documents the applied research process to evaluate the energy savings potential for efficiency optimizing control strategies for grid interactive heat pump water heaters, attic-mounted phase change materials for residential buildings, and daylighting retrofits for commercial buildings. While the applied research experiments will be limited to specific buildings and locations, this plan also describes the process for scaling the results statewide through technology demonstrations and large-scale deployment.

The process for applied research includes the following components:

1. Literature review to understand past research and identify unresolved questions.
2. Laboratory testing under controlled conditions.
3. Field testing of electricity savings and cost-effectiveness in occupied buildings.
4. Building energy simulation to evaluate technologies in other climates and building types.
5. Evaluation against success factors for inclusion in future technology demonstration projects, the Energy Marketplace, and/or state-wide energy efficiency programs.

Technology specific approaches are described in Chapters 3-5 of this document.

# CHAPTER 1: Introduction

The Lead Locally Grant is an innovative programmatic approach to existing buildings research, development and demonstration that includes a range of innovative technologies, program features, and market strategies to engage new customers in energy efficiency upgrades and deliver benefits to California's electric ratepayers. The Grant is led by Sonoma Clean Power (SCP) under funding by the California Energy Commission (CEC) through the Electric Program Investment Charge (EPIC) program. SCP is a Community Choice Aggregate providing electricity to 189,000 residential and 31,000 commercial customers in Sonoma and Mendocino Counties. This robust existing building initiative will also serve to complement current fire recovery efforts in Sonoma and Mendocino Counties, enabling SCP programs to have impact far and beyond the scope of this project.

The applied research portion of Lead Locally focuses on several innovative technologies that will be evaluated through laboratory and field testing with the objective of expanding SCP's and other energy efficiency program administrators' portfolios of cost-effective retrofit options. These applied research projects are designed to remove uncertainty around the installed performance and cost of the technology, especially in combination with other retrofit measures, prior to broad deployment of the technology through the Lead Locally Energy Marketplace. Lead Locally will focus on adapting proven technologies and concepts to new applications by optimizing their performance in creative ways, providing building owners and contractors with the knowledge and tools they need to select the right applications, and installing the technologies in a manner that yields the expected energy savings. If at any point specific technologies prove nonviable for near-term application in Northern California, the remaining funding will be applied to more promising technology demonstration projects or technologies identified through the Energy Marketplace. The four applied research projects have been split into Phase 1 and Phase 2 technologies, allowing accelerated planning and preparation for the projects with the tightest timelines. Phase 1 technologies were previously addressed in the *Phase 1 Research, Instrumentation, and Monitoring Plan*, and included (1) radiant panels with air-to-water heat pumps and (2) enhanced commercial daylighting. Phase 2 technologies are the subject of this document, and include efficiency optimizing control strategies for grid interactive heat pump water heaters (HPWHs) and attic-mounted phase change materials (PCMs) for residential buildings. This report also provides details on the research plan for enhanced daylighting and advanced controls for commercial buildings, which was addressed at a high level in the Phase 1 Plan.

## Purpose

The purpose of this *Phase 2 Research, Instrumentation, and Monitoring Plan (Plan)* is to document the methodology that will be used by the project team to select, refine, characterize, and evaluate specific retrofit measures involving innovative building technologies or applications that present some level of performance or economic risk to building owners and occupants. Phase 2 technologies are not on the critical path for Lead Locally, but still require a clear and detailed plan to successfully achieve program targets for deployment and technology transfer within the 3½ year timeframe of the grant.

## Scope

This Plan addresses three technologies:

1. Optimizing control strategies for grid interactive HPWHs in residential applications.
2. Attic-mounted PCM products for residential applications.
3. Daylighting retrofits for commercial building applications.

In the sections that follow, general strategies will be presented for conducting the applied research activities for Lead Locally. These strategies are relevant for Phase 1 as well as Phase 2 technologies. The Plan will also address proposed steps in the applied research process tailored to the specific technology and retrofit application, culminating in decision criteria for whether the technology is a suitable candidate for large-scale deployment in Sonoma and Mendocino Counties, or elsewhere in Northern California.

In most cases, a successful applied research project will include the following components:

1. Literature review to understand past research and identify unresolved questions.
2. Laboratory testing under controlled conditions.
3. Field testing of electricity savings and cost-effectiveness in occupied buildings.
4. Building energy simulation to evaluate technologies in other climates and building types.
5. Evaluation against success factors for inclusion in future technology demonstration projects, the Energy Marketplace, and/or state-wide energy efficiency programs.

## EM&V Coordination

SCP is working with its partners Frontier Energy and DNV GL (collectively referred to as the Team in this document) to deliver a collaborative process for Evaluation, Measurement and Verification (EM&V) methods, baseline methodology, certainty of reported results, data management protocols and application of updates. These methodologies are documented in the Phase 2 EM&V Framework (Framework), which is a corollary to this Plan. The Framework, written by DNV GL, addresses the following:

- a detailed summary on independent project monitoring and verification, using Investor Owned Utility accepted protocols and the CPUC's California Energy Efficiency Evaluation Protocols.
- a detailed timeline of the evaluation period pre- and post-installation.
- a description of data assumptions and inputs to be used for building simulation models.
- a description of data extrapolation strategies.

- and description of on-going monitoring and verification to evaluate persistence and sustainability of savings, post-EPIC funding.

Frontier Energy has provided feedback on the Phase 2 Framework document and has ensured that this Plan is consistent with the requirements set-out in the Framework. Frontier's and DNV GL's collective experiences of implementing and evaluating CEC research programs and CPUC ratepayer Energy Efficiency programs across the state of California will be used to ensure Lead Locally technologies are deployed and evaluated with an eye for how successful measures and strategies could be integrated into statewide energy efficiency portfolios.

The applied research stage of the project will quantify actual technology energy savings through monitoring equipment for the specific installation context, supported by building simulations to normalize and extrapolate the results to additional applications and climates. The EM&V efforts will ensure that these activities are conducted in a technically sound and objective manner, leading to reliable conclusions that can be trusted and acted upon by SCP and other program implementers.

Table 1 details the general roles of Frontier and DNV GL in relation to EM&V during the Applied Research Stage:

**Table 1: Applied Research Stage EM&V Roles.**

| Frontier Energy | DNV GL |
|---|---|
| Write Research, Instrumentation, and Monitoring Plan consistent with the EM&V framework, including minimum data sets and collection methods specified by DNV GL. | Write EM&V Framework for applied research projects consistent with the project vision articulated in the proposal and the Research, Instrumentation, and Monitoring Plan. |
| Determine characteristics of target test houses for each technology. | Advise Frontier if additional test houses, operating scenarios, or control samples will be needed to obtain reliable energy savings estimates. |
| Identify and purchase appropriate monitoring equipment and instrumentation. | Verify that all sources of uncertainty are monitored or addressed. |
| Install pre-retrofit instrumentation in test houses, install additional sensors if needed following retrofit, and remove instrumentation after one year of post-retrofit monitoring. | Perform quality assurance on monitored data, and inform Frontier when problems are observed. |
| Provide DNV GL with access to monitored data. | Obtain and store utility billing data for test houses. |
| Characterize the performance of each technology in terms of energy savings and comfort relative to expectations. | Extrapolate energy savings to the rest of California using market diffusion modeling |

| | |
|---|---|
| | and Frontier’s energy savings, cost, and target market data. |
| Develop energy models and analyze the expected cost-effectiveness of technologies in alternative building types, applications and California climate zones based on test results and cost data. | Verify inputs to the energy models.<br>Ensure that energy models adequately reflect energy end-use and premise data. |
| Provide technical data for use in evaluating whether success factors were met. | Recommend whether to abandon a technology, proceed with a Technology Demonstration, or begin deployment. |

The Team will maintain accurate, up-to-date, and secure records for individual project sites and overall grant/project data over the course of the grant (minimum: 3½ years). Reporting on customer sites will continue for up to 3 years of activity, potentially across multiple technologies and multiple phases of the project.

Baseline monitoring will be used to determine the conditions prior to the energy efficiency technology being installed. In all cases, it will be attempted to capture representative operating modes of the building (system) or the equipment during a normal seasonal operating cycle; the baseline period will representatively account for both heating and cooling seasons.

The reporting activities for each technology in the Project will include the following:

- The measurement period start and end points in time.
- Observed data of the reporting period.
- The values of independent variables.
- Description/justification for any corrections made to the recorded data.
- Any estimated values used in the calculations.
- Utility rates used.
- Details of any non-routine adjustments performed on the baseline.
- Explanation of the change in conditions since the baseline period.
- All observed facts and assumptions.
- Engineering calculations leading to any adjustments of the baseline.
- Computed reductions in energy use, electricity demand and energy costs.
- First cost (current and projected at maturity) and impacts on operating and maintenance costs.

The Project will roll-out to additional sites to get to 300,000 square feet of building space achieving an average minimum site electric savings of 10% for residential sites and 20% for commercial sites. This will likely be somewhere in the neighborhood of 100-150 sites across all technologies, which may or may not include “Sites with Monitoring”.

# CHAPTER 2:
# Lead Locally Research Approach

This section describes general concepts, strategies, and resources relevant to all Lead Locally applied research projects, including both Phase 1 and Phase 2, as well as many of the technology demonstration projects that are designed to address more limited performance uncertainties. Detailed methodologies tailored to specific Phase 2 technologies are discussed in Sections 3-5 of this Plan.

## Literature Review

The first step in any well-conceived research project is to understand the state of the technology and the results of previous work conducted by other researchers. This is accomplished primarily through a literature search, supplemented with direct conversations with manufacturers and researchers. It is essential to properly leverage project funds by building upon the work of others, especially when past work has been performed by independent third parties, as opposed to manufacturers or advocates.

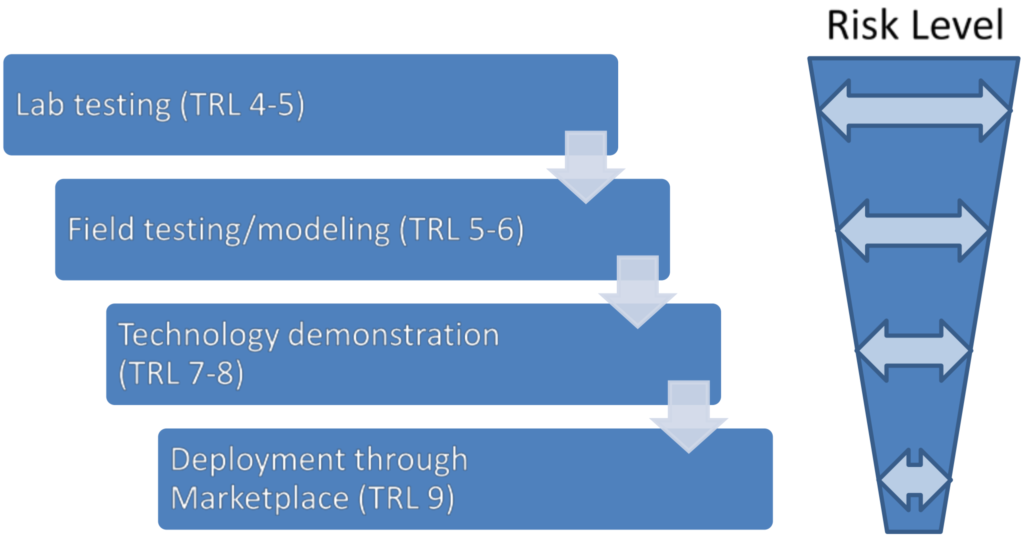
Through the literature review, the Team will estimate projected energy savings when the technology is applied to target building sectors and climate zones. If the literature indicates that the technology has the potential to help Lead Locally achieve 10% electricity savings in residential buildings or 20% in commercial buildings, the Team will investigate installation costs, interactions with other building system, durability, reliability, noise, aesthetics, savings persistence, and documented risks related to occupant comfort, health, and safety. For some technologies, installed performance may be well understood through past laboratory and field studies, and only the technology's effectiveness in retrofit applications or specific climates remains untested. In other cases, the technology may be very new and largely unproven, in which case a more comprehensive research approach is required to manage risk to SCP ratepayers.

## Risk Management

There are several categories of risk that must be considered for a research project involving real homeowners and building occupants. Performance risk involves the possibility that energy savings may be less than expected, and there is even a chance that energy bills will increase. This risk can be mitigated by carefully selecting appropriate technology applications, educating occupants about proper operation and maintenance, spotting problems early by monitoring operating characteristics continuously over a range of conditions, and fielding and responding to customer questions and concerns during the test period. There are application risks when a technology is moved from the controlled conditions of a laboratory to a real building. Unexpected systems interactions, occupant complaints, permitting issues, and other practical challenges may arise. Cost risk should not be a major issue for applied research projects, because the CEC and/or SCP will pay for the equipment purchase and installation. However, it will be important to track installation costs at the test sites to determine if the technology was cost-effective, and perhaps find ways to reduce future costs through contractor training and certification efforts. With a sufficient quantity and diversity of field test sites, the Team hopes to identify many of these issues early and provide solutions to building owners and contractors during the deployment phase though education and training.

Technology Readiness Level (TRL) is a good indicator of the level of risk associated with a technology or product. The applied research projects for Lead Locally are considered either TRL 4 (Component and/or system validation in laboratory environment) or TRL 5 (Laboratory scale, similar system validation in relevant environment). Our objective is to move the technologies to TRL 8 (Actual system completed and qualified through test and demonstration) over the course of the program and take steps toward TRL 9. Lead Locally has adopted a gradual risk reduction process that includes lab testing, field testing, modeling, and technology demonstration, before proceeding with large scale deployment (see Figure 1).

**Figure 1: Risk reduction strategy for Lead Locally.**



Another important output of the literature review is a listing of important, unresolved research questions that will be answered during the execution of the project. Research questions are similar to hypotheses, except they don’t state an expected conclusion that might give the appearance of bias. Research questions should be specific, objective, and relevant to the goals of the research project. The following are examples of poorly developed research questions:

- Is the technology cost-effective? (too broad)
- Why is the technology underused in commercial buildings? (biased)
- What product design modifications would improve performance? (not within scope)

Appropriate research questions include the following:

- Is the technology cost-effective as a retrofit for classrooms in K-12 schools in Climate Zone 2?

- What are the technology, cost, and market barriers for application of the technology in commercial buildings?
- Does installed performance align with expectations based on the manufacturer's published data?

These questions may be addressed in any or all of the research stages shown in Figure 1. If there are no relevant questions to be addressed in a particular research stage, that stage will be skipped. For example, if the only unanswered questions about the performance of a product relate to occupant interaction or acceptance, the lab testing stage is unnecessary. Similarly, if the Team is unable to answer key research questions during a particular stage, it may be necessary to either perform additional work before moving on to the next stage, or abandon the applied research project in favor of other technologies or opportunities. Research questions will also guide the amount of instrumentation, data intervals, test duration, and other aspects of the test plans. Collecting data that isn't useful for answering research questions can be costly and inefficient. Similarly, key data points from the instrumentation plan may be accidentally omitted if the desired outputs and prerequisite calculations aren't carefully considered.

# Laboratory Testing

Most of the energy consuming equipment used in buildings undergoes standardized testing at a certified laboratory to establish rated performance characteristics that consumers can understand and can be used as the basis for comparing products. However, the performance of rated equipment in new applications or as part of a complete system may not be known with a high degree of confidence, and additional laboratory testing may be necessary to reduce performance uncertainty prior to implementation in occupied buildings. The lab testing activities in support of Lead Locally will focus on technology evaluation under a range of operating and environmental conditions that encompass the conditions expected in actual building installations.

Three separate laboratory facilities will be leveraged for the testing of appropriate Lead Locally technologies under controlled conditions:

1. Frontier's Building Science Research Laboratory (BSRL) is a 2200 ft$^2$ facility in Davis, California, that has been used since 2003 for testing equipment, fabricating prototypes, and maintaining field monitoring systems. The BSRL has been used for the evaluation of heat recovery systems, evaporative cooling technologies, tankless water heaters, furnaces and fan coils, and ventilation cooling systems. Improvements made in 2017 included construction of two large environmental chambers (see Figure 2) that can be used for the testing of residential and commercial HVAC technologies, water heating equipment, and building envelope components such as phase change materials (PCMs). A 10-ton variable speed packaged unit is currently used for conditioning the air in the larger test chamber and introducing the desired thermal loads on outdoor equipment. An additional radiant heating and cooling capability will be added to the smaller chamber as part of Lead Locally to simulate both indoor and semi-conditioned spaces and allow testing of subtler thermal phenomena such as heat transfer rates for PCMs. An air-to-water heat pump and tankless gas water heater are available for providing heated and chilled water for testing hydronic coils, radiant panels, and drain water heat

recovery devices. A LabView setup will be used to monitor and control equipment during experiments.

2. Frontier's Food Service Technology Center (FSTC) in San Ramon, California, is an ISO-certified testing lab designed to run ASTM/EnergySTAR/ASHRAE tests pertaining to commercial foodservice equipment. The facility includes six National Instruments/Labview portable data loggers which can take 20 thermocouple channels, as well as 3 pulse channels and an electric meter with a multiple-point input. There are two lab spaces at FSTC:
    - Space 1 is the main set of test cells. There are enough spaces for 6 appliances to be tested simultaneously. It has 208V, 120V, natural gas and water service. Metering equipment includes a calorimeter, numerous diaphragm gas meters, multiple grades of water meters and pressure regulators. The ventilation equipment is equipped with variable frequency drives and manual controllers, and each side of the hood can operate independently.
    - Space 2 is the Commercial Kitchen Ventilation (CKV) lab, shown in Figure 3. This space is conditioned with highly controllable ventilation, supply and return air equipment, and floor-to-shoulder diffusers. The lab is set up to easily exchange hoods, and includes a humidifier, multiple RH sensors, a few thermocouple trees, and some more-sophisticated logging software.
3. The California Lighting Technology Center (CLTC) in Davis, California, includes full-scale laboratories for research and development of next-generation, energy-efficient lighting and daylighting technologies (See Figure 4). CLTC also conducts independent product testing and market research, providing accurate data on the state of the lighting market to regulators and end-users. For Lead Locally, the CLTC test facilities will be used to evaluate the effectiveness of daylight harvesting sensors and control algorithms, and to characterize the performance of daylight enhancement technologies such as fiber optics under controlled conditions.

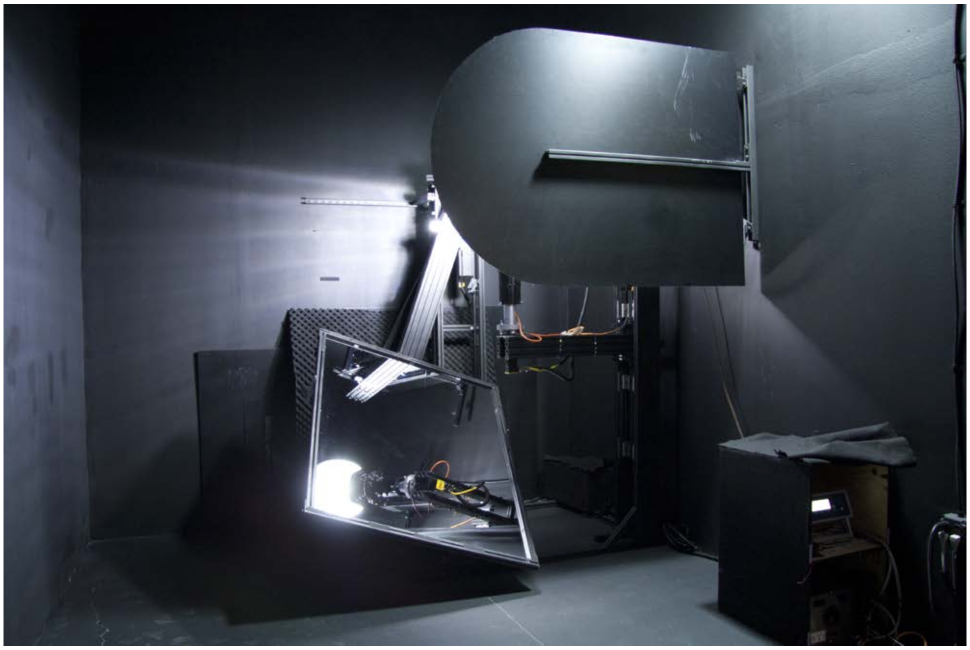
**Figure 2: Environmental test chambers at the Frontier Energy – Davis lab facility**

Credit: Joshua McNeil

**Figure 3: Commercial Kitchen Ventilation Laboratory at the FSTC in San Ramon.**

Credit: Michael Slater

**Figure 4: One of several test chambers used for lighting technology evaluation at CLTC.**



Credit: CLTC

The lab testing activities for Lead Locally will address multiple technologies over a compressed timeframe during the first year of the program. As a result, significant coordination is required to prioritize and schedule lab testing at each of the three facilities so disruption from competing test activities is minimized. Outlook schedules have been set up to reserve time in each chamber at the Frontier-Davis facility. A laboratory manager has been assigned by Frontier to ensure the smooth execution of all lab test activities, identify and implement any necessary lab modifications in preparation for upcoming tests, track CEC-funded equipment and test apparatus, and resolve competing requests for access to test facilities or staff. In addition, Frontier has performed job safety analyses for the laboratories in Davis and San Ramon, and has established safety protocols compliant with PG&E's safety policy, including an extensive training program for all laboratory and field test staff. CLTC has instituted similar safety programs and protocols.

# Field Testing

Once laboratory testing has verified that expected performance is achieved within a reasonable margin under well-controlled operating conditions, each technology will be installed and monitored in a small number of occupied buildings. These field tests will help identify unexpected performance issues that only become apparent when the technology is subjected to realistic weather conditions and occupant behavior.

## Site Selection

In general, the Team will target field test sites that offer the best opportunities for success, in terms of both electricity savings and cost-effectiveness. If the technologies do not perform well in these applications, SCP will recommend investing remaining funds into promising alternative technologies identified through the Energy Marketplace vendor solicitation. If the technologies prove successful, building energy simulations will be used to extrapolate the results to other CEC climate zones and less ideal applications. The applied research projects will also transition to the technology demonstration stage, where a larger and more diverse set of buildings can be evaluated.

The first step in the site selection process is to develop a screening matrix that lists the essential, important, and desired characteristics of the field test sites. The criteria may be driven by technology performance considerations (e.g. heat recovery ventilators save more energy when outside temperatures are more extreme), cost limitations (e.g. the budget for residential phase change materials may limit the size of the attic footprint), or practical issues (e.g. there must be enough space to install a heat pump water heater). Additional considerations will include criteria that may influence the realization of energy savings (e.g. is the building occupied year-round) and health and safety issues specific to any retrofits (e.g. is the building likely to contain asbestos based on vintage). These criteria will help ensure effective field tests with minimal complications.

The SCP, Frontier, and DNV GL teams will use the screening matrix to identify features that will be essential, important, or desirable for each of the applied research technologies. These features will then be assigned a score so that interested sites can be evaluated according to their overall fit for Lead Locally and the specific technology to be field tested. Based on the cost of direct mail, the initial customer outreach and solicitation will be through digital channels (e-mail, social media, etc.). Interested customers will be directed to an SCP-hosted web page with additional details on Lead Locally, expectations and benefits for customer participation, and select qualifying questions based on identified screening criteria. Responses to these questions will be merged with data sets SCP has access to, including: internal customer billing data and account information; other customer data on file including participation in SCP programs; parcel data from the Sonoma County and Mendocino County Assessor's and Recorder's Offices; and building department data from Sonoma and Mendocino County building departments. SCP customer care specialists and Frontier staff will use the screening matrix to filter incoming interest from building owners to qualify sites. If the screening criteria prove overly restrictive and result in very few candidate test sites, the criteria will be loosened up in non-essential categories. The time stamp for receipt of responses from interested customers with qualified sites will be used to establish the order of qualified sites for site visits.  This coupled with the scored criteria will establish a fair and defensible process for selecting sites in case there are more qualified sites than can be served within the Applied Research budget.

SCP customer care specialists are experienced in a range of outreach and marketing strategies and customer service best-practices. This is important because the recruitment effort may need to include a range of customer engagement activities to reach the target number of selected sites. Customers may be excited about the opportunity to participate in the project and have new high performing equipment installed in their home or business at no cost to them. However, some customers may be skeptical or risk-averse, especially if they are asked to accept certain responsibilities through a Customer Participation and Access Agreement. An effective strategy to recruit interested and qualified sites will increase the likelihood that those sites can be selected for the project following an initial site visit and reduce the risk of significant time and effort being spent visiting sites that turn out to be poorly suited for the project.

Once a manageable number of candidate sites have been identified and recruited, a short walk-through audit will be conducted to determine if there are any unexpected features of the building or its occupants that could affect its viability as a test site. Possible issues might include incorrect screening results, unsafe conditions, or inadequate space for the equipment. A homeowner orientation will also be held with building owners and occupants to make sure their expectations are realistic and consistent with the goals of the project. Following this final filtering step, the remaining candidates will be ranked and narrowed down to the desired number of test sites, as defined in Table 2. Customers at sites that are selected as a test site will be required to sign a Lead Locally Customer Participation and Access Agreement. Customers not selected will be thanked for their interest and encouraged to participate in future Lead Locally activities and offerings. SCP staff will retain information on all interested customers to support engagement on such activities.

**Table 2: Number of Phase 2 Sites During Each Stage of Screening Process**

| Phase II Technology | Pre-Screened Sites from SCP Data Sources | Recruited Sites from further SCP qualification | Sites Selected for Monitoring |
|---|---|---|---|
| Optimizing Controls for HPWHs[1] | N/A | N/A | N/A |
| PCM | 200 | 10 | 5 |
| Daylighting | 120 | 6 | 3 |

## Measure Installation

Specific measure design and installation plans will be developed once the test sites have been selected. All necessary permits will be obtained prior to the start of measure installation at each test site. Installation of each measure will be performed by subcontractors that are well-trained and knowledgeable about best practices for installing and commissioning the technology in various applications. All activities will be well-coordinated with building owners to minimize inconvenience to occupants.

## Customer Care

As field testing is conducted the Team will ensure that homeowners and building occupants understand the benefits of participating in the program and are given excellent customer care. All participating building owners will be presented with a Customer Participation and Access Agreement, which will clarify what participating in the program will entail such as: expected performance and benefits of installed technologies, the installation process, monitoring required during the testing period, responsibility of proper operation and maintenance, protection of personal information, and how to address performance issues that may arise with the technology installation. This agreement, in addition to initial recruitment and site visits, will help to communicate what the building owner should expect from participation in the program. All participants' personal information will be protected and stored in a safe encrypted environment. The agreement will also protect and set expectations for SCP and subcontractor staff accessing properties. All staff accessing properties will be trained on how to safely access customer properties and work sites to help prevent incidents.

Part of delivering excellent customer care and program satisfaction is communicating effectively and responding to requests in a timely matter. A monitored call line and Sonoma Clean Power email address will be available for participants to communicate performance issues, feedback or general questions. Customer care specialist staff monitoring these communication channels will be trained on how to address performance issues and ensure that next steps are taken to resolve issues promptly. This will include notification of points of contact at SCP and resolving the issue through work of a subcontractor or other project team member.

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[1] This Plan's discussion of applied research monitoring activities for the optimizing controls for HPWHs will be performed in the laboratory and will not require test sites. Sites for this technology will be recruited as part of the grid-interactive HPWH technology demonstration project, which will be addressed in the *Technology Demonstration and Deployment Implementation Plan*.

To help determine overall satisfaction of installed equipment each participant will fill out a questionnaire sharing their experience. This questionnaire will provide the program with valuable feedback on the usability of the technology on a day-to-day basis, and address any detailed issues not captured when the instrument package is installed.

Not only is this level of care important from a customer service perspective for SCP, but it will also help ensure that the program elicits good responsiveness and data from customers. When a customer has a positive experience participating in a program, this helps earn the program and the Energy Marketplace some of the best marketing possible – word of mouth.

## Baseline Determination

Each field test must include a well-established baseline that can be compared to the retrofit case for the purpose of calculating energy savings:

- **Pre-retrofit**. The most common baseline is the site itself prior to the energy retrofit, because the space geometry, operating conditions, internal gains, air leakage, climatic conditions, and other building attributes are usually identical. However, year-to-year weather differences must be accounted for, and there must be verification that occupancy levels and usage patterns did not change significantly. In some cases, the retrofit may be part of a remodeling effort that corresponds to a change in occupancy. In those cases, the pre-retrofit case is not a viable control for the field test, except as a hypothetical scenario analyzed using building energy simulation.
- **Similar buildings**. Buildings with similar physical characteristics and occupancy types are sometimes used as the control case when pre-retrofit data is unavailable or inappropriate due to a change in occupancy or major remodeling that coincides with the energy retrofits. This approach is more common with new construction in residential neighborhoods with standard home models, and usually requires large sample sizes to achieve reasonable accuracy and overcome variations in occupant behavior. It is unlikely that similar buildings will be used as a control case for this project.
- **Similar spaces in the same building**. In larger commercial buildings, there may be very similar spaces on different floors or different section of the buildings. This option can avoid challenges related to year-to-year weather differences, reduce the overall timeline for the field test, and be more efficient from a cost standpoint. However, spaces are never identical, and uncertainty can be introduced by small differences in geometry, layout, and occupant behavior.
- **Modeled baseline case**. When no physical control case is available, such as when a building is repurposed, an energy model can be used to analyze the theoretical energy use of the test site prior to retrofit. Often the most convenient theoretical baseline is code minimum. Because validation of the baseline model is impossible in this scenario, validation should be performed for the retrofit case, and the results (e.g. air leakage, internal gains, operating conditions) should be applied to both models. This approach is sometimes referred to as “Model Enhanced Monitoring”.

The selection of an appropriate baseline depends on the nature of the technology and the characteristics of the test site. Further details on this topic are provided in the specific technology sections of this plan.

## Monitoring Approach

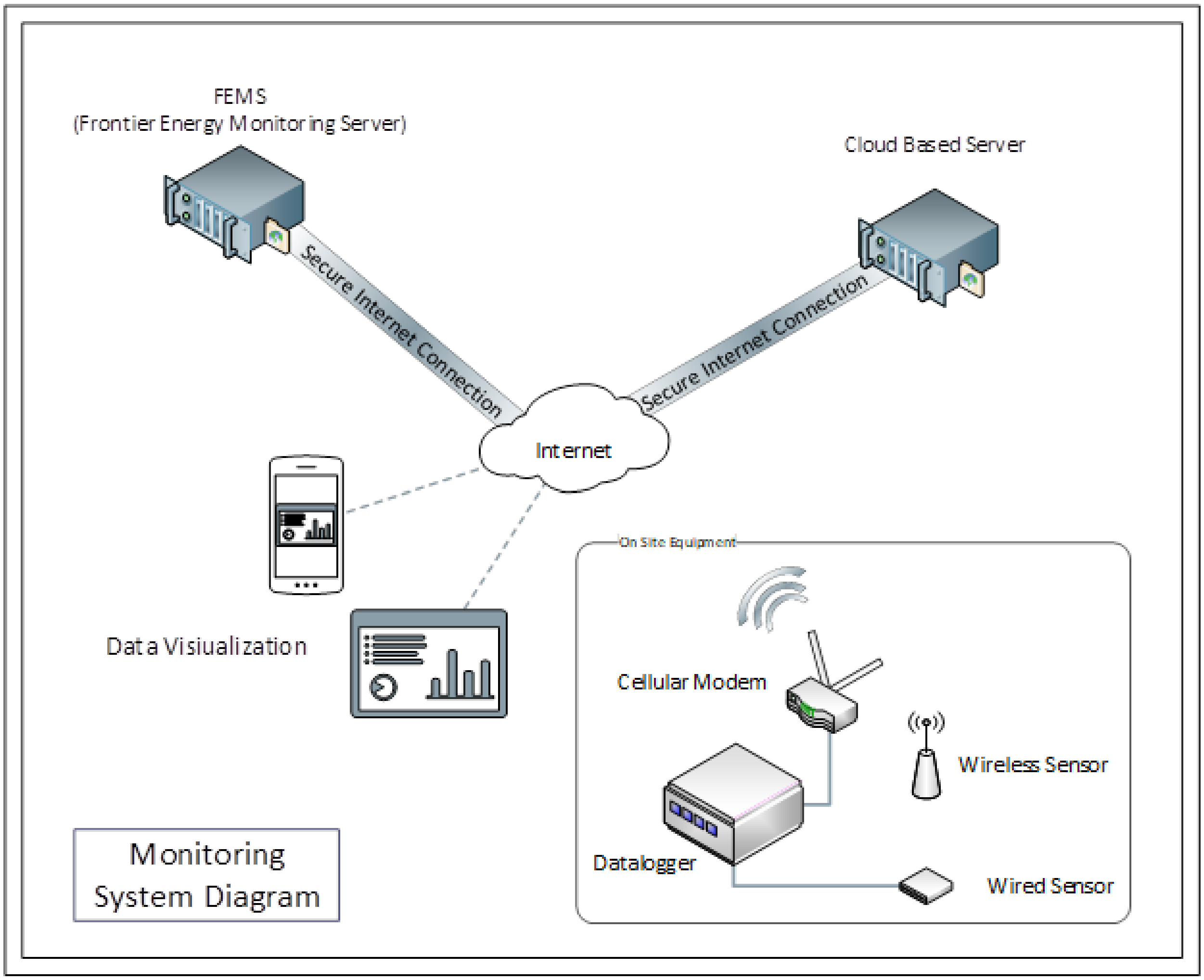
Field test data will be monitored for all test sites (baseline and post-retrofit) for the length of time necessary to ensure performance is observed under the full range of weather conditions, typically between six months and one year. Additional factors may affect test duration depending on the technology and building type, such as seasonal variations in operating conditions and ground water temperature. The range of performance data that will be collected is highly dependent on the technology, risk areas, and research questions that must be addressed, but electricity savings, comfort impacts, and cost data will be tracked for all projects.

The specific monitoring approach will be tailored to the systems and research goals at each building, though basic methods and devices will be kept as uniform as possible across field monitoring efforts. Figure 5 provides a high-level diagram of the monitoring methods and systems described in this section.

To the greatest extent possible, the monitoring systems and sensors used in the baseline monitoring periods will continue to be used in the retrofit monitoring periods at each site. Data will be collected from both wireless and wired sensors by one or more dataloggers. The dataloggers will securely transmit data over the internet through a program-supplied cellular modem independent from the site internet service.

Two basic types of dataloggers may be used: customizable and programmable dataloggers (e.g. dataTaker, Campbell Scientific, etc.) or dataloggers that are part of residential and commercial energy management systems (EMS) (e.g. SiteSage, inView, and Ecobee). All custom dataloggers and most EMS dataloggers will provide some on-site data storage to prevent data loss due to internet connection issues and power outages.

Figure 5: Frontier Energy Monitoring System.



EMS dataloggers will send data over a secure connection to a cloud server operated by the respective EMS providers. These EMS systems provide additional benefit to field test site owners and occupants, who will be provided access to any available EMS features. Some EMS systems also provide data visualization both at an aggregate level for use in the Energy Marketplace and at an individual site level to assist with equipment commissioning and troubleshooting.

The Frontier Energy Monitoring Server (FEMS) will centrally manage and collect monitoring data from all data sources for all monitoring sites. The FEMS is a secure industrial computer system with redundant data backup and redundant secure internet connections. It automates data collection by retrieving data from field monitoring sites, checking retrieved data for errors and common equipment issues, and automatically notifying key personnel about possible problems detected. The FEMS also tracks the internet connection status of monitoring equipment and sends weekly data summaries to key personnel.

The FEMS can be set up to retrieve data in any file format from any datalogger at any specified interval. Data from EMS dataloggers are automatically downloaded through a secure login to the

EMS cloud server and typically retrieved daily. Custom dataloggers communicate directly with the FEMS over a secure connection, uploading data files directly to the FEMS secure FTP server. The FEMS provides secure storage for all retrieved data by project and by site. In addition to retaining the raw data files, the FEMS automatically combines all data for each site into a site-specific binary data file for use in analyses. Direct access to the FEMS is kept limited to specific personnel for security and reliability reasons. Access to data collected by the FEMS will be provided to other Team members via Frontier Energy's SharePoint service as necessary.

### Site Close-out

At the conclusion of the field test period, all instrumentation will be removed, and the condition of the building will be returned to its original state, except for the efficiency measures themselves, which will remain unless the building owner is dissatisfied with measure performance. In such cases, the original equipment will be re-installed if the complaints are well-founded, but it is expected that this scenario will be uncommon because of the careful risk-reduction strategies employed by the Team.

## Building Energy Simulation

Energy simulation is an important supplement to most field test activities. Because field tests are conducted with uncontrolled occupant behavior and weather conditions, it is usually necessary to normalize energy use data before and after the retrofit. The energy savings can then be calculated under standard operating conditions and compared across test sites or to expectations based on manufacturer specifications. The most accurate method for this normalization process is the use of a whole-building model informed by field test measurements and occupant surveys, with adjustments made to uncertain inputs when necessary to align with measured data. This process can be time-consuming and expensive, especially when the retrofits involve numerous measures for which energy savings must be disaggregated. Models of commercial buildings are more difficult to create, but operating conditions tend to be more predictable than residential buildings, reducing the number of uncertain parameters. Weather data used for modeling can either be collected directly with an on-site weather station or downloaded from one of several providers of historical weather data. Modeling tools will be selected based on the research questions and technologies to be analyzed for each applied research project. Once validated through comparisons with measured data, the models can be used to estimate the energy savings potential for the technology in other building applications and climate zones, which is important for developing sector targeting strategies and quantifying state-wide program impact. The models can also identify positive and negative systems interactions with other measures, which will help guide measure bundling strategies used in the Energy Marketplace.

Modeling can be supported by laboratory testing when controlled conditions are needed to develop input parameters or performance maps for use with more complex modeling tools like EnergyPlus. These laboratory-validated algorithms can provide greater confidence in whole-building models during the subsequent field test phase. However, installed equipment performance cannot always be predicted based on laboratory testing, especially when the technology relies on occupant interactions or complex control algorithms. Daylight harvesting is an example of a technology where the Team expects to encounter some surprises when moving from the laboratory to occupied buildings.

For Lead Locally, the Team expects to use energy models informed by field test data for most of the research and technology demonstration projects that involve multiple retrofit measures. The energy savings for single-measure projects, such as phase change materials (PCMs) and induction cooking, may be calculated analytically using direct measurements and simple normalization equations. The details will be discussed in the technology-specific sections of the research and technology demonstration plans. These plans will be based on current expectations of the technologies and equipment that will be included in the lab and field test program, but early test results may open up new research questions and the plan must be adaptable when necessary to address all performance uncertainties before large-scale deployment is pursued.

# Success Criteria

Each technology measure will have defined specific success metrics for both the lab testing and field testing stages which will need to be met in order for the technology to progress to the next stage and eventually be included in the Energy Marketplace. During the lab testing stage, success could take many different forms depending on the specific objectives and research questions being addressed. At the field test stage, success will primarily be evaluated in terms of costs and benefits for each measure. Specific criteria will depend on the technology and application under consideration, but will be defined using the following metrics:

**Table 3: Cost Benefit Analysis criteria**

| Costs | Benefits |
|---|---|
| Administration/permitting | Gross site electricity savings % |
| Equipment costs | Normalized site electricity savings |
| Installation costs | Gross site electrical demand savings% |
| Bill increases (electricity and gas) | Normalized site demand savings |
| Maintenance costs | Bill reductions (electricity and gas) |
|  | GHG reductions |
|  | Load shifting |
|  | Tax credits |
|  | Non-energy participant benefits |
|  | Non-energy social and environmental benefits |

## Electricity Savings

The technologies being evaluated are expected to notably improve the existing baseline site electricity consumption, moving it towards the portfolio level target of 10% site electricity reduction for the residential sector and 20% for the commercial sector. To contribute to the overall targets, there will be an expectation of significant system level savings for each technology and this is specifically outlined in each technology section. Where appropriate measure(s) will also be compared to the existing building requirements of Title 24 (Part 6) that are applicable at the time of permit issue. Energy savings for each measure or combination of measures will be evaluated both individually and at a portfolio level. Where practicable, energy savings will be also evaluated in terms of the time-sensitive savings value for each technology because of its relationship to the California utility grid and CPUC's avoided cost model.

## Economic Benefits

Technologies will be evaluated in terms of their benefits and applicability for wider adoption across the entire SCP territory of over half a million customers, and further across the State of California through IOU EE programs. Success of the initial trials will likely also highlight contractors' skills and capability gaps, which will allow for SCP to strategize development of a Workforce Education and Training delivery program to increase scaling through the Energy Marketplace. The development of territory-wide energy efficiency (EE) programs that include the successfully verified innovative technologies will have long-lasting positive economic benefits to the residents of Mendocino and Sonoma Counties.

Cost effectiveness of measures will be evaluated from two different standpoints. Firstly, that of the homeowner whose home is being retrofitted, utilizing metrics such as simple payback and return on investment. Secondly, data will be collated to support the evaluation of the overall program in conjunction with the CPUC framework for cost effectiveness, which will be needed for future inclusion of the measures in rate payer funded EE programs. Installed costs at different scales will be evaluated for different technologies and retrofit packages.

## Non-energy Benefits

The Team will monitor and record baseline non-energy factors such as indoor air quality, thermal comfort and acoustic levels to help identify and track any changes due to the introduction of a measure in the participating property. Project completion will include a comprehensive occupant acceptance procedure inclusive of a building owner questionnaire that will identify any issues requiring further investigation prior to the measure being included in the Energy Marketplace. Where feasible, preference will be given to subcontractors with local presence in the SCP service territory to allow for rapid rectification of any installation issues. In addition, materials and products will be sourced through California based companies to mitigate possible delays associated with out-of-state procurement. In the event a technology yields unsatisfactory results, or upon a reasonable request from the building owner, the offending technology will be removed, and a mutually agreed upon alternative will be re-installed.

# CHAPTER 3:
# Efficiency Optimizing Control Strategies for Grid Interactive Heat Pump Water Heaters

## Technology Overview

Grid interactive HPWHs respond to signals from the utility to operate in better ways than a HPWH could independently. Previous projects studying grid interactive HPWHs have focused on their load shifting potential. This project expands on that concept by using machine learning and model predictive control to create new control strategies for heat pump water heaters (HPWHs) in residential buildings to minimize the electricity cost of using HPWHs. It does this by optimizing the operating efficiency, or coefficient of performance (COP), of the water heater and adjusting operating times in response to time of use (TOU) electricity rates. It is based on three fundamental facts:

1. The backup electric resistance elements, which supplement the heat pump heating capacity, operate at much lower efficiency than the heat pump itself. Therefore, any change to controls that decrease resistance element use and replace it with heat pump use will increase the COP of the HPWH.
2. The COP of the heat pump is a function of the temperature of the ambient air and the temperature of the water in the tank. Therefore, any change to controls that operates the heat pump when those temperatures are favorable, i.e. when the water temperature is low or the ambient temperature is high, will increase the COP of the HPWH.
3. Utilities are now rolling out time of use rates which more accurately represent the cost of using electricity at different times of day. Electric utilities in California typically experience low load, due to high PV production, around noon and high load, due to high air conditioning use, in the late afternoon.

Programming a fixed control strategy into a HPWH to take advantage of these facts would be extremely difficult due to the differences from one installation to another. Both changes in household usage and climate impact operating efficiency. A HPWH in the garage of a 2-occupant house in Tahoe will experience different ambient temperatures and draw profiles from one in conditioned space in a 4-occupant house in San Diego. Additionally, TOU rates will vary from one utility to another. The variance between installations means that any advanced control strategy must be responsive to local conditions, and not hard-coded from the factory.

The combination of machine learning and model predictive control is both flexible and intelligent enough to overcome this obstacle. Machine learning techniques create an understanding of typical conditions in a specific installation such as typical hot water use behavior in that house, and typical surrounding air temperature in that room. Model predictive control then uses simulation model predictions and an optimization algorithm to find the best way to operate a product. In this case high performance operation means meeting the hot water needs of the household at least as well as traditional controls while using less energy.

The control approach used in this project will be based on a combination of HPWHsim[2], an optimization algorithm, and machine learning techniques. HPWHsim will be the core of the control logic, representing the internal control logic and performance of the HPWH itself. An optimization algorithm will perform numerous simulations on the system, searching for the most energy efficient way to meet the needs of the occupants. It will have the power to vary the set temperature of the HPWH throughout the day to change the behavior and efficiency of the HPWH. Finally, machine learning techniques will be used to study the behavior of the occupants in the house[3] and provide the predicted hot water draw profile to the simulation models. Depending on the machine learning technique used, the draw profile predictions and set temperatures will be updated either daily or every 30 minutes. This results in a control strategy where HPWHsim predicts the energy consumption and hot water availability using the behavior of the occupants predicted by the machine learning algorithms, and the optimal set temperature profile identified by the optimization algorithm.

Some examples of potential ways this control logic could improve the performance of the HPWH include:

1. The machine learning algorithms will be able to predict periods of large hot water draws based on previous hot water use patterns, thus giving the HPWH a chance to prepare for them in advance by adjusting the set temperature profile of the tank. One potential case of this is several showers back to back. This represents a situation where large volumes of hot water are withdrawn from the storage tank. Traditional controls would require either 1) the resistance element to engage, operating at low efficiency, to meet the hot water demand or 2) the occupants increasing the hot water set temperature in advance, thus permanently reducing the COP of the heat pump and increasing the tank standby losses. Since the machine learning algorithm will be able to predict these occurrences, the optimization script will be able to identify that it can meet the load in a more energy efficient manner by increasing the set temperature in the tank only shortly before the draws begin. This way the demand can be met solely with the high COP heat pump without permanently increasing the set temperature.
2. In an alternate scenario, the machine learning algorithm will be able to predict times when the occupants don't use large quantities of water. The optimization algorithm will be able to identify this situation and reduce the set temperature in the tank accordingly. By doing so, it can delay heating the water in the tank until a time when the surrounding air temperature is higher thus increasing the COP of the heat pump.
3. The optimization script will also be able to anticipate and avoid times when the HPWH must use the resistance element because the ambient temperature is too cold to safely use the heat pump. If it identifies that the resistance elements will activate during a cold morning it will have the opportunity to increase the set temperature and engage the heat pump the prior evening, thus ensuring that there is enough energy stored in the tank to avoid heating in the morning. It will analyze the trade-off between greater heat

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[2] HPWHsim is an extensively calibrated and validated simulation model of HPWHs developed by Ecotope, Inc. (Kvaltine, Lodgson, & Larson, 2016).

[3] This sentence describes the operation of the technology when it is installed in a house and learning the behavior of the occupants of that house. Since this project will be performed in a laboratory the occupant behavior and draw profiles will be replicated with monitored data collected during previous projects.

losses from the tank overnight, and poor COP in the morning due to operation of the resistance heater, then select the best option.[4]

4. As our final example, the control logic could improve on existing controls by using the time of use rates to identify a very effective cost-saving load shifting strategy. On a day when occupants use high volumes of hot water in the afternoon, a traditional HPWH will engage either the heat pump or the resistance elements during the peak period. With time of use rates, this will be expensive. An automated controller, equipped with predictions of hot water use and time of use rates, will be able to identify that high cost water heating and replace it with pre-emptive compressor use at the low-cost time of day.

This approach to controls in the built environment has been gaining traction in recent years. BuildingIQ is an Australian company with significant presence in the U.S. that bases their business model on this approach. They implement model predictive control in larger commercial buildings such as hotels and hospitals, saving their clients significant amounts of energy (BuildingIQ, Inc., 2018). Researchers at the National Renewable Energy Laboratory (NREL) have performed a simulation study specifically investigating the potential to improve the energy efficiency of HPWHs with model predictive control. They focused on predicting the occurrence of hot water draws and activating the heat pump in advance to avoid electric resistance element use (Example 1 above) (Jin, Maguire, & Christensen, 2014).

One major question regarding this technology is how it interfaces with existing load shifting controls now sometimes employed in grid interactive HPWHs. The answer to this question is not clear at this time, as it partly depends on how the final controls are implemented. This question will be explored as part of this project.

## Existing Test and Evaluation Standards

Currently there are no relevant test protocols or evaluation standards for this technology. The existing test standard for HPWHs is the Uniform Energy Factor (UEF) test protocol (Department of Energy, 2016). This test standard is designed to estimate the efficiency of a consumer water heater under controlled conditions using a representative hot water draw profile. Being targeted at rating the performance of consumer products, it mandates a constant ambient temperature and set temperature in the water heater. These requirements make it overly rigid, and inappropriate for modern research improving the performance of HPWHs. This is because the modern research topics, including this topic and load shifting studies, require varying set temperatures (Grant & Huestis, 2018). Data from the UEF test will not provide adequate data to identify the performance of HPWHs with these advanced control strategies. Due to these limitations, the UEF protocol will not be used in this project. This project will provide valuable data and insights that can be used to help develop new test protocols in future projects.

## Technological Approach

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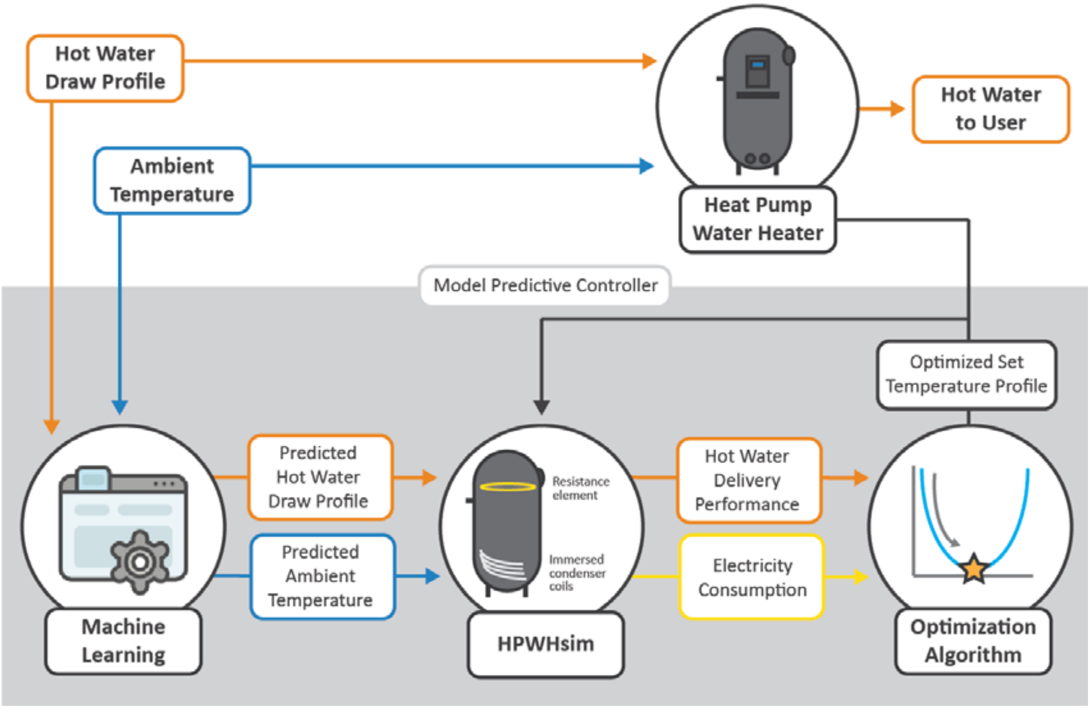
[4] Sonoma Clean Power offers a load shifting program to their customers, and many grid interactive HPWHs take advantage of that opportunity. The climate in the Sonoma Clean Power service territory sometimes results in a significant peak, even in the winter when this example is most relevant. This means that the control logic will also need to be able to identify load shed periods and avoid pre-heating the tank at those times.

As previously described, this project will combine machine learning, HPWHsim and an optimization algorithm to create a model predictive controller for HPWHs. The system will use measured occupant hot water use behavior and ambient temperature as inputs, then perform their roles and pass information back and forth accordingly. The result will be a varying set temperature, optimized by the optimization algorithm, that delivers the same or better hot water availability to the occupants while reducing electricity cost by both increasing the effective COP of the HPWH[5] and shifting the electricity use to low cost times of day. The different components in the system are interrelated as shown in Figure 6.

**Figure 6: Control Logic Driving the Model Predictive Controller to Optimize the COP of HPWHs**



The inputs driving the model are the occupant's hot water draw profile and the ambient temperature where the HPWH is located[6]. This is the case because they are the two factors that drive the electricity consumption of the HPWH; the hot water draw profile dictates how much hot water is used (energy removed from the tank), and how much the electric resistance element must operate to meet the load, while the ambient temperature strongly impacts the COP of the heat pump. In Figure 6 these inputs feed directly in to the HPWH because they directly impact the performance of the HPWH, and the hot water draw profile details the needs of the occupants that must be met by the HPWH.

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[5] In this document "effective COP" refers to the COP of the HPWH as an entire system, not solely the COP of the compressor. This calculation considers the COP of the heat pump, the energy consumed by the resistance element, and the jacket losses. It will be calculated by comparing the energy delivered to the occupants in the form of hot water to the electrical energy consumed by the device.

[6] The cold water inlet, or mains temperature, also affects system performance but does not change significantly over the course of a day.

Those two inputs also feed into the machine learning algorithm because that algorithm will be using previous hot water use and ambient temperature patterns to learn the conditions that this HPWH typically experiences. That understanding will then be used to create predictions of what the HPWH will experience in the near future. The machine learning techniques to be applied are not yet determined, but the averaging bin method and template matching[7] are two algorithms which will be tested. Some examples of how this could function include:

1. Typical hot water use patterns show that there are typically two showers in the morning every weekday, followed by a period of no hot water use during the daytime, and one shower in the evening every Wednesday. The machine learning algorithm will then create draw schedules for each weekday giving the controller knowledge of what hot water demands need to be met.
2. A low ambient temperature in the morning indicates that the coming day will be colder than recent days, and possibly that it's a rainy winter day which will continue to have a low ambient temperature in the afternoon. The machine learning algorithm will use this information to predict the daily ambient temperature profile and give this information to the controller, so it can predict how the COP of the heat pump could change throughout the day.

These predicted conditions will then be passed into HPWHsim. Models available in HPWHsim are already calibrated to match each specific HPWH available on the market, indicating that simulations performed using HPWHsim and accurate draw profile/ambient temperature inputs should yield accurate predictions of the performance of the HPWH (Kvaltine, Lodgson, & Larson, 2016). However, these predictions will be further validated during the laboratory test phase of this project. Simulations performed using HPWHsim and the predictions from the machine learning techniques will provide predictions of the performance, both in terms of hot water delivery and in terms of electricity consumption and will provide predictions of how the HPWH will perform on any given day. The accuracy of these predictions will heavily depend on the accuracy of the machine learning algorithms. If the predicted conditions sent to HPWHsim are inaccurate then the simulations performed by HPWHsim will be inaccurate; on the other hand, accurate predictions of the conditions lead to accurate performance predictions. The performance predictions from HPWHsim will be combined into a single cost function based on actual utility rates, including possible time-of-use rates. This cost function will heavily penalize any instances where the occupants are delivered cool water (below the desired set point), to ensure that the hot water delivery performance remains paramount, and it will include the predicted electricity consumption.

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[7] Averaging bin method is a technique where average hot water consumption values over specified time intervals are used to create a daily draw profile. For example, a daily draw profile could be created by monitoring the occupants for 10 days, breaking up each day into 30-minute periods, and placing the average hot water consumption for each 30-minute period over the 10 days into separate bins. This provides 48 bins representing each 30-minute period of a 24-hour day, which can be combined to create a 24-hour draw profile. Template matching is a technique that compares current behavior to previous behavior searching for similar patterns. As each day progresses the occupant behavior is compared to previous days. If the algorithm finds a previous day which closely matches the current day it will use that previous day as assumed behavior for the rest of the current day, and devise control logic accordingly. If there is no previous day that closely matches, it will save the current day as a new template so that future days can be matched to it as appropriate.

The cost function output from HPWHsim will be sent to an optimization algorithm. The goal of the optimization algorithm is to minimize the cost function, thereby providing the needed hot water delivery performance while using as little electricity as possible. It will do this by modifying the HPWHs set temperature profile. In traditional HPWH controls, there is a fixed set temperature and the internal control logic engages the heat pump and resistance elements to maintain that set temperature. In this approach, the model predictive controller will create set temperature profiles, changing the set temperature throughout the day, and the HPWH internal controls will engage the heat pump and resistance elements as needed to respond to this changing set temperature. The optimization algorithm will then be able to change the set temperature of the HPWH as needed to save electricity cost in the ways specified in Technology Overview, as well as other ways that may be identified by the system.

The optimization algorithm cannot operate independently. Instead, it operates in tandem with HPWHsim. The process works as follows: 1) HPWHsim performs an initial simulation using a static 125˚F set temperature given the inputs from the machine learning algorithm, predicts the performance of the HPWH, calculates the cost function, and sends that information to the optimization algorithm, 2) the optimization algorithm receives the cost function and sends a new set temperature profile to HPWHsim, 3) HPWHsim performs a new simulation using the same draw profiles[8] from the machine learning algorithms and the new set temperature profile from the optimization algorithm, then calculates the new cost function value and sends it to the optimization algorithm, 4) the optimization algorithm receives the new cost function value, matches it to that set temperature profile, and creates a new set temperature profile to pass to HPWHsim, and 5) this process is performed repeatedly until the optimization algorithm has identified a nearly optimal set temperature profile, and improvements in the cost function value with changes to the set temperature profile are minimal. After the optimal set temperature is found the optimization algorithm will pass the set temperature profile to the model predictive controller, which will send signals adjusting the set temperature of the HPWH accordingly.

The HPWH will then operate the heat pump and resistance elements as needed to maintain the modulating set temperature in the storage tank, with possible recalculation of the set temperatures every 30 minutes depending on the specific strategy chosen. It will do this while responding to the actual hot water demands of the occupants, and the COP of the heat pump will be impacted by the actual ambient temperature. In the case where the model predictive controller significantly underpredicts hot water use, the internal controls of the HPWH will engage the resistance elements as needed to ensure the occupants get hot water. The worst case scenario is that the system ends up using the resistance elements more than expected, while hot water delivery performance is maintained.

The accuracy of the machine learning algorithms, and their ability to predict the occupant's hot water use behavior, is critical to this process. Errors in hot water predictions would turn into

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[8] It's important to note that the machine learning algorithms will predict the mixed water draw profiles, representing what the occupants experience at the fixture. Calculations adjusting the mixed water draw profiles to the hot water profiles used by HPWHsim will be important when the set temperature changes.

errors in HPWHsim performance predictions, and errors in the set temperature profile returned by the optimization algorithm. To minimize these errors, the machine learning algorithms will constantly update their predictions. At the end of each day predictions from the algorithms will be compared to what actually happened, and any differences will be used to improve the algorithms so they can improve their future predictions. Because people are never completely predictable, no algorithm can anticipate behavior with perfect accuracy and fully optimize HPWH performance, but significant electricity savings are achievable by coming close. In some cases, occupant behavior may be so unpredictable that no savings can be achieved using the machine learning strategy. This possibility will be briefly explored during the laboratory testing portion of the project, and carefully examined during the technology demonstration stage of the project. The performance of the machine learning algorithms, and techniques to maximize their accuracy, will be studied in the laboratory and simulation environment.

The operation of the model predictive controller will be verified by the project team using a simulation study. Previously collected hot water use and ambient temperature data will be input into the simulation environment, feeding inputs to both the model predictive controller and HPWH model. Simulations spanning 1-7 days of monitored data will predict the performance of the model predictive controller over the test period. Outputs will include reports on hot water delivery performance, electricity consumption, performance of the hot water draw profile prediction algorithms, convergence of the optimization algorithm, ideal set temperature profiles, and the ability of the HPWH to match that profile. These results will be used to ensure that all aspects of the model predictive controller are operating correctly, from the machine learning algorithms predicting the real world conditions correctly, to the optimization algorithm obtaining convergence on an optimal set temperature profile, to the optimization algorithm returning a reasonable set temperature profile[9], to the ability of the HPWH to match the profile specified by the controller, and finally to the desired results of high hot water delivery performance and electricity cost savings.

When simulation studies show that the controller is working according to the intended logic, laboratory experimentation will be used to validate the performance of the system. A laboratory test rig, allowing the model predictive controller to control physical HPWHs, will be constructed. The test rig will have the ability to control the ambient temperature around the HPWH, the flow rate and temperature of the water entering the HPWH, and the set temperature of the HPWH itself. Additionally, it will include measurements of the temperature of water in the tank, temperature of water exiting the tank, and electricity consumed by the HPWH. This will enable experiments where the HPWH is exposed to the same ambient temperature and draw conditions as the simulation model, the HPWH set temperature is controlled by the model predictive controller, and the actual performance of the system can be compared to the simulated predictions. Experiments studying the same test periods as were used in the

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[9] This will include three checks. First, the profile should include gradual changes in set temperature. Profiles with dramatic, seemingly arbitrary temperature changes (E.g. 150˚F from 10:30-11:00, followed by 115˚F from 11:00-11:30, followed by 123˚F from 11:30-12:00) will be considered suspect. Second, the upper limit of the set temperature will be set at 150˚F. Temperatures higher than that dramatically reduce heat pump COP while providing marginal more stored energy than is typically needed. Finally, the lower limit of the set temperature will be 115˚F. This minimum set temperature is high enough to prevent growth of legionella.

verification simulations will provide the data needed to determine if the simulation results match what occurs when the model predictive controller is used to control a HPWH. Differences between the simulation results and the experimental results will be documented and rectified as needed.

## Technology Benefits

This technology is based on intelligently controlling the HPWH to meet the hot water demands of the occupants in a more efficient manner. As a result, there will be three likely benefits of this technology.

1. Energy Savings: The controls will operate the HPWH in a more energy efficient manner, through the three methods described in the introduction to Technology Overview above. All of these could result in reduced electricity consumption.
2. Optimization of Occupant Electricity Cost: Sonoma Clean Power is in the process of phasing out flat electricity rates and introducing new time of use rates. These time of use rates will feature lower electricity prices in the middle of the day, when solar power is plentiful, and higher electricity prices during the afternoon peak period, when the grid is under significant stress. The cost function used in the optimization script can be programmed to minimize occupant electricity cost, factoring in time of use rates, instead of focusing directly on electricity consumption. This change will lead to increased cost savings for the occupants and improved economics for the control strategy. Due to the nature of the time of use rate structure, controls minimizing the occupants' electricity cost will also provide significant load shifting benefits.
3. Better Hot Water Delivery: Since the control logic will be carefully controlling operation of the device to meet the anticipated hot water demands, it will increase the stored energy as necessary to ensure that the occupants always receive hot water as desired. Standard HPWH controls don't do that. They focus solely on keeping the hot water in the tank at the set temperature, with no ability to predict occupant behavior and adjust accordingly. As a result, it is possible that the system using these controls will do a better job of reliably delivering hot water to the occupants than a standard system.

## Performance Uncertainties

While model predictive control has been successfully adopted in some applications, it has not been successful demonstrated in the residential hot water industry. NREL performed a simulation study showing that there is potential for the approach (Jin, Maguire, & Christensen, 2014), but there has not been an experimental or field study to date. It's possible that the experiments in this study will demonstrate performance problems that have not been previously identified in the NREL simulation studies.

Additionally, this approach hinges on the ability to monitor the occupant's hot water use behavior and develop a model that accurately predicts their future behavior. The performance of this prediction model is vital to the success of this control strategy. NREL used an averaging bin method in their study and showed that some energy savings is possible with that approach. In this project, more advanced machine learning techniques will be explored in the hopes that they lead to higher performance and more energy savings. It is still uncertain that these other techniques can do a better job than the averaging bin method, and those hoped for improvements may not come to be.

## Potential Inclusion in the Energy Marketplace and EE Programs

This project is starting as a laboratory experiment and simulation-based research project, implementing previously demonstrated model predictive control strategies into HPWHs. The result of that portion of the project will be observations of how well the system performed, and predictions of how much energy could be saved in Sonoma Clean Power territory if widely deployed. If the experiment and simulation portion of the project demonstrate that this technology has the potential to be successful, it may be included in other portions of the project. Success in the laboratory could lead to implementation in a few demonstration sites to test the performance of these controls in real residential buildings, assuming a manufacturer partner is willing to include the efficiency optimization strategy in the controls for one of their product lines. If field demonstrations indicate that the technology can be cost-effective, the technology will be included in the Energy Marketplace.

# Laboratory Testing

## Research Questions and Success Metrics

1. What are the best techniques for predicting occupant hot water use?

The ability of the machine learning algorithms to accurately predict the occupant's hot water use is critical to the success of this project. The goal of the model predictive controller is to use an accurate prediction of the impending hot water demands and find a more energy efficient method of delivering that hot water. Since this is an important aspect of the controller, it is important that it be done correctly. Unfortunately, the best way to use machine learning to predict hot water use characteristics is not something that has been done many times. NREL has released a paper where they used the averaging bin method to create weekday and weekend profiles and based their simulation study on those draw profile predictions (Jin, Maguire, & Christensen, 2014). Template matching is a commonly used machine learning technique, which matches data that gets read in to previously observed data sets. This approach provides another potential means of predicting hot water use, by observing behavior early in the day, matching that behavior to previous days to select a template, and making predictions for the rest of the day based on that template. These two approaches will be considered, along with other machine learning techniques that appear relevant.

Since the NREL study showed that the averaging bin method returns acceptably accurate predictions of hot water performance, it will be used as the benchmark for success. Methods that return hot water use predictions as accurate as the averaging bin method will be considered acceptable. Other methods which return more accurate predictions will be considered successful. For these approaches, we will target a normalized mean bias error (NMBE) of less than 5% and a coefficient of variance of root mean square error (CVRMSE) of less than 15% . However, because those values are used for monthly energy simulation results instead of predicting unknown future behavior, meeting them will not be considered mandatory.

2. Does a model predictive controller based on HPWHsim return valid results?

The goal of this project is to identify the electricity savings that are possible when implementing model predictive controls in HPWHs. HPWHsim, Ecotope's simulation model, is a well-established and proven simulation model for HPWHs, and provides an excellent possibility of implementing this control strategy. That said, the ability of a model predictive controller to save energy depends heavily on the performance of the underlying simulation model. Specifically, it relies on the following two characteristics:

- **Accuracy:** For the model predictive controller to return an optimal set temperature profile, the simulation model must be able to accurately predict the performance of the HPWH. Otherwise the set temperature profile is likely to result in inadequate hot water delivery performance, or unnecessary electric resistance element operation. On the other hand, highly accurate predictions from HPWHsim will result in the model predictive controller returning a profile that meets demand while reducing electricity usage. The most critical elements are predicting hot water delivery performance and predicting internal control logic decisions to use the resistance element.
- **Computation Time**: Since the model predictive controller is based on an optimization algorithm, it will be performing many simulations predicting the performance of the HPWH to develop the ideal set temperature profile. Fast computation times are necessary to enable this number of simulations in the available time.

The ability of HPWHsim to perform well on these two metrics will have a profound impact on the results of the project and the viability of the technology for near term deployment.

3. How much electricity can be saved by implementing model predictive controls?

There is potential for significant electricity savings in this project, achieved through improved control of the heat pump. More advanced controls could potentially result in heat pump operation at times when higher ambient temperatures yield higher COPs, or prevent resistance element operation replacing it with higher efficiency heat pump operation. The amount of energy that can be saved through these strategies has not yet been identified, and estimating the potential savings will be a key research finding in this project.

4. How simplified can the models be without sacrificing performance, and how simple do they need to be to enable real-time operation?

Research question 2 addressed the ability of HPWHsim to predict the performance of the HPWH accurately and rapidly enough to enable the model predictive controls. This research question addresses the same question from a different angle. Simulation models for storage tank-based water heaters, including HPWHs, divide the water in the storage tank into multiplevertical sections and predict different temperatures for the water in each of those sections. More sections in the tank yield higher accuracy at the cost of longer computation times. As part of this research, the impact of reducing the number of sections in the tank on computation time and HPWHsim accuracy will be investigated. The goal will be to identify the minimum number of sections, minimizing computation time without sacrificing the ability of HPWHsim to accurately predict electricity consumption and hot water delivery performance.

5. Do these approaches yield a significant improvement in hot water delivery performance?

There are times when occupants use high volumes of hot water, and storage tank based water heaters are unable to meet the demand. They begin heating the water when they notice the water in the tank falling below the set temperature and heat the water as fast as they can, but the demands of the occupants remove energy from the tank faster than the heater can add it. This results in cool water being delivered to the occupants. Traditional feedback controls that react to hot water demands, rather than anticipating them, will always struggle with these events. However, if machine learning algorithms can be utilized to predict these large hot water draw occurrences, then the model predictive controller will be able to begin heating the water before the draws commence. In this way it can increase the energy stored in the tank and meet the demands of hot water events to which traditional controls would be unable to adequately respond. This research will include testing on large hot water draw events, and compare the ability of the model predictive controller to meet these demands to the ability of traditional controls.

## Test Facility

The BSRL already provides most of the capabilities needed to perform this testing. The testing will be performed in the large chamber, which is heated or cooled using a 10-ton packaged unit. Thus, the ambient temperature in the space will be controlled at the value needed for each test and monitored to ensure that the correct input can be used for simulation models. Additionally, the infrastructure to provide conditioned water to the chamber will be provided by two storage tanks, a gas tankless water heater for heating water, and a PHNIX heat pump for cooling water. This infrastructure will ensure that the HPWHs used in testing will be exposed to controlled inlet water temperatures that are typical of mains temperatures in the state of California.

A test rig for the HPWHs themselves will be installed in the large chamber. The modifications will include:

- Installing HPWHs to be tested in the chamber;
- Installing computer controlled mixing valves to combine the hot and cold water from the lab to create the desired inlet water temperature for the test;
- Installing instrumentation including BTU meters and immersed thermocouples in the tank to monitor the performance of the HPWHs; and
- Installing flow control valves to control the flow rate and volume of water through the system.
- Return water plumbing directing the water used in the test back to the water conditioning system.

These upgrades will provide the controls and measurements specific to the HPWH testing, enabling experimentation to support model development, to validate the development of the simulation models, and to validate the performance of the completed model predictive controller.

## Test Matrix

Testing for this project will include both simulations and experiments. All the tests will be used to create and validate the performance of different aspects of the model predictive controller. The tests will be broken into four different categories accordingly. The four categories are:

- Testing machine learning algorithms,
- Fine-tuning the parameters of HPWHsim,
- Fine-tuning the model-predictive controller, and
- Validating the complete model-predictive controller.

The following sections provide more details on each category.

### Tested Units and Manufacturing Partners

This project will include testing of two or three HPWHs that are currently available on the market. The specific models have not yet been determined, and will be selected based on criteria including manufacturer, storage tank volume, UEF rating, and market share.

This project does not require collaboration with our industry partners, and none is currently anticipated. However, we will continue communicating with them throughout the project to search for collaboration opportunities and share the results of the work. The ideal outcome would be that Lead Locally demonstrates the potential of this technology, and a manufacturing partner adopts the approach in their on-board controls and product lines.

### Testing Machine Learning Algorithms

The ability of machine learning algorithms to learn the behavior of the occupants and predict future hot water use is critical to the performance of the model predictive controller. To pursue this aspect of the project, several different machine learning approaches will be tested using simulation only. The machine learning techniques to be investigated include the averaging bin method, template matching, and other approaches to be determined later.

Simulations will determine the performance of each technique by studying their performance on previously monitored domestic hot water use data. The data set was collected by Davis Energy Group and Gas Technology Institute in a project monitoring the behavior of occupants in single family homes in California. The data was then used to create a design guide for engineers and architects designing high performance hot water systems (Davis Energy Group and Gas Technology Institute, 2013). The different machine learning algorithms will be coded into Python scripts, then given a data set representing hot water use in a specific house. They will start with no knowledge of the user’s typical behavior, use initial data to learn how the occupants behave, then begin to predict behavior later in the test period. The performance of each algorithm will be based on 1) how accurately they predict future hot water use, 2) how much learning data is necessary before they start providing useful predictions, and 3) how much computation time is needed to form predictions at each time step.

There is a tradeoff between accuracy and computational time in this portion of the project. More computations will provide more accurate results but may result in a system that runs too slowly to be used in a real installation. The simulation testing will include adjusting parameters, including goodness of fit expectations, to find the optimal combination of high accuracy results and fast computational time.

### Fine-Tuning the Parameters of HPWHsim

HPWHsim is another portion of the project where there is a tradeoff between accuracy and computational time. It's a simulation model which can include up to 12 different sections of the storage tank, each with a different calculated water temperature. More sections yield higher accuracy but require more computation time. In this phase of the project, simulations will identify the optimal number of sections in the HPWHsim model with the best balance of accuracy and computation time.

To identify the accuracy of HPWHsim with different numbers of sections, it is necessary to have measured data to use as the baseline. Experiments will be performed on each HPWH exposed to different 24-hour draw profiles. The draw profiles from 4-7 days will be combined to form a long, diverse draw profile. Comparisons between HPWHsim predictions and the measured data will determine the optimal number of sections in the HPWHsim model.

### Fine-Tuning the Model Predictive Controller

In this phase, HPWHsim will be combined with the optimization algorithm to create the core of the model predictive controller. This module will take the draw profile predictions from the machine learning algorithm, perform repeated simulations to find the optimal set temperature profile, and send that profile to the HPWH. This process will require fine tuning, because of the same accuracy vs computation time tradeoffs previously discussed. The selected optimization algorithm, parameters of the algorithm, and freedom given to it in choosing parameters will all have a strong impact on both the accuracy of results and the time required to find a solution. Simulations with varying parameters will study the impact of each input and determine the best settings.

Once the optimization algorithm settings are identified, a final simulation will identify the energy consumption of the HPWH with the model predictive controller over a seven-day draw profile. The result of that simulation will be compared to the energy consumption of a HPWH over the same seven-day draw profile assuming a standard 125°F set temperature. This comparison will provide an estimate of the potential energy savings from model predictive control.

This phase will also include an experiment showing the energy consumption and hot water delivery performance of the HPWHs when following the hot water set temperature profile identified by the model predictive controller. This experiment will validate the performance of the model predictive controller when it is given the hot water draw profile in advance.

### Validating the Complete Model Predictive Controller

The final step of the process is validating the performance of the complete model predictive controller. In this phase simulations of the model predictive controller directly controlling the set temperature of the HPWH will estimate the energy consumption of the HPWH with varying draw profiles. This implementation will feature two different implementations of HPWHsim; one will be included in the model predictive controller and drive the set temperature profile based on draw profile predictions from the machine learning algorithms, while the other will implement the set temperature profile set by the model predictive controller and simulate the HPWH performance given the actual draw profile. Simulations performed using the same draw profile, and a static 125˚F set temperature will provide a baseline allowing estimation of the energy savings. These simulations will cover long periods of time to provide enough data to enable the machine learning algorithms to learn the occupants' behavior, and to provide data over a meaningful number of days to estimate savings.

This step will also include experimentation to validate the simulation model. In these experiments, the model predictive controller will have full control over the set temperature of the HPWHs installed in the lab. The draw profiles used in the experiments will be the same draw profiles used in the simulations. Since the simulations will span up to one year, which would be an impractical time period for lab testing, the experiments will be limited to representative sections of the full data set. For each test the model predictive controller will start with the same information that the simulation had at that point (e.g. If an experiment starts on June 1st of the simulated year the machine learning algorithms will be provided with historical data from January 1st to May 30th) to ensure that the controller behaves the same way in the experiment as in the simulations. The experiments will be performed twice, once with the model predictive controller and once with a base case emulating typical operation in Sonoma Clean Power Territory, to allow estimations of the energy savings and hot water delivery performance impacts. Since Sonoma Clean Power currently has a load shifting program in place, the base case will feature a base 125 ˚F set temperature with a load up period from 3-5 PM and a load shed period from 5-8 PM.

## Building Simulation

This project focuses specifically on HPWHs. As a result, whole building simulation is not necessary to predict the impacts of this technology and will not be performed. Instead, the impacts of this technology will be estimated using calibrated simulation models of HPWHs specifically. The project will make extensive use of Ecotope's HPWHsim simulation model. This model has been extensively validated, and is now included in other simulation packages, including the Title 24 compliance software, California Building Energy Compliance Calculator (CBECC-Res).

The laboratory phase of this project will include combining HPWHsim with an optimization algorithm that can predict occupant behavior and creating a COP optimizing control strategy for that installation. A purely simulation version of that control strategy that can predict the performance of this technology in California is a simpler application, because it can use the

CBECC-Res draw profiles instead of predicting behavior each day. This approach will be used to perform simulations and estimate the potential electricity savings in the 2100 $ft^2$ and 2700 $ft^2$ prototype homes in all 16 Californian climate zones. The simulation models will consist of calibrated HPWHsim models for multiple brand HPWHs, an optimization algorithm to identify the best set temperature profile, the CBECC-Res inputs for hot water use and inlet water temperature, as well as assumptions for the ambient temperature in the space the HPWH is located. Annual simulations will be performed to identify the total electricity use of the system should it be installed in the prototype homes. Annual simulations will be performed twice for each building/climate zone combination, once with and once without COP optimizing controls, to estimate the potential electricity savings for each of the two prototype buildings in each Californian climate zone.

This portion of the project is heavily focused on laboratory and simulation testing, implementing cutting-edge model predictive control approaches in HPWHs. There are currently several research questions about the viability of this approach, most notably the computation time and computational power required, that must be resolved in this portion of the project. If these questions are resolved, and the approach demonstrates potential energy savings, this system will be tested in 1-3 homes during the Tech Demo and Deployment phase of Lead Locally.

## Project Timeline

Table 4 shows the high-level project milestones and deliverables with anticipated completion and due dates.

**Table 4: Anticipated project schedule for research on efficiency optimizing control strategies for GIHPWHs.**

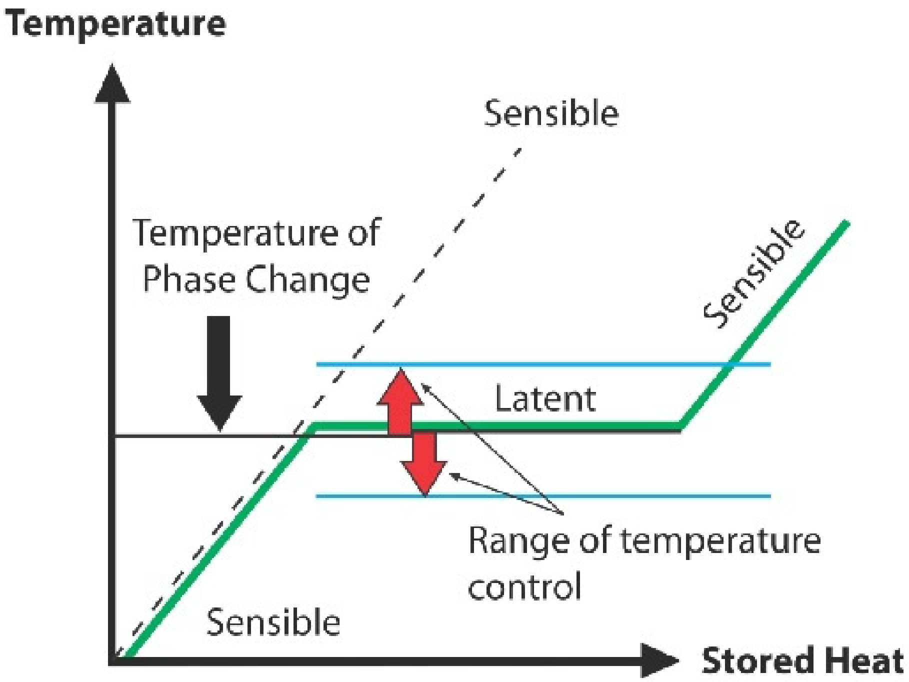
| Project Milestones | Completion/Due Date |
|---|---|
| Laboratory Test Rig Constructed | 2/28/2019 |
| Machine Learning Algorithms Implemented and Tested | 5/31/2019 |
| HPWHsim Parameters Selected | 5/31/2019 |
| Model Predictive Control Parameters Selected | 6/30/2019 |
| Model Predictive Controller Simulation Tests Completed | 8/31/2019 |
| Model Predictive Controller Validation Completed | 11/31/2019 |
| Simulations Predicting Savings in Californian Applications Completed | 12/31/2019 |
| Draft Efficiency Optimizing Control Strategies for Grid Interactive Heat Pump Water Heaters Report | 1/31/2020 |
| Final Efficiency Optimizing Control Strategies for Grid Interactive Heat Pump Water Heaters Report | 3/3/2020 |

# CHAPTER 4:
# Phase Change Materials in Residential Applications

## Technology Overview

PCMs are materials that absorb heat as they melt and release heat as they freeze. This type of heat transfer is called "latent" heat transfer, in contrast to "sensible" heat transfer which occurs when the temperature of a material changes, but its state does not. Latent heat transfer also occurs when a gas changes phase into liquid, such as when water vapor condenses on a cold surface. The most common example of a solid PCM is ice, but there are many other materials in everyday life that melt at a variety of temperatures, including wax, plastic, and even most metals. Unlike thermal mass, phase change occurs over a relatively constant temperature and requires much less volume. This is the difference between the sensible heat gain of a solid or liquid as it warms up in accordance with its specific heat, and the latent heat of fusion as a solid absorbs heat and converts into a liquid, or the latent heat of vaporization as a liquid turns into a gas. These phenomena are illustrated in Figure 7.

**Figure 7: Latent and sensible heat transfer in PCMs**



Credit: RGEES (https://rgees.com/technology.php)

PCM melting points can be tuned to match the needs of the application, making PCMs an appealing technology for use in building envelopes, including in walls and attics. PCMs do not contribute to the R-value of the building envelope, but when installed adjacent to the insulation, the PCM can reduce the temperature difference across the insulation while it freezes or melts, thereby reducing heat transfer into or out of the conditioned space. Three conditions must be met to take advantage of the PCM in a building application:

1. The PCM must be exposed to temperature changes on both sides of its melting point over the course of the day.
2. The duration of these temperature swings must be long enough to solidify and melt the PCM.
3. The heat transfer rate to and from the PCM must be fast enough to melt and freeze it within the duration of the temperature swing.

Interest in the use of PCMs to reduce heating and cooling loads has increased greatly in the past 10-15 years due to advances in higher performance PCM compositions and the availability of a broader range of commercial products that can be readily integrated into building envelopes (James & Delaney, 2012). Products range from PCM embedded in wallboard to thin sheets with encapsulated PCM cells. Past studies have indicated heating and cooling loads can be reduced by 10-30%, depending on many factors such as the thermal conductivity of the PCM, the melting point selection for the application, and the range of outdoor temperatures. Most applications have focused on commercial buildings, so very little information is available about potential benefits in residential applications, especially in northern California where the climate is generally milder than other locations. However, the presence of large diurnal outdoor temperature swings in California for much of the year, especially in attics, offers an appealing application that will be studied for this applied research project.

The encapsulated PCM product Infinite R, manufactured by Insolcorp and sold by Lead Locally partner Winwerks, will be the technology evaluated for this project. Infinite R has almost exclusively been used for commercial building applications in flat attics but has similar potential for certain residential applications with standard wood-framed vented attics. There is minimal risk for this technology, because the original insulation will remain in place, and the worst-case scenario is that the PCM does not melt and solidify consistently enough to have a measurable impact on energy use.

## Existing Test and Evaluation Standards

Numerous standards exist for PCM products, including methods for evaluating thermal properties, fire resistance, and durability. However, these standards do not address the installed performance of PCMs in building applications, including complex systems interactions, which are the focus of this project. The Team will study various configurations of PCM installations in residential attics through a combination of lab testing, field testing, and building simulation. Research results will be documented in the *Phase Change Materials in Residential Applications Applied Research Final Report*, including recommendations for possible test standards that could provide useful technical information for designers and installers for future projects. The Team will also provide guidance for selecting appropriate applications and optimal installation configurations for residential buildings in the *Phase Change Materials in Residential Applications Best Practice Installation Guide.*

## Technology Benefits

PCMs in residential attics offer several benefits:

- **Energy savings**. When installed in an application that allows frequent melting and freezing of the PCM, a significant reduction in the space conditioning load is possible. Some of the heat that would have flowed through the insulation is instead stored as latent heat in the PCM. The frequency and extent of phase change depends on a number of variables, including exterior temperature swings from day to night, heat transfer to the attic through solar gains, roof absorption and reradiation, attic ventilation, PCM location relative to insulation, and indoor thermostat settings.
- **Peak demand reduction**. Energy stored in the PCM can help houses stay cool longer during hot days following cool nights. Pre-cooling the house using the air conditioner or a whole-house fan can ensure the PCM fully reaches its frozen state, thereby further extending the number of hours a house can avoid cooling during peak demand periods.
- **Thermal comfort**. PCMs freeze and melt at a constant temperature, therefore, the ceiling above the conditioned space will remain cooler during the summer and warmer in the winter whenever the PCM is activated. This will reduce the radiative effects on occupants, increasing thermal comfort.
- **Ease of installation.** PCMs come in sheets that can be easily installed above or below insulation with minimal complications except shaping the PCM sheets around joists, ductwork, and ceiling penetrations. There are no moving parts, and no other building components need to be replaced or modified (except insulation, depending on the configuration). Unlike insulation, it is not critical that the PCM covers all hard to reach areas of the attic floor.

## Performance Uncertainties

There are several aspects of PCMs that can negatively affect its performance and cost-effectiveness:

- **Cost.** We anticipate that the cost of purchasing and installing PCMs in a typical 1500 ft2 attic will be in the range of \$5000-\$7000. The amount of energy savings necessary to make this measure cost-effective within a 5-10 year timeframe may be difficult to achieve.
- **Dependence on weather.** PCMs require significant diurnal swings to properly charge and discharge over the course of a day. Most areas in both Sonoma and Mendocino Counties have relatively mild weather, which could greatly reduce the amount of energy that can be stored in the PCM. Sunny and hot days with clear and cool nights will be necessary to achieve optimal performance during the cooling season. Sunny days in winter that can warm the attic to the melting point of the PCM may be necessary for heating energy savings.
- **Dependence on thermostat settings.** Interior temperatures also have a significant effect on the energy savings potential of PCMs. Occupants that use temperature setup and setback or use a whole house fan will likely see greater energy savings for

configurations where the PCM is placed under the attic insulation. For the field test phase of this project, the melting point will be selected to give the best performance for the current occupants. However, if the house is sold and different thermostat settings are used, the PCM may not perform as well.

- **Durability.** PCMs have rarely been used in residential applications, and the long-term durability of commercially available products has not been verified in real houses.
- **Unfamiliarity.** Home contractors and trades have minimal if any experience with PCMs in residential applications. The energy savings potential of the technology is less intuitive than insulation and may not be readily accepted by homeowners. For this applied research project, we will work with partners Winwerks and Insolcorp to identify contractors that have worked with the Infinite R product in the past, but broader deployment will depend on training efforts through the Energy Marketplace and other avenues.

### Potential Inclusion in the Energy Marketplace and EE Programs

Once PCMs in residential attics have been proven effective and reliable through laboratory and field testing, they will be eligible for technology demonstrations and inclusion in the Energy Marketplace. Winwerks has already committed to a 10% discount for Lead Locally participants, which will improve the likelihood of cost-effectiveness in more applications. Further analysis of the energy savings potential of PCMs in various climates when exposed to a range of thermostat settings will inform the *PCM Installation Guide* and allow the Team to provide homeowners and contractors the information they need to assess each situation individually and select the ideal melting point and physical configuration for the PCM installation.

## Laboratory Testing

Laboratory testing will be conducted at the Frontier Energy BSLR. The purpose of the laboratory testing will be to determine the optimal placement of the PCM in the attic retrofits during the field-testing phase and to verify the PCM’s cooling/heating load reduction potential under controlled conditions. In the laboratory testing phase, the PCM will be evaluated in the following three configurations: below the insulation, above the insulation, and under the attic roof deck. Various levels of insulation will be evaluated within the three PCM configurations to determine the correlation of insulation level and the performance of the PCM. Additionally, the installation and ease of use of the PCM will be evaluated when installing the material in the laboratory chamber. The results will be used to assist with the design of the attic retrofits for the field-testing phase of the project.

### Research Questions and Success Metrics

Laboratory testing will be used to do an initial evaluation of PCM in attic retrofits, as well as to inform the project team what the best application for PCM is during the field-testing portion of the project. The research questions for the laboratory phase of the project are the following:

- What is the optimal placement of PCM in residential attic retrofits to reduce heating/cooling loads in Sonoma and Mendocino Counties?
- What is the preferred melting point for the PCM in each configuration?

- Is there sufficient heat transfer rate to fully charge and discharge the PCM under realistic conditions?
- What is the heating/cooling load reduction generated by the addition of PCM in unconditioned attic spaces?
- What is the correlation between insulation level and the performance of the PCM.
- Are there any unexpected performance issues that may result from the addition of PCM to unconditioned attic spaces?

The success metric to advance PCM to the field test phase is verifying a meaningful reduction in cooling and/or heating loads when PCM is added to an unconditioned attic space.

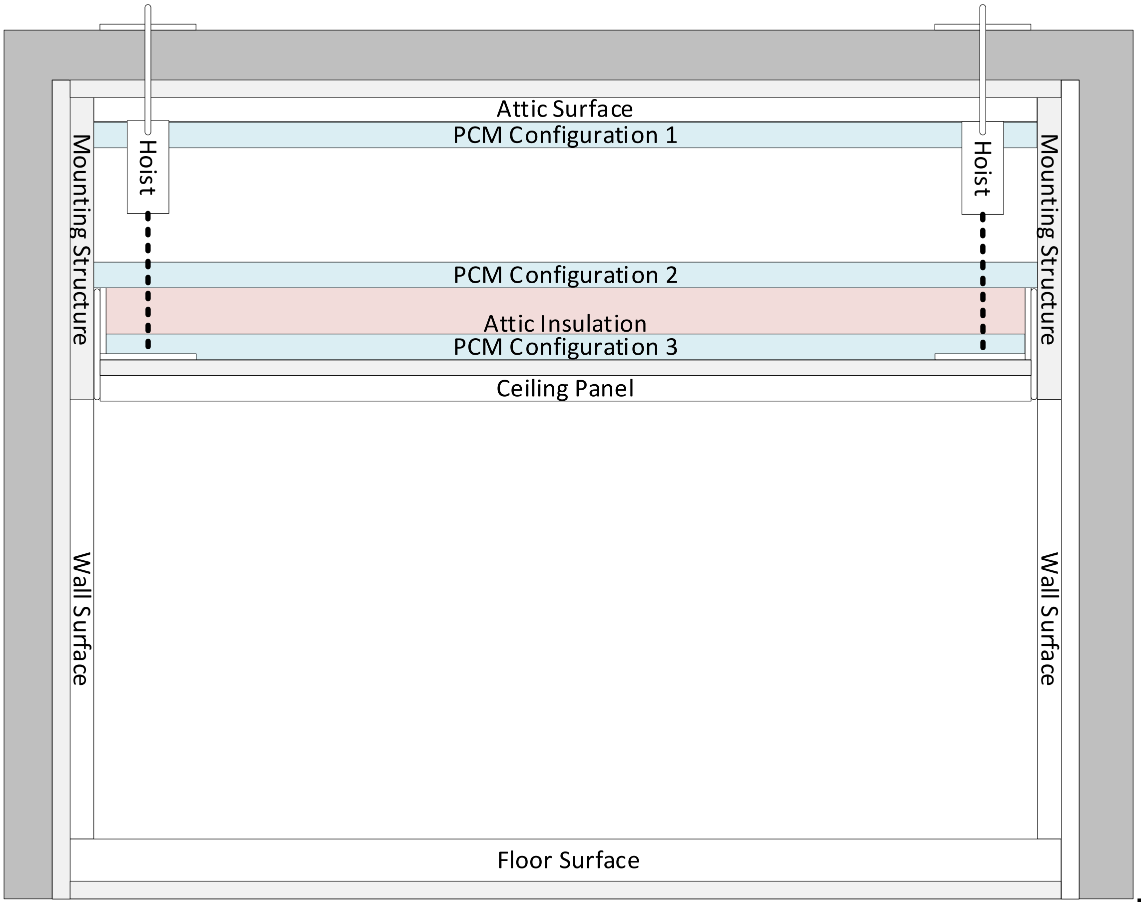
## Test Facility

The BSRL facility will be modified for other projects under Lead Locally and these upgrades will be utilized by the PCM in Residential Applications laboratory portion. BSRL has two environmental simulation chambers: one larger chamber that can simulate outdoor conditions and a smaller chamber that will be referred to as the indoor chamber, for simulating indoor conditions. Controls are currently provided by ADAM remote input/output modules communicating with a LabVIEW System computer using Modbus serial protocol.

The upgrades to the BSRL facility for other Lead Locally projects will include a simulated attic section in the indoor chamber, which can be used for testing both PCM and radiant ceiling panels. The attic portion of the chamber will be temperature controlled by a radiant panel that is going to be on the roof of the simulated attic. This panel will be used to simulate the ambient air temperature of an attic during the testing of the PCM. The simulated attic will include a removable ceiling to allow adjustments to the insulation level and allow installation of the PCM in various configurations, as shown in Figure 8 below. The ceiling panel will also be temperature controlled and it will simulate indoor conditions.

The instrumentation upgrades that will be utilized for this project include a National Instruments Compact DAQ system and a redundant data backup system for data acquisition and controls. The temperature-controlled chamber ceiling (representing the underside of the roof deck) will be used to simulate the exterior load on an attic in Climate Zone 16, which is among the climate zones that the field testing may be performed in and has the highest cooling and heating load.

**Figure 8: Diagram of planned PCM configurations in the BSRL indoor environmental chamber**



Credit: James Haile

## Test Matrix

The purpose of the PCM in Residential Applications laboratory testing is to determine the optimal placement of PCM in retrofitted vented attics and find the correlation of insulation levels with the performance of the PCM. During the testing period there will be three PCM location configurations that will be tested, two different levels of insulation, two melting points, and attic temperatures representing realistic conditions for an average heating day and cooling day in Climate Zone 16. Below are the various cases for a total of 25 cases.

- PCM configurations – below roof deck, above ceiling insulation, below ceiling insulation
- Insulation levels – R-30, R-38
- Simulated Melting Point – additional simulated melting point
- Climate Zone 16 attic temperatures – average cooling day, average heating day
- Indoor temperature – constant, optimal setup and setback (below ceiling insulation only)

For each PCM configuration the insulation level will be adjusted, and the attic will be simulated for an average heating day and an average cooling day. Baseline monitoring data for actual field test sites may be used instead of simulated Climate Zone attic temperatures for both an average heating and cooling day. Then, the next configuration will be set up and testing will continue for each insulation level until all three PCM configurations have been tested.

Data points collected will include the following

- Ambient temperatures and humidity in the simulated attic and conditioned space
- Water flow rates, inlet and outlet water temperatures for radiant panels as a check for heat exchange into conditioned space.
- Heat flux below the attic surface radiant panel
- Surface temperature above and below the PCM at several locations
- Heat flux above and below the PCM at several locations

Sensor data will be collected at 1-minute intervals. This sampling rate will allow the data acquisition system to capture the change in temperatures under test and therefore determine the performance of the PCM for each case. Each configuration will be tested for approximately one week and the total laboratory testing will be three weeks for all configuration cases.

# Field Testing

The field-testing portion of the project will be conducted at five single family homes that will undergo an attic retrofit that includes installing PCM in the attic space, with no other changes to the house that could complicate interpretation of the results. Each home will be monitored during two stages. The first stage will be used as the baseline and the second will follow the attic retrofit and will be used to evaluate the PCM performance. The baseline stage will last between 5-6 months and the homes will be instrumented with sensors and a data logging system to capture the baseline performance. Some of the performance characteristics that will be monitored include: heat transfer through the ceiling, attic ambient temperatures and humidity, roof deck surface temperatures, and indoor ambient temperatures and humidity. Changes in heating and cooling energy will be monitored directly. A retrofit design will be developed prior to the retrofits and baseline monitoring data will be used to determine the ideal melting temperature of the PCM for each site. The PCM will be placed in a configuration that will be determined by the results of the laboratory phase of the project. After the attic has been retrofitted with PCM, additional sensors will be added to capture the performance of the PCM in the attic space as detailed in the general test strategy section. Data will be captured for a duration of one year after the retrofit for the post-retrofit stage to capture both a full heating and cooling season.

During the retrofit stage, the costs will be tracked to evaluate the total cost for each retrofit. Homeowners will be asked to provide access to their utility data and allow technicians to enter the residence for data collection, maintenance, or repairs with a reasonable notice.

The payback period will be calculated by comparing the total cost of the retrofit and the energy savings that is provided by the PCM addition to the attic through reduction in heating and cooling loads.

## Research Questions and Success Metrics

The following are the research questions that will be addressed by the field-testing phase:

1) What is the cost-effectiveness of PCM addition to vented attics in Sonoma and Mendocino Counties?
2) What is the cooling/heating load reductions with PCM addition in vented attics?
3) Does the PCM demonstrate durability and effectiveness after being installed in attic spaces for an extended period?
4) Which climates in Northern California provide the proper environmental conditions for PCM in attic spaces to go through the proper thermal cycles to see energy savings?
5) What are the ideal practices for performing a successful attic retrofit with PCM?

It will be determined if PCM for attic retrofits in residential applications is ready to be included in the Energy Marketplace based on the results of the research questions and the occupant surveys. The success of the technology will be based on whether the technology has a simple payback of < 5 years.

## Test Sites

Field test sites will be located within Sonoma and Mendocino counties and will be selected from the SCP customer base. The criteria for these sites are outlined in Table 5. The site selection criteria were selected to find site locations that would allow the research team to evaluate the performance of the PCM technology in a best-case setting within the constraints of the project goals and resources. Results from these test sites along with building simulation modeling will be used to determine the effectiveness of PCM in attic retrofits for other conditions. The criteria have the following weight definitions:

- Essential –Criteria must be met to be a candidate field test location for this project.
- Important – Meeting Criteria is desirable and would aid research goals.
- Desired – Criteria to be used only in an abundance of candidates. Locations that meet all criteria including “desired” would be considered “near perfect” candidates for the work.

**Table 5: Field test site selection criteria**

| Category | Criterion | Criterion Value | Criterion Weight |
|---|---|---|---|
| Occupant | Occupied? | Yes | Essential |
| | Owned by current residents? | Yes | Essential |
| | Occupants will remain for 2 years? | Yes | Essential |
| | Full time residence? | Yes | Essential |
| Site | Year Built | 1978 < x < 2005 | Essential |
| | Dwelling Type | Single Family | Essential |
| | Sq. feet of conditioned living space | <1500 | Essential |
| | Utility data available | Yes | Important |
| | Year built | 1978 < x < 2005 | Essential |
| | Dwelling type | Single Family | Essential |
| Building Envelope | Attic type | Traditional, Vented | Important |
| Mechanical | HVAC system functional? | Yes | Important |
| | Central Cooling? | Yes | Important |
| | Propane heating? | No | Essential |
| | HVAC asbestos ducts? | No | Essential |
| | HVAC whole house fan? | Yes | Important |
| | Smart thermostat? | Yes | Desired |

## Retrofit Systems and Equipment

The PCM that will be used during the field-testing phase is an inorganic compound that was developed by Insolcorp called Infinite R. It is made of hydrated salts, hydrated magnesium aluminum silicate, and hydrated sodium calcium aluminosilicate. The compound is stored in a white poly film pocket and sealed in a multilayer white poly film. The poly film packaging comes in 24" X 48" sheets and 16" X 48" as seen in Figure 9 below. The PCM comes in a variety of melting points ranging from 66-84˚F. The melting point will be selected based on the results of the baseline monitoring to ensure the optimal melting point for each application. The PCM quantity installed in the attic will depend on the accessible attic space and the project budget.

**Figure 9: Insolcorp Infinite R PCM matt**

Image credit: Insolcorp, LLC

The infinite R PCM sheets have the characteristics and performance values shown in Table 6 and Table 7:

**Table 6: Infinite R Physical Properties**

| Physical Properties | Values |
|---|---|
| Melting Point | 66 - 84˚F |
| Specific Heat | 1.35 BTU/lb·˚F |
| Latent Heat | ~86 BTU/lb·˚F |
| Thermal Conductivity | ~0.16 W/ft/K Liquid |
|  | ~0.33 W/ft/K Solid |
| Dimensions | 24.5" X 48" |
|  | 16.5" X 48" |
| Thickness | 0.25" |
| Weight | 0.75 lb/sq. ft. |

Table 7: Infinite R Fire Ratings

| **Fire Testing** | UL 723 |
|---|---|
| Flame Spread | 5 |
| Smoke Development | 10 |

During the laboratory phase of the project three different configurations will be evaluated and based on the laboratory results a design will be selected for the optimal performance of the PCM in the attic retrofits. The attic retrofits will have the PCM located in one of three locations as shown in the example retrofit configuration in Figure 10 - Figure 12 below. In addition to laboratory testing, the PCM configurations will be evaluated using building simulation software such as EnergyPlus to confirm the optimal placement of PCM to reduce cooling/heating loads in the conditioned space.

If the PCM is located above the insulation, the PCM will be placed on top of the ceiling joist so that the insulation will not be compacted by the PCM over time, as shown in Figure 10. If the laboratory tests suggest that the best placement is below the insulation then the existing insulation will be removed and the PCM sheets will be placed directly on top of the gypsum board, in between the ceiling joists. The insulation will then be placed directly on top of the PCM sheets as shown in Figure 11. Alternatively, if the ideal placement is below the roof deck, then the PCM will be placed directly below the roof deck in between the roof rafters. If there is a radiant barrier directly on the roof deck then the PCM will be installed directly on the roof rafters, leaving a space between the radiant barrier and the PCM (see Figure 12).

If needed, the attic insulation level will be inspected and upgraded to the current minimum requirement for new construction in Title 24 for that climate zone, prior to baseline monitoring. This will be done to remove any inconsistencies due to low insulation in the attics.

**Figure 10: Example attic retrofit with PCM above the insulation**

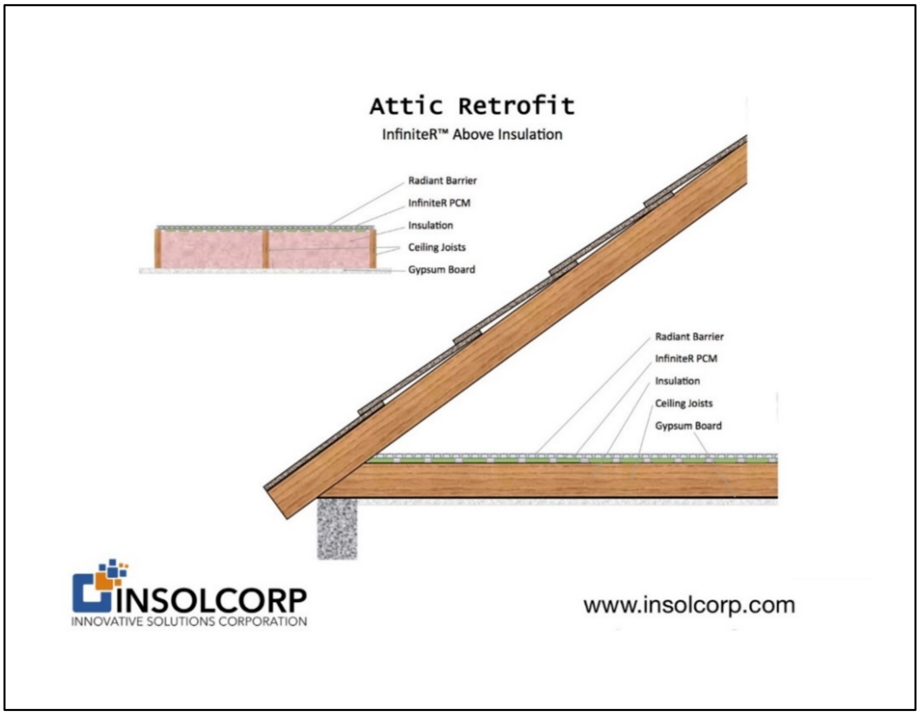


Image credit: Insolcorp, LLC

**Figure 11: Example attic retrofit with PCM below the insulation**

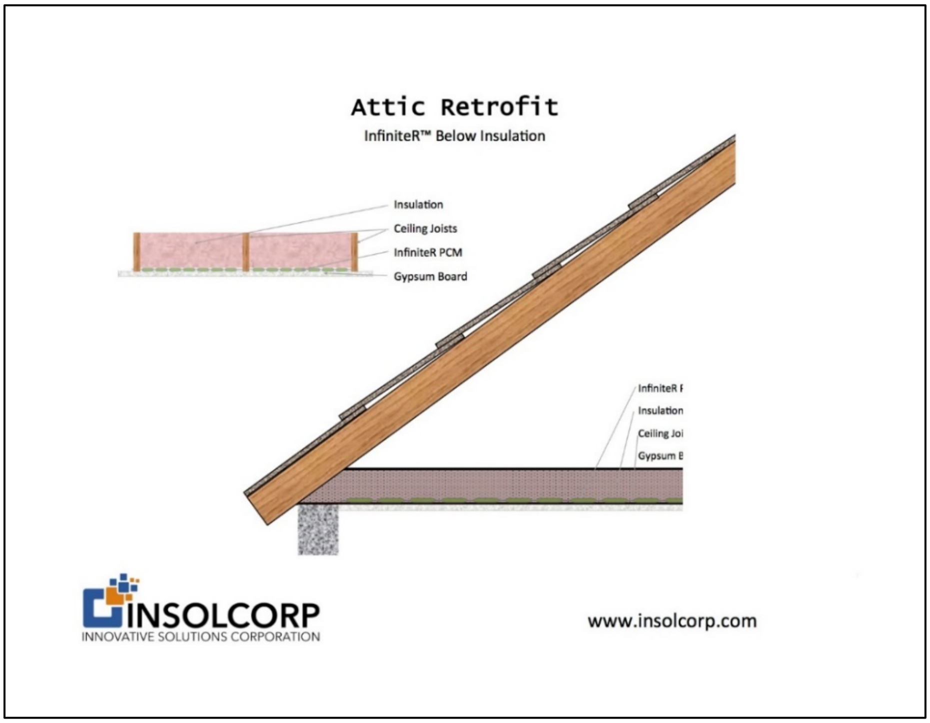


Image credit: Insolcorp, LLC

**Figure 12: Example attic retrofit with PCM on the attic roof deck**

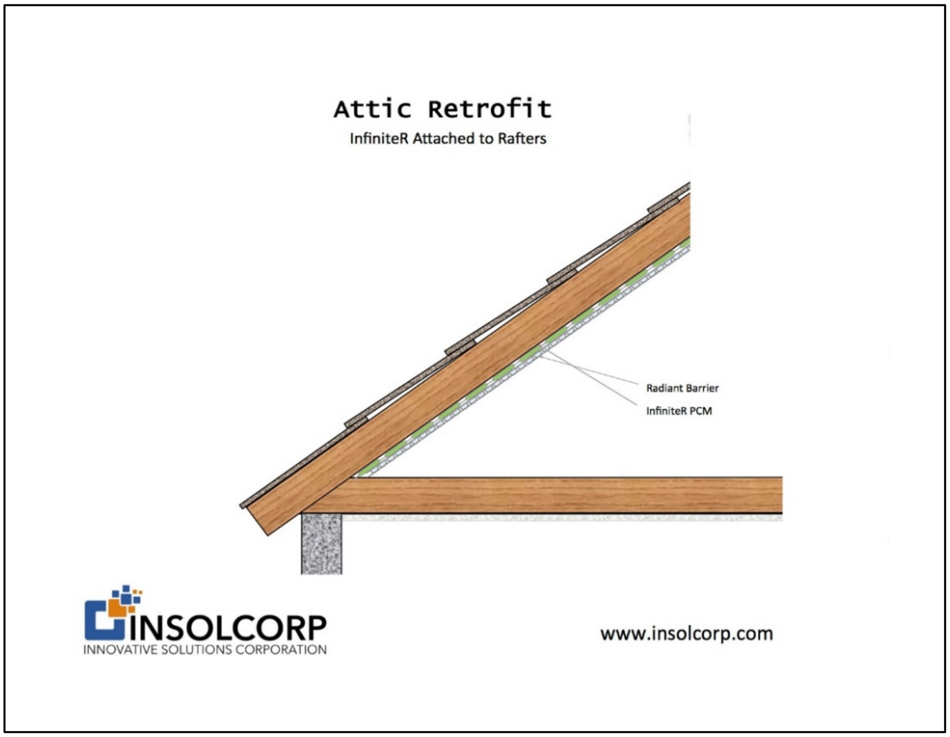


Image credit: Insolcorp, LLC

## General Test Strategy

During the field test phase of the project there will be a baseline monitoring period for a duration of 5-6 months and a post-retrofit monitoring period for a duration of 12 months. During the baseline monitoring period the test site will be instrumented with sensors to capture the existing conditions of the attic and conditioned space. Additional sensors will be added after the retrofit to capture the performance of the PCM that will be installed. For each of the field test sites, the post-retrofit monitoring data will be compared to the baseline monitoring data to evaluate the performance of the PCM in retrofitted vented attics using the following strategies:

- Energy use: Energy consumption of the HVAC system will be monitored for both the baseline and post retrofit period using power meters and/or gas meters (depending on the HVAC system fuel types).
- System performance: The PCM performance will be monitored in the post retrofit period using heat flux and surface temperature sensors both above and below the PCM in the attic. This will be used to determine the heating and cooling load reductions and the thermal cycles that have taken place. Both the baseline and post-retrofit period will have heat flux sensors installed on the roof deck, and ambient temperature and humidity sensors in the attic space to evaluate attic conditions. Additionally, both periods will have a logging thermostat to log the indoor conditions.

# Building Simulation

The primary use of building simulation for this applied research project will be to evaluate alternative configurations of the PCM in the attic for the purpose of designing the retrofits to be used in the field tests. The laboratory tests will provide important insights into the effectiveness of each configuration, including cost effectiveness, but performance under the full range of operating conditions must be analyzed using a model informed by the lab test results. Because residential building simulation tools such as BEopt have very few options for attic PCM configurations, and CBECC-Res does not yet have any options for PCM, it is likely that EnergyPlus will be the tool used for this project. EnergyPlus offers excellent flexibility but is not as user-friendly as most other tools. BEopt, which uses the EnergyPlus simulation engine, will be used to generate typical California house specifications, then the underlying building model will be modified to include PCMs using EnergyPlus directly.

The Team does not envision simulation in support of field testing because the performance of the PCM can be fully characterized through direct measurements of load reduction and heating/cooling energy use, as discussed earlier. Simple weather normalization techniques will be used to calculate energy savings under standard conditions. Building simulation may not improve accuracy, given the complex physics involved in attic modeling and the presence of only a single measure. However, simulations informed by the laboratory and field tests will be used to evaluate cost-effectiveness in alternative applications across Northern California. Simulations will also assist in the design of the retrofits to analyze each configuration and take into consideration cost-effectiveness.

# Project Timeline

Table 8 shows the high-level project milestones and deliverables with anticipated completion and due dates.

**Table 8: Anticipated project schedule for research on PCMs in residential buildings.**

| Project Milestones | Completion/Due Date |
|---|---|
| Laboratory Tests | April 2019 |
| Field Tests - Site Screening/Selection | December 2018 |
| Field Tests - Design Retrofits | March 2019 |
| Field Tests - Baseline Monitoring | June 2019 |
| Field Tests - Retrofit Monitoring | July 2020 |
| Program Participant Satisfaction Questionnaire for Homeowners | July 2020 |
| Model Development | March 2020 |
| Draft PCM Installation Guide | November 2020 |
| Final PCM Installation Guide | December 2020 |
| Draft PCM in Residential Applications Report | August 2020 |
| Final PCM in Residential Applications Report | September 2020 |

# CHAPTER 5:
# Commercial Daylighting Retrofits

Interior lighting remains a large component of electricity use in non-residential buildings. In California, electric lighting has both a direct effect on peak load, and an indirect effect by increasing cooling requirements during summer peak hours. Effective daylighting combined with electric lighting dimming controls can directly offset electric lighting energy by reducing lighting levels when necessary to reduce the load on the cooling system. However, in existing buildings where glazing area and location are likely to be fixed, there are a limited number of proven methods available for enhancing the level and quality of daylighting.

To address these challenges, the Team will create and implement a multi-pronged project to assess the potential energy savings and load shifting potential for several promising daylighting technologies. These technologies will reduce lighting electricity use by a minimum of 20% when packaged into an optimal combination for typical buildings in Sonoma and Mendocino Counties, while targeting even higher savings for ideal building sectors (e.g. schools or office buildings). CLTC will perform laboratory testing of innovative daylight harvesting technologies that show promise for cost-effective retrofits in commercial buildings. Lab-verified control technologies will be further tested as part of a field evaluation of alternate daylighting retrofit technologies in three non-residential buildings. The approach will include the implementation of several techniques for extending daylighting into dark interior spaces at two field test sites. In similar test buildings or occupied spaces with substantial existing daylight, CLTC will verify the ability of advanced control algorithms to manage the operation of the electric lighting and daylighting systems to optimize the overall energy efficiency of the building and reduce peak demand. Any comfort or operational issues will be identified through surveys of building owners, occupants and facility managers.

The following sections provide a detailed description of the research strategy that will be employed to evaluate innovative daylighting measures for Lead Locally. High-level plans for the enhanced daylighting project were addressed in Chapter 4 of the *Phase 1 Research, Instrumentation, and Monitoring Plan*.

## Technology Overview

Recent advances in commercial daylight harvesting technologies and control algorithms have opened the door to greater integration with related building systems and optimized overall performance, offering the potential for significant energy savings and peak load reduction in the commercial retrofit market. However, some of these technologies require further evaluation individually and in combination before lighting designers will feel comfortable including them for commercial building retrofits. Specific technologies that will be investigated include dimmable light-emitting diode (LED) lighting with motion- and photo-sensor-based controls and integrated communication technologies. In addition, daylighting management technologies will also be considered to help realize electric lighting savings and provide additional HVAC energy savings through automated management of solar heat gain and possibly natural ventilation and cooling. These technologies include automated Venetian blinds, roll-down shades, electrochromic glazing, tubular daylighting devices, sun-tracking skylights with mirrors and/or optical fibers, along with motion-sensing for detection of occupancy and photo-sensing to determine light levels for illumination and potential for glare from direct solar penetration.

A literature review will be performed at the start of the project to investigate manufacturers claims and learn from previously completed research and demonstration studies for each daylighting technology. The Team will estimate the lighting and HVAC energy savings that can be experienced through enhanced daylighting technologies that integrate automated operation of electric lighting, dynamic fenestration systems and HVAC. Opportunities for leveraging the advanced automated lighting controls for reducing peak electricity demand will also be an important topic of study.

## Daylighting Retrofit Technologies

Several technologies for enhanced daylight harvesting will be considered for the purposes of this project. This section is focused on examples of the types of technologies that will be considered, during the literature search.

### Electric Lighting Controls

Electric lighting controls have traditionally been synonymous with daylight harvesting controls and aim at continuously adjusting electric lighting output based on available daylight. They have been required by building energy codes in California and many other states for a long time. The automated operation has been traditionally based on the signal of a photo sensor, which is intended to monitor daylight changes in the space. Two main photo-sensing strategies have been traditionally in use, referred to as “open-loop” and “closed-loop” sensing.

In open-loop sensing, the photo sensor placement is aimed at sensing only daylight, i.e., the adjustment of electric lighting does not affect the signal of the control photosensor. In closed-loop sensing, the photo sensor placement is aimed at sensing the combination of electric lighting and daylighting, preferably in the space served by the electric lighting. In this case, the signal of the control photosensor is affected by the electric lighting being controlled. Unfortunately, none of these two traditional approaches has proven effective in sensing daylight changes reliably and cost-effectively.

Both sensing approaches require on-site commissioning, to determine the sensor signal set points for increasing and decreasing the output of the electric lighting so that the overall illumination stays above the Illuminating Engineering Society minimum requirements for the anticipated tasks in the space. The commissioning process is the most expensive component of the overall cost of electric lighting controls. One of the major disadvantages of both sensing approaches is that commissioning needs to be repeated every time there are significant changes in the geometry and/or reflectance of interior surfaces that affect the daylight levels in the space.

Close-loop sensing is also affected by small changes in geometry and reflectance of surfaces within the field of view of the sensor, such as occupants moving in the space. This is very common in most occupied spaces and there is no way to differentiate between them and true daylight changes using a single photosensor. To address this issue, most closed-loop sensing controls include a time delay before they adjust the output of the electric lighting. This, however, is not a solution to the problem, as it also applies to true daylight changes, when it should not. The result can be short but frequent periods of inadequate or excessive lighting when the sun becomes shaded by clouds, trees, overhangs, or adjacent buildings. The lack of immediate response to large perceivable differences in daylight levels may also have a negative effect in occupant acceptance.

In this project we will use new technological approaches, using either a combination of open-loop and closed-loop sensing (referred to as “dual-loop”), or redundant closed loop sensing across the space to improve reliability in sensing daylight changes. These approaches are capable of differentiating between true daylight changes and changes in interior surfaces. Moreover, they support automated and continuous calibration, which eliminates the commissioning process, greatly reducing the associated costs (Figure 13). This dual-sensing approach will be implemented in collaboration with PLC Multipoint, a Lead Locally industry partner.

**Figure 13. Dual Loop Photo-Sensing Technology for Skylight Applications**

Image credit: Legrand

**Dynamic Fenestration Systems**

Dynamic fenestration systems have traditionally included exterior and interior shading systems, such as Venetian blinds, horizontal and vertical louvers, roll up/down shades, etc. During the last 20 years, they are becoming increasingly available with motorized controls, which are now combined with environmental sensors for automated operation, to achieve optimal performance in terms of comfort and energy efficiency.

Shading systems have been used in buildings worldwide for a long time and are usually operated manually by occupants, based on their needs and desires, such as view, privacy, comfort and illumination. Manual operation, however, has proven to be a major problem for realizing electric lighting savings. This is because most occupants adjust shading systems to block daylight penetration at the first occurrence of discomfort from direct sun penetration, and that adjustment can remain for very long periods, while their illumination needs are met by electric lighting, which is at full output when there is minimal or no available daylight.

The new daylighting technologies that will be used in this project include automated dynamic fenestration systems, that adjust their status based on occupancy, potential for glare, and the status of the electric lighting and HVAC systems. The latter requires controls integration, which can be achieved with commercially available hardware technologies and requires software to establish communication between an "integration controller" and the individual controllers of the electric lighting, fenestration and HVAC systems. CLTC has developed such integrated approaches in the laboratory and is currently preparing to demonstrate and evaluate them in a building at the UC Davis campus.

The controls integration is based on a simple and effective algorithmic approach, which is designed to prioritize comfort during occupancy and energy efficiency during vacancy. The goal of the algorithmic approach during occupancy is to provide as much light as needed to minimize electric lighting output, without producing glare from direct solar penetration. After the electric lighting is at minimum output, the algorithmic approach uses the status of the HVAC system to either bring in as much solar heat gain as possible (without glare) when the HVAC is in heating mode or keep the total daylight flux constant when the HVAC is in cooling mode, because additional unnecessary daylight would increase cooling loads. During vacancy, the electric lighting is turned off or set to minimum output and the fenestration is adjusted to maximize or minimize solar heat gain, based on the status of the HVAC and without concern about glare.

Examples of dynamic fenestration systems that will be considered in the literature review include Venetian blinds, rolling shades and films and electrochromic glazings, which can change their transmittance on demand (Figure 14, Figure 15, Figure 16).

**Figure 14. Example of motorized exterior Venetian blinds**

Image credit: MISDAR Architectural Shading Solutions

**Figure 15. Example of automated rolling shades**

Image credit: MechoSystems

**Figure 16. Example of electrochromic glazings**

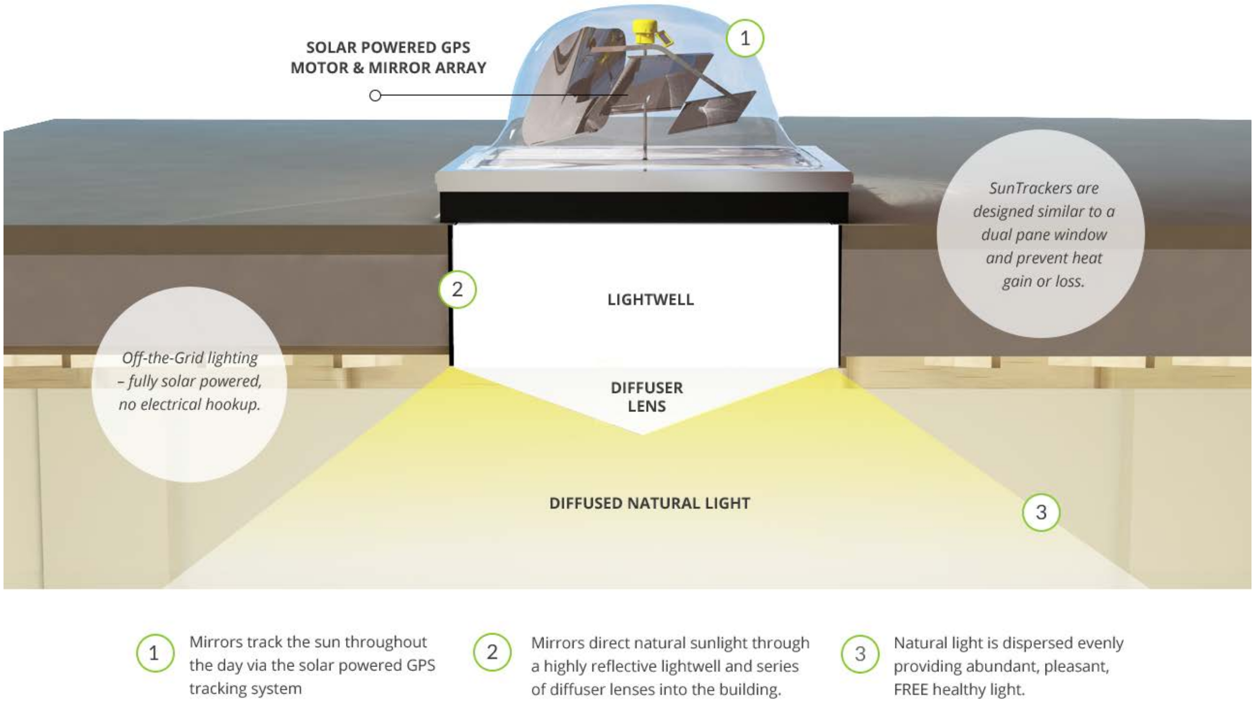
Image Credit: SageGlass

### Sun-Tracking Skylights

Skylights have proven to be very effective in saving electric lighting energy and associated HVAC loads in commercial buildings, especially in single-story buildings and the top floor of multi-story buildings. The California building energy standards require daylight illumination and electric lighting controls over at least 75% of floor area in new commercial buildings larger than 5,000 $ft^2$ that are directly under a roof with ceiling heights greater than 15 feet. For commercial building retrofits, the potential savings for skylights remains high, but the installation cost for installing new skylights in an existing roof without existing skylights can be prohibitive. Replacement of existing skylights, however, could prove cost-effective and provide better lighting.

One of the key shortcomings of skylights is the uneven contribution of daylight during the course of a day, with significantly less daylight during times that the sun is at lower altitude angles (e.g., early morning and later afternoon) and significantly more daylight during times that the sun is at higher altitudes angles (later morning through early afternoon). This results in low electric lighting energy savings during early morning and late afternoon and increased solar heat gain during late morning through early afternoon. Sun tracking skylights are designed to increase daylight penetration from low solar altitude angles and reduce it from high solar altitude angles. To achieve this, mirrors hanging under the skylight are placed at well-configured angles and rotate azimuthally, tracking the path of the sun over the course of the day. The mirrors reflect direct sunlight from low altitude angles downwards and block direct sunlight from high altitude angles (Figure 17).

**Figure 17. Example of sun-tracking skylights**



*SunTrackers are designed similar to a dual pane window and prevent heat gain or loss.*

*Off-the-Grid lighting – fully solar powered, no electrical hookup.*

① Mirrors track the sun throughout the day via the solar powered GPS tracking system

② Mirrors direct natural sunlight through a highly reflective lightwell and series of diffuser lenses into the building.

③ Natural light is dispersed evenly providing abundant, pleasant, FREE healthy light.

Image credit: Ciralight Global, Inc.

### Building-Core Sun-lighting Systems

Building-core sun-lighting systems are aimed at providing daylight illumination in spaces at the building core, i.e., away from daylight apertures, by capturing direct sunlight outdoors and then transporting and distributing it to interior building spaces. Such systems have been at the research and development stage for many years, but have not seen commercial success, except for the Parans system, distributed by Lead Locally partner Huvco, LLC. The Parans system uses optics to collect and concentrate sunlight, fiber optic cable to transfer it to the building-core spaces, and customized luminaires for ambient and accent lighting to distribute it within each space (Figure 18). Because fiber optic cable is flexible and can easily turn corners, the daylit space does not have to be directly under the collector.

**Figure 18. Fiber-Optic Core Sun-Lighting System**

Image credit: Parans

### Tubular Daylighting Devices

Tubular daylighting devices (TDDs) can be considered as hybrids of skylights and building-core sun-lighting systems. They admit daylight through a small skylight-like aperture on the roof with optics aimed at addressing high and low altitude angles, just like the sun-tracking skylights, but without moving parts. The admitted daylight is “transported” through tubes with very high interior reflectance, over significantly long distances, to reach the ceiling of the space to be illuminated. The daylight is then distributed into the space using diffusers similar in appearance to electric lighting. Some manufacturers, like Solatube, which first introduced this strategy in the market, include mechanisms to control the flow of daylight in the tubes, to produce an end results similar to that of dimming an electric lighting luminaire (Figure 19). Unlike fiber optic systems, TDDs must follow a straight vertical pathway from the lighted space up to the roof. However, they are much less expensive.

Figure 19. Examples of Tubular Daylighting Devices in commercial applications

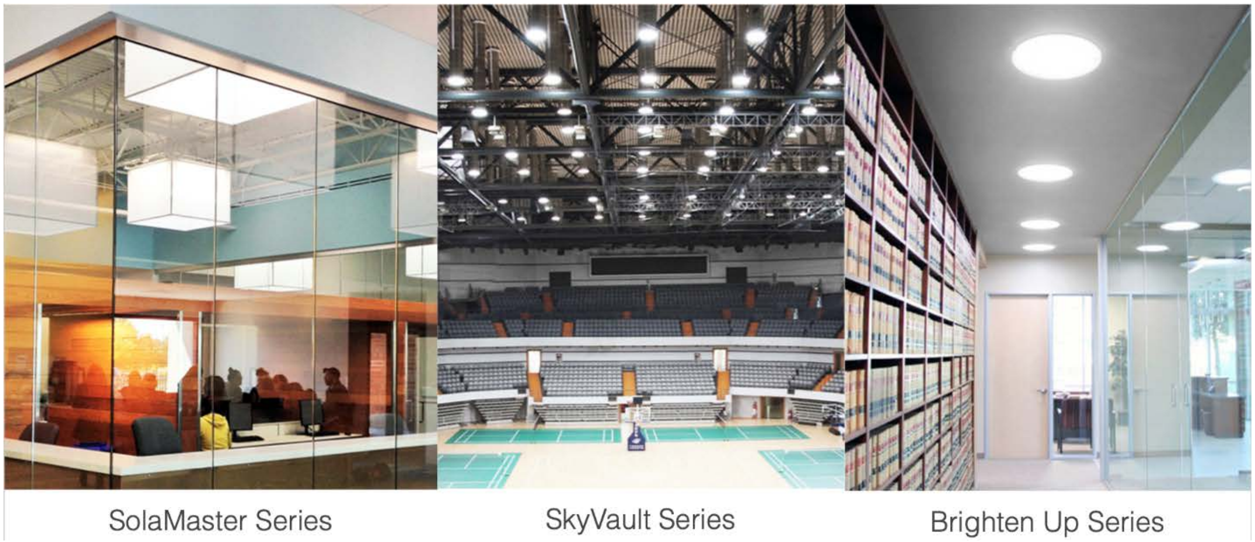


Image credit: Solatube

### Venting Fenestration Systems

In addition to lighting, heating and cooling loads reduction through shading mechanisms, dynamic fenestration systems can also reduce ventilation and cooling loads through venting mechanisms (see Figure 20). This is especially beneficial for energy savings in California, where the difference between daytime and nighttime temperatures varies significantly, especially in San Joaquin Valley.

Figure 20. Example of venting skylight

Image credit: Crystalite

## Enhanced Daylighting Benefits

Economic benefits that could be experienced from commercial daylighting applications include cost savings through reduced energy requirements and lower lamp replacement, commissioning and operational costs. Health and comfort benefits may also be felt by building occupants, such as improved effects on circadian rhythms, less sensitivity to illumination levels and reduced glare potential, lower internal solar heat gains, significant reduction in radiation asymmetry, and better acoustic insulation performance.

## Enhanced Daylighting Performance Uncertainties

Key performance issues and uncertainties that may be expected with the above-mentioned technologies include delayed response times, decreased occupant acceptance, stricter maintenance and cleaning requirements, and dependency on climate and fenestration orientation. Installed costs for many of the technologies may be uncertain as well. Most of the performance uncertainties are related to the effectiveness of sensors to accurately sense conditions in the space, and controllers to effectively use the sensor's output to manage electric lighting, fenestration, and HVAC for proper operation.

While it is easy to measure illuminance levels, it is not as easy to determine the potential for glare from direct solar penetration. Currently available systems use illuminance and/or irradiance measurements to determine the presence of direct solar radiation, and/or time of day to determine solar position. That information is then coupled with geometric information about the building and its surroundings, along with custom algorithms for each window, to address window orientation and external obstructions that could possibly provide shading. These approaches are expensive to implement due to the required upfront work and programming, as well as commissioning.

A new approach that uses analysis of video streams of each window view holds promise for not only identifying direct solar presence, but also identifying reflected solar radiation and perceiving more than one sources of glare, e.g., direct sun and reflected sun at the same time, which may come from different directions. The most important functionality of the new approach is that the analysis of the video stream includes computation of the relative polar coordinates of each potential glare source, which in turn supports very accurate adjustment of shading systems. This new approach may be considered in this project during laboratory testing to evaluate its effectiveness.

Another uncertainly for the proposed daylighting technologies is the harmonization of the automated operation of all systems with manual operation by occupants. Several approaches will be tested in the field evaluation to determine the most effective ones. Similarly, the automated operation of venting mechanisms for natural ventilation and cooling must be harmonized with the operation of the HVAC systems, to ensure that there are no conflicts and issues, such as pressurization.

## Potential Inclusion in the Energy Marketplace and EE Programs

The dual-loop and multi-closed-loop sensing approaches have great potential for inclusion in the Energy Marketplace and statewide EE programs. The same is true for dynamic fenestration systems, which have significant potential for realizing electric lighting savings and providing additional energy savings through reduction of HVAC loads. Dynamic lighting and fenestration systems are already available and specified in building retrofit projects and these technologies bring them to the next level of automation for realization of optimized system-level performance for energy and comfort.

The inclusion of enhanced daylighting technologies in the Energy Marketplace and in wider EE Programs will depend on the following factors:

- Achieving the specific technology Success Metrics, first in the lab and then in the field-testing phases.
- Achieving electricity savings potential, as identified by the literature review for the technologies.
- The successful delivery of energy savings contributing to the overall portfolio level site electricity savings target of 20% for commercial buildings. For the applied research part of the project, savings will be isolated to the measure level. In most cases the wider rollout of successful measures will be through specific technologies bundled as components of retrofit packages.
- Local supply chains capable of delivering the technology products for fast installation turnaround following order.
- Positive feedback from participating commercial buildings during the Technology Demonstration stage e.g. savings benefits, improved comfort, and quality of installation.

## Research Questions

The Lead Locally team will look to answer the following research questions as part of the laboratory and field test activities conducted by CLTC:

- Do technologies perform as expected under controlled anticipated daylight and occupancy conditions?
- Do technologies perform as expected in the field?
- How do occupants feel about these technologies in terms of their automated operation and the harmonization with manual override?

The following questions will be addressed through simulations conducted by Frontier Energy with input from CLTC:

- Can existing daylighting and energy simulation tools model the dynamic nature of the daylight harvesting technologies effectively?
- How do simulation results compare to actual performance in the laboratory and in the field?
- What is the estimated annual performance of the daylighting technologies in different applications in terms of occupancy, climatic conditions and fenestration orientation?

Additional questions may arise as more information is discovered during the analysis portion of the project. These additional questions may result in potential future research work to discover better uses or applications of these technologies.

# Laboratory Testing

After the completion of the literature review, specific daylight harvesting technologies will be tested in the laboratory to verify the effectiveness of their automated operation. The focus of the laboratory testing will be on verifying proper operation of the integrated controls for effective operation of the electric lighting and the dynamic fenestration systems. The integrated controls approach will be tested under many different occupancy and daylighting scenarios, to ensure that the algorithms are effective and operate properly. The scenarios will also include manual overriding to address potential issues with harmonizing manual and automated operation, and to prepare the required algorithms for the field-testing part of the project.

## Research Questions and Success Metrics

The following research questions will be considered during the laboratory testing, focusing on verifying the claims of each daylight technology:

- Do the dual-loop and multi-closed-sensor systems effectively detect daylight changes? Do they result in proper operation of electric lighting? Do they effectively provide continuous calibration?
- Is the operation of the integrated controls accurate and effective during occupied and unoccupied periods?
- Are the sensing approaches for glare potential effective in detecting glare conditions?
- Do the dynamic fenestration systems operate effectively to reduce glare potential?
- Does manual override for each system work harmoniously with automated operation?

The success metrics will focus on effective automated operation, in terms of timing and accuracy of:

- Detection of environmental conditions
- Communication among controllers
- Execution of control algorithms
- Effective adjustment of dynamic systems

## Test Facility

Laboratory testing of all commercial daylight harvesting technologies will be performed at the CLTC in Davis, California. CLTC includes an Integrated Building Controls Laboratory (IBCL) which is highly adaptable to research needs, and can accommodate virtually any combination of windows, skylights, blinds, shades, electric light fixtures, and lighting controls. The IBCL includes a simulator of daylight changes, which supports testing under customized daylight scenarios, such as sunrise, sunset, and partly cloudy periods (see Figure 21). The IBCL supports consideration of windows and skylights and has been used to develop the integrated approach for the daylighting technologies that will be used in this project.

**Figure 21. The CLTC Integrated Building Controls Laboratory (IBCL)**

Image credit: California Lighting Technology Center

The CLTC IBCL facility will be modified to accommodate the commercial daylight harvesting technologies being evaluated, and to identify any issues related to installation, commissioning, integration, and operation of these technologies. Selected CLTC spaces will also be modified to test the performance of daylighting technologies under real sun and sky conditions.

### Test Matrix

For each laboratory test, a broad range of parameters will be monitored, including power, energy, illumination levels, glare potential, response times, and harmonization of manual and automated operation, i.e., finding the appropriate triggering events and/or timing for switching to automated operation after manual overrides. The independent variables will be focused on environmental conditions, such as sky conditions, daylight levels, sun position and movement, long-term changes in geometry and reflectance of interior surfaces, and short-term changes caused by movement of occupants in the space.

In addition to verifying effective operation of each daylighting technology, the following will also be considered to determine readiness for field testing in occupied buildings:

- Potential for effective installation, commissioning and operation
- Potential to realize expected energy and peak demand reduction
- Potential to realize comfort and cost benefits

## Field Testing

After the completion of the laboratory testing, specific daylighting technologies will be selected for field testing in occupied commercial buildings in Sonoma or Mendocino County. The field sites will be selected based on the selected technologies, to ensure that they will be installed in spaces that can benefit from their capabilities. The focus of the field testing will be on verifying proper operation, energy and peak demand reduction, and acceptance by occupants and facility managers.

## Research Questions and Success Metrics

The field testing will focus on the following research questions:

- Is the operation of each technology accurate and effective during occupied and unoccupied periods?
- Is the integrated operation accurate and effective?
- Is the automated operation harmonized with manual controls effectively?
- How do space occupants feel about the technologies and their operation?
- What are the electric lighting energy savings?
- What is the impact on heating and cooling loads?
- What is the impact on ventilation and cooling loads (for venting systems)

In addition to these research questions, the field testing will monitor all associated costs, including the cost of the technologies, their installation, commissioning and maintenance.

## Test Sites

Site selection requirements for all daylighting technologies include the following:

- Building owner to approve window and/or skylight changes and/or installation of new skylights and tubular daylighting devices.
- Spatially fixed work stations within the approved sites, such as office and classroom spaces, with year-round occupancy between 7 am and 6 pm, 5 days/week.
- At least two similar spaces with significant daylighting potential, only one of which will receive daylighting retrofits. This will allow side-by-side evaluation of the daylighting measures in spaces subjected to very similar weather and operating conditions.
- LED lighting with occupancy and photo-sensor controls capable of communicating through standardized protocols, such as BACNET IP, manually operated Venetian blinds or rolling shades, and a T-bar drop ceiling.

Requirements for spaces with windows include:

- Window orientation should be South, ranging from SE to SW and those windows should have an unobstructed view of the sky.
- Window-to-wall ratio of at least 40%, and high-performance glazing, in a space deeper than two window-heights from the window wall.

Requirements for spaces away from windows and skylights include:

- Essential that the space is in the top two floors of the building and supports penetration through the roof and ceiling. (Basements can be considered depending on ease of penetration access to such spaces)
- Unobstructed view of the sky hemisphere above the roof.

## Retrofit Systems and Equipment

The retrofit design will be performed in collaboration with industry partners that manufacture or market the selected technologies, and the owner and facility manager of the facility. Lead Locally team members, including SCP, Frontier, and DNV GL, will be consulted prior to the installation of retrofits to help determine the best approach for each building.

## General Test Strategy

Pre-retrofit instrumentation will be focused on determination of energy consumption, peak electricity demand, illumination levels and potential for glare introduced by daylight. The pre-retrofit test duration will be limited to about 3 months, which should provide sufficient data to understand the general quality of existing daylighting and the general usage patterns for the space. The Baselines for the project will include similar spaces within the same buildings that are not retrofit. These spaces will be monitored simultaneously with the enhanced daylit spaces for a period of at least one year. This side-by-side evaluation of the daylighting measures will provide a more meaningful evaluation of the technologies and a better estimate of electricity savings, because the relevant spaces will be subjected to very similar weather and operating conditions.

The retrofit implementation will follow the retrofit design specifically selected for each site. The post-retrofit instrumentation will match the pre-retrofit instrumentation to the extent possible in order to facilitate comparative evaluation. Data for pre-retrofit (or non-retrofit) spaces and post-retrofit spaces will be analyzed comparatively to evaluate the performance of the daylighting technologies in terms of energy, cost and comfort.

## Success Metrics

Performance relative to the following metrics will be reviewed and ultimately determine which daylighting technologies are ready for deployment to the broader retrofit market in Northern California:

- Verification of expected performance in the field in terms of energy savings and peak demand reduction.
- Ascertaining a positive response from the facility manager and space occupants in terms of overall lighting quality.
- Understanding of design and installation challenges, and methods for overcoming them.
- Recommendations for cost-effective applications in the commercial building sector.

# Building Simulation

Simulations may be performed to estimate annual energy performance of the commercial daylight harvesting technologies under standard operating conditions, and to extrapolate results to other building types and climates. Any daylighting models developed under this project will be validated against measured lab and/or field test data.

## Project Timeline

Table 9 shows the high-level project milestones and deliverables with anticipated completion and due dates.

**Table 9. Anticipated project schedule for research on commercial daylighting retrofits**

| Project Milestones | Completion/Due Date |
|---|---|
| **Literature review and selection of technologies for lab testing** | January 2019 |
| **Laboratory tests – Installation of technologies** | March 2019 |
| **Laboratory Tests** | June 2019 |
| **Laboratory Test Report** | July 2019 |
| **Field Tests - Site Screening/Selection** | March 2019 |
| **Field Tests - Baseline Monitoring** | Mid-July 2019 |
| **Field Tests - Design Retrofits** | August 2019 |
| **Field Tests – Retrofits Installation** | November 2019 |
| **Field Tests - Retrofit Monitoring** | November 2020 |
| **Model Simulations** | November 2020 |
| **Satisfaction Questionnaire for Owners and Occupants** | December 2020 |
| **Draft Report** | December 2020 |
| **Final Report** | January 2021 |

# CHAPTER 5:
# Conclusion and Next Steps

This Phase 2 Research, Instrumentation, and Monitoring Plan (Plan) establishes clear methodologies for evaluating three applied research technologies: (1) Efficiency optimizing control strategies for grid interactive heat pump water heaters, (2) attic-mounted phase change materials for residential buildings, and (3) enhanced daylighting for commercial buildings. Key subcontracts related to this research effort are in place, and all industry partners have provided significant feedback to ensure that the scope and milestones are achievable within the budgetary, staffing, and administrative (permits, prevailing wage) constraints of the Lead Locally grant.

Specific details on the make/model, locations, and accuracy of the instrumentation package will be provided in Monthly Progress Reports for the grant as they are defined based on the characteristics of the retrofit packages, the realities of the test sites, and the criteria established in the Phase 2 EM&V Framework. An effective research program must be adaptable to changing circumstances and unexpected challenges that may be encountered during the execution of the project. As a result, the emphasis of this Plan is to document the decision-making process and overall strategies that will guide the choice of test sites, selection of research questions, and approaches to answering those questions accurately and completely. Ultimately, this Plan supports the important Lead Locally project implementation goal of expanding the range of retrofit technologies with proven performance and cost-effectiveness in Northern California.

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# GLOSSARY

| Term | Definition |
|---|---|
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| ASTM | American Society for Testing and Materials |
| AWHP | Air to Water Heat Pump |
| BSRL | Building Science Research Laboratory |
| BTU | British Thermal Unit |
| CEC | California Energy Commission |
| CLTC | California Lighting Technology Center |
| COP | Coefficient of Performance |
| CPUC | California Public Utilities Commission |
| CVRMSE | Coefficient of Variance of Root Mean Square Error |
| DHL | CLTC's Daylight Harvesting Laboratory |
| EE | Energy Efficiency |
| EM&V | Evaluation, Measurement and Verification |
| EMS | Energy Management System |
| EPIC | Electric Program Investment Charge |
| Framework | Phase 1 EM&V Framework |
| FSTC | Food Service Technology Center |
| HPWH | Heat Pump Water Heater |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IBCL | Integrated Building Controls Laboratory |
| IOU | Investor Owned Utility |
| Lb | Pound |
| LED | Light-Emitting Diode |
| NMBE | Normalized Mean Bias Error |

| | |
|---|---|
| NREL | National Renewable Energy Laboratory |
| PCM | Phase Change Material |
| Plan | Phase 2 Research, Instrumentation, and Monitoring Plan |
| SCP | Sonoma Clean Power |
| TDD | Tubular daylighting device |
| Team | All Lead Locally Program Partners |
| TRL | Technology Readiness Level |
| UC | University of California |
| UEF | Uniform Energy Factor |
| UL | Underwriters Laboratories |
| W | Watt |