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# Session 5: TES with HVAC in Today's Market

## S4B Annual Meeting – Thermal Energy Storage Integration in Commercial and District Applications

**Chair**: Dr. Min Gyung Yu, Control System Engineer, PNNL

**Presenters:** Dr. Tim J. LaClair (NREL), Dr. Marco Pritoni (LBNL), Vishaldeep Sharma (ORNL), Dr. Spencer Dutton (LBNL)

**Stor4Build Annual Meeting**
August 26–27, 2024
Oak Ridge National Laboratory

# Agenda

- Presentation 1: Thermal Energy Storage Evaluation for the California State University Dominquez Hill Campus Central Plant
- Presentation 2: Campus-wide Field Demonstration of Load-shifting, Peak Reduction, and Full Renewable Utilization with Thermal Energy Storage
- Presentation 3: Quick Service Restaurant Walk-in Freezer Demand-load Reduction
- Presentation 4: Deployment of a Commercial Packaged Heat Pump and Compact Thermal Energy Storage for Small Buildings
- Q&A

# Thermal Energy Storage Evaluation for the California State University Dominguez Hill Campus Central Plant

**Presenter:** Tim J. LaClair, NREL

**Contributors:** Korbaga Woldekidan, Zahra Fallahi, Carlo Bianchi

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NREL/PR-5500-91060

# CSU Dominguez Hills Campus TES system

**Background:** Curtailment of renewable power in California has increased rapidly in recent years, and solutions are being pursued to avoid or reduce curtailment to maximize the use of clean energy sources. California State University Dominguez Hills (CSUDH) seeks to implement a large TES system capable of capturing renewable energy that would otherwise be curtailed with a *goal of storing sufficient energy within a 5-hour period each day to meet the campus' entire 24-hour heating and cooling needs*.

**Innovation / approach:**

- Evaluation of **TES options for both heating and cooling**
- This project aims to lay the **groundwork for establishing the feasibility of campus-scale TES** installations that, if successful, **can be deployed across all 23 campuses** of the California State University system

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# Project Objectives

- Develop a framework to establish both the technical and economic potential for installation of an on-campus TES system
  - Enable broader use of renewable energy
  - Provide heating and cooling requirements at the CSU Dominguez Hills campus
- Tool development for sizing and TES load estimation to scale-up the use of this method in other locations
  - Flexible, plug-and-play approach that will enable future feasibility assessments to be performed at other locations
  - Assist other facilities in rapid decision making and deployment by providing a simple analysis framework

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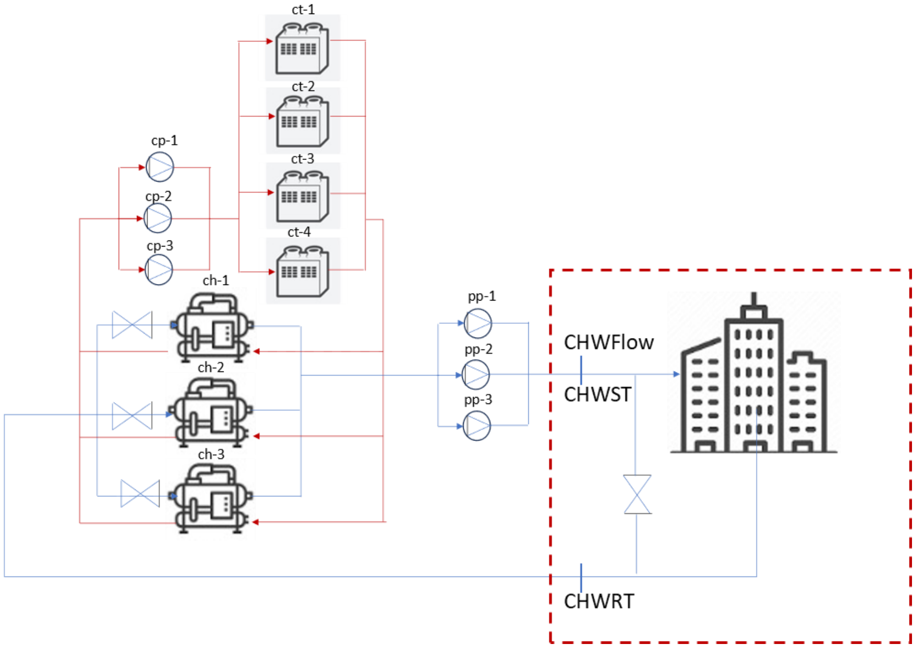
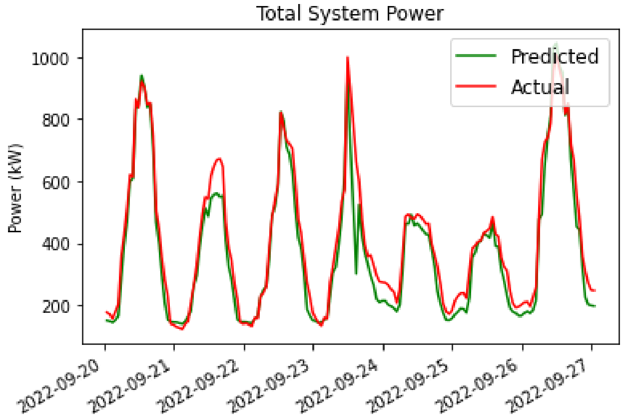
# Cooling System Overview

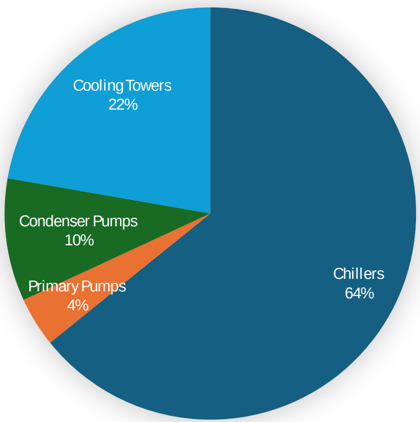
- Provides cooling to 52 AHUs serving 900,000sf of building space
- Comprised of:
    - Three 1000 Ton variable speed electric chillers
    - Three 125 HP variable speed primary pumps
    - Three 100 HP variable speed condenser pumps
    - Four cooling towers (eight 7.5 HP variable speed fans per tower)



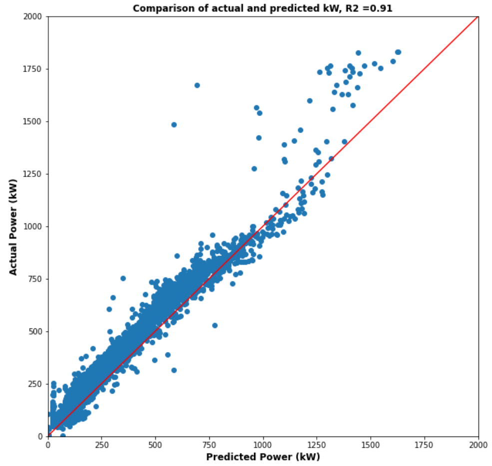
# Equipment Models

- Empirical sub-models developed to estimate the energy consumption of system components across all normal operating conditions
- Sub-models for:
  - Chillers
  - Chilled water pumps
  - Condenser pumps, and
  - Cooling towers



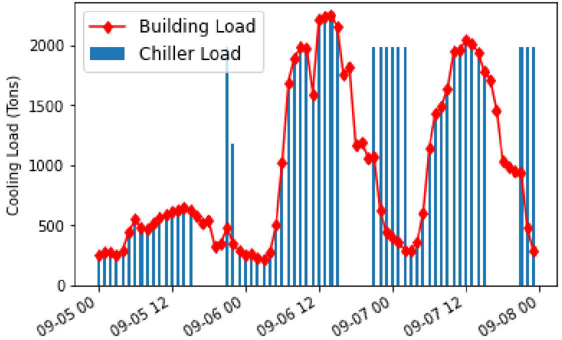

Energy Consumption among central plant sub-systems



# TES Sizing and Operation

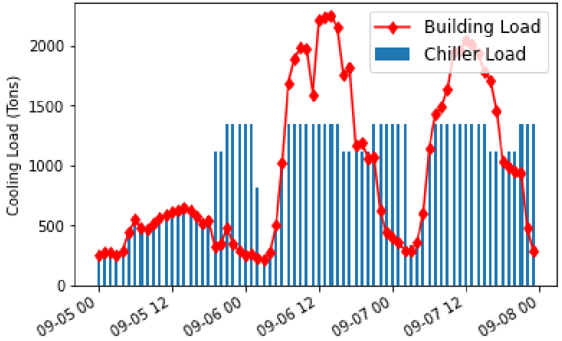
Four sizing and operation approaches considered:

- Full storage
  - Shifts the entire on-peak load to off-peak hours and halts chiller operation during peak hours
  - Preferable when on-peak demand charges are high, or the on-peak hours are short




- Load leveling (Partial Storage)
  - Peak hour cooling needs are satisfied by simultaneous operation of chillers and TES.
  - Preferable strategy when the peak cooling load is much higher than the average

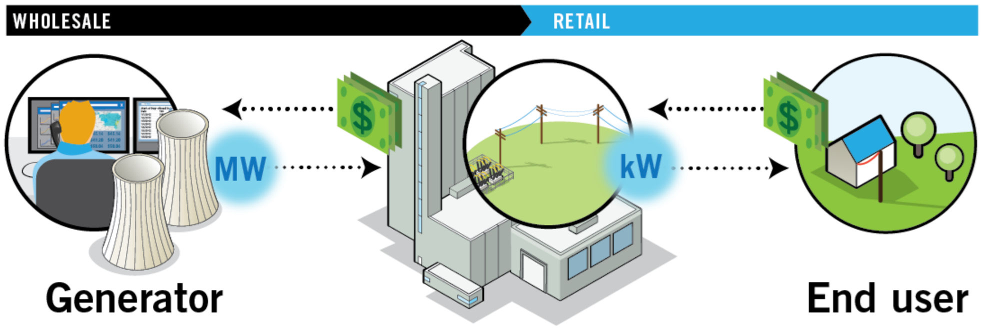
- Peak Demand limiting
  - Chillers run at reduced capacity during on-peak hours




- Curtailment hours charging
  - Chillers operate at full capacity during curtailment hours to support the cooling needs during non-curtailment hour
- Additional evaluations considering simultaneous battery operation

(Note: the model considers full campus loads for load shifting, not just the central plant, to maximize cost savings)

# Operational Cost Analysis: Electricity Billing




**Reseller**

i.e., electricity utility companies, competitive power providers and electricity marketers

FERC
https://www.ferc.gov/understanding-and-participating-california-iso-caiso-processes

Provides wholesale electricity — Shell Global

Direct Access
CSUDH and other campuses

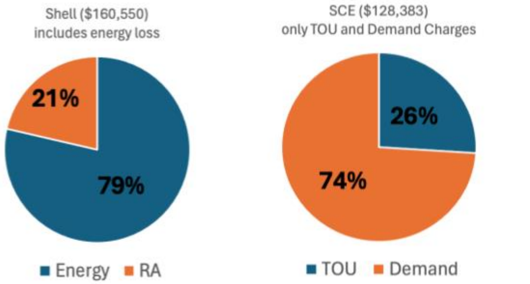
CSUDH

Provides transmission and distribution — SOUTHERN CALIFORNIA EDISON

Delivery

| Shell Bill<br>Annual contract | | August 2023 |
|---|---|---|
| - | Energy costs<br>($/kWh) metered + losses | 0.097 |
| - | Resource Adequacy costs<br>($/kW) | 11.900 |

| SCE Bill<br>Seasonal changes | | August 2023 |
|---|---|---|
| - | TOU costs<br>($/kWh) | 0.02909 to 0.03020 |
| - | Demand charges<br>($/kW) | 20.84 to 35.34 |




Energy (kWh) and demand charge (kW) costs, Aug 2023

# Technoeconomic Analysis

- Cost model developed and validated against past electric bills
- Capital and operational costs evaluated to determine payback for each operating scenario
- Greatest savings achieved using full storage scenario to maximize campus-wide peak demand

TEA results for full storage TES implemented without battery storage:

| | | |
|---|---|---|
| Tank Size/capacity | 1,655,768 Gallon | 12,658 ton-hour |
| Capital Cost | $3,553,749 | |
| Capital Cost, with IRA | $2,132,250 | 40 % discount |
| Annual operational cost savings* | **$265,046** | |

Payback period (years):

| | | | | | | |
|---|---|---|---|---|---|---|
| Discount rate | 0.00% | 1.00% | 2.00% | 3.00% | 4.00% | 5.00% |
| Payback period, without tax incentives | 14 | 15 | 16 | 17 | 19 | 21 |
| Payback with 40% IRA tax credit | 9 | 9 | 9 | 10 | 10 | 10 |

* Cost evaluation does not include impacts on Shell bill, which is aggregated with other CSU campuses

# Final Remarks

## Key Findings:

- Detailed model evaluated multiple control strategies for load shifting, and considers campus battery use
- Current tax credits under IRA result in a **very favorable payback (9-10 yrs) for full load-shifting campus TES system** without a battery, and there is a reasonable payback (14-21 yrs) even without the tax incentive

## Next Steps:

- A **simplified approach** will be developed and validated in FY25 to allow other campuses to **complete basic feasibility evaluation with minimal inputs** (central plant load profile, electricity rate structure and historical electric loads)
- Results will be **expansible across 23 other CSU campuses**, and applicable to other district systems

## Policy Issues/Potential Concerns:

- **Existing utility rate structures effectively discourage** the practice of using curtailed electricity to charge TES
- Battery energy storage systems yield similar load shifting capabilities as TES. **Existing utility programs and 3rd party offerings can make BES a cheap option, which effectively disincentivizes TES deployment**, even though TES is expected to be more favorable from a sustainability perspective over the long run

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# Campus-wide Field Demonstration of Load-shifting, Peak Reduction, and Full Renewable Utilization with Thermal Energy Storage

## S4B Annual Meeting - Integration Thrust Area

Photo from iStock-1199224443


**Presenter**: Marco Pritoni

**Contributors**: Donghun Kim (PI), Armando Casillas


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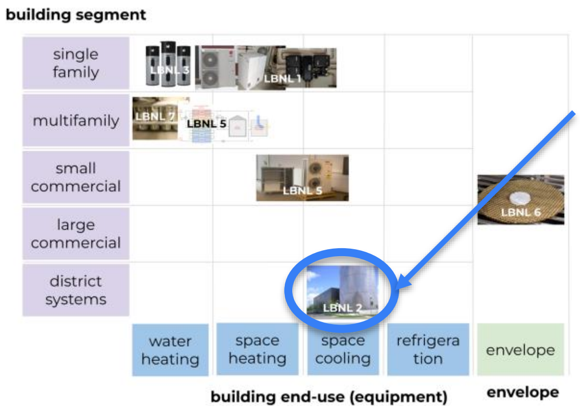
BERKELEY LAB | OAK RIDGE National Laboratory | ACEEE American Council for an Energy-Efficient Economy

NREL Transforming ENERGY | Pacific Northwest NATIONAL LABORATORY

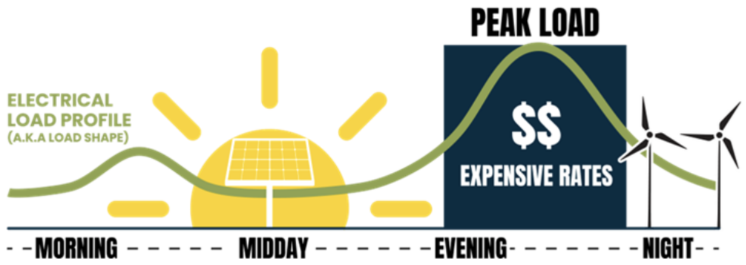



Campus-wide Field Demonstration of Load-shifting, Peak Reduction, and Full Renewable Utilization with Thermal Energy Storage

2024 Annual Meeting

# CalFlexHub

- Identify, evaluate, develop, and demonstrate pre-commercial, load flexible technologies
- **Standardize the signals** used to communicate dynamic price and GHG information to devices



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| | |
|---|---|
| Sector/Building Type | District Energy Systems |
| Technology & End Use | Chiller plants,<br>Chilled water tank,<br>PVs |
| Communications Pathway | price/CO2 signal -> MPC server <-> ALC <-> HVAC |
| Grid-Edge Benefit | - Automated load shifting in response to grid signals<br>- Peak demand reduction<br>- Better on-site renewable integration (more use of self generation) |
| Testing Status (Timeline) | Test performed in summer and winter 2023, continuing in 2024-25 |

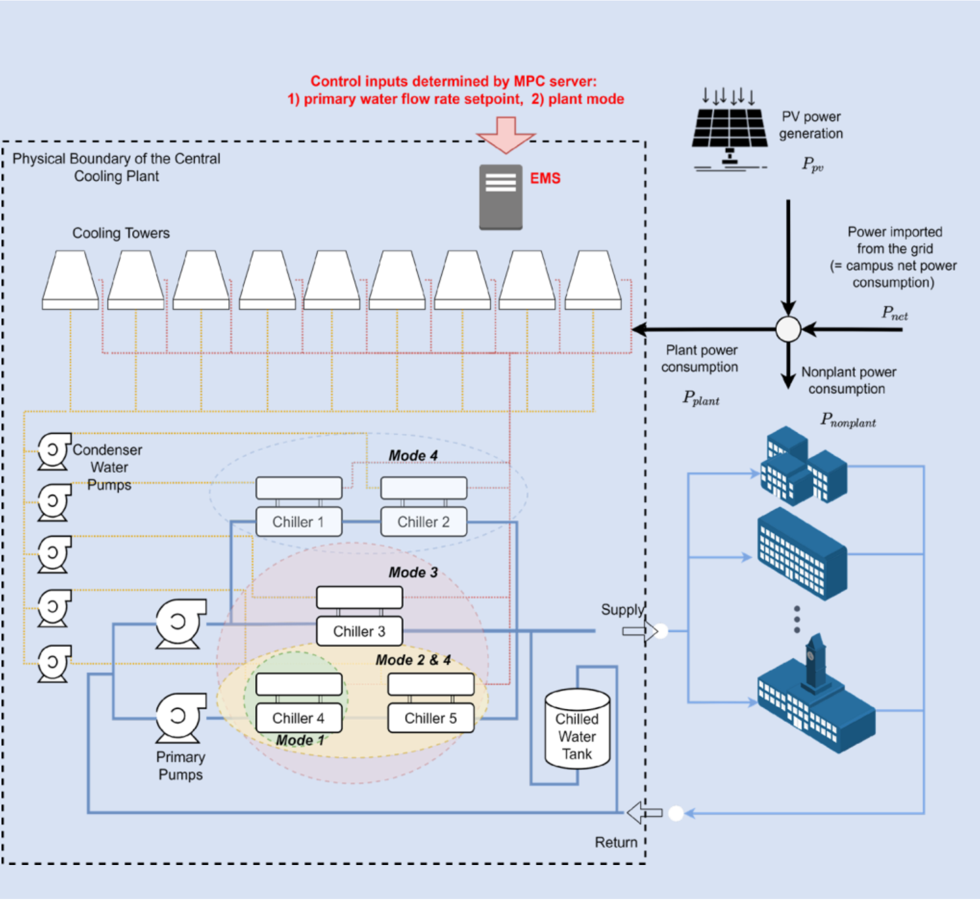

UC Merced:

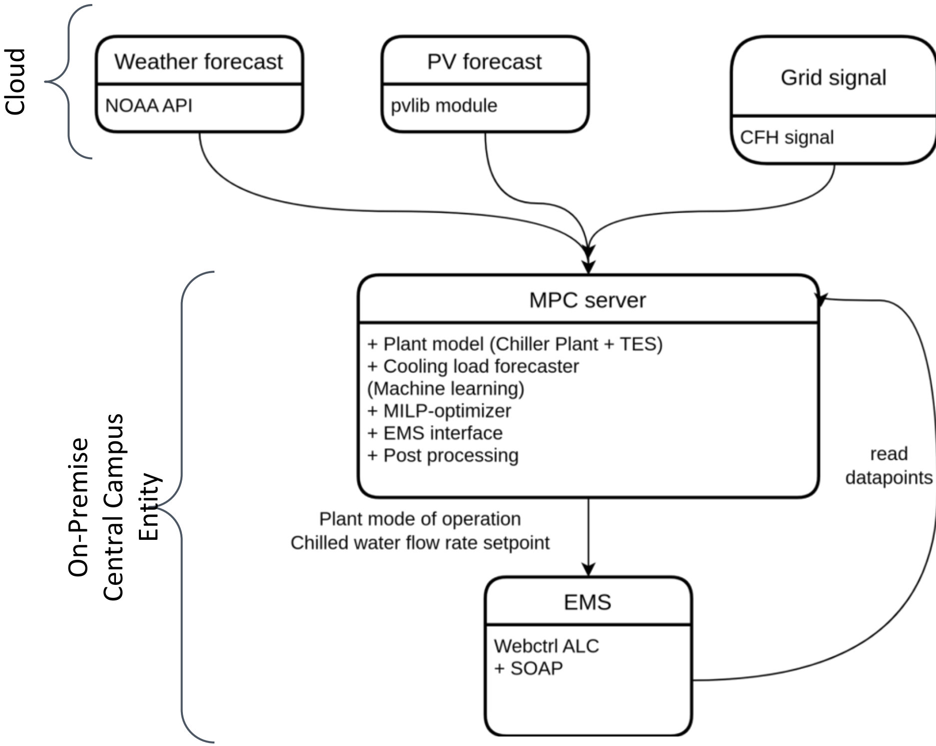
- 9,000 students, 40 buildings, growing fast
- Chiller plant, 17.6 MW, 5000 ton of refrigeration
- 5MW PV system + 500 kWh battery
- 30,000 ton-hr Chilled Water TES Tank

# Research Objectives

- Can we develop and deploy predictive controls that:
  - Owner objectives
    - Maximize PV self consumption
    - Reduce Demand Charges (Utility Bills)
  - Utility objective
    - Respond to Grid Signals (Prices) to reduce pressure on Grid Edge
- What are the implementation challenges?
- Is this approach scalable to other campuses?

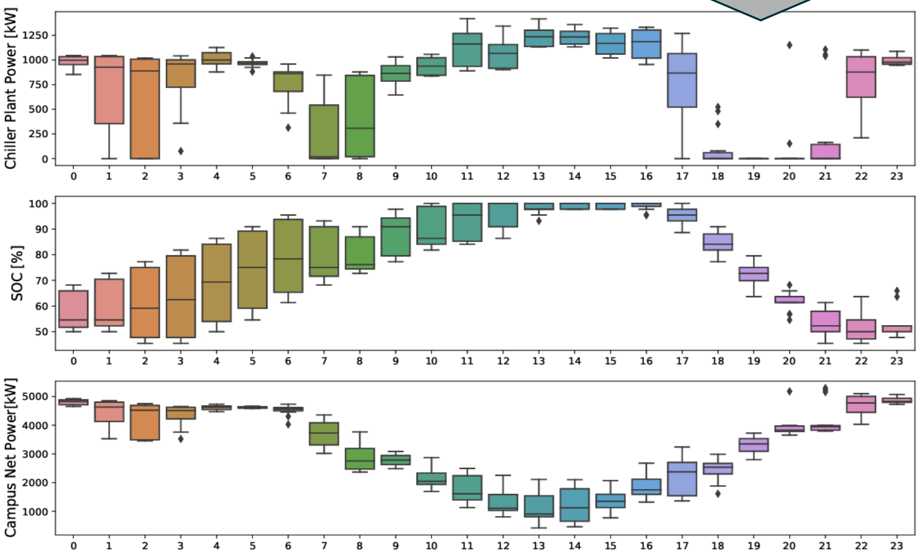
# Implementation: Control and Communication Architecture



# Field test results with a highly dynamic price signal

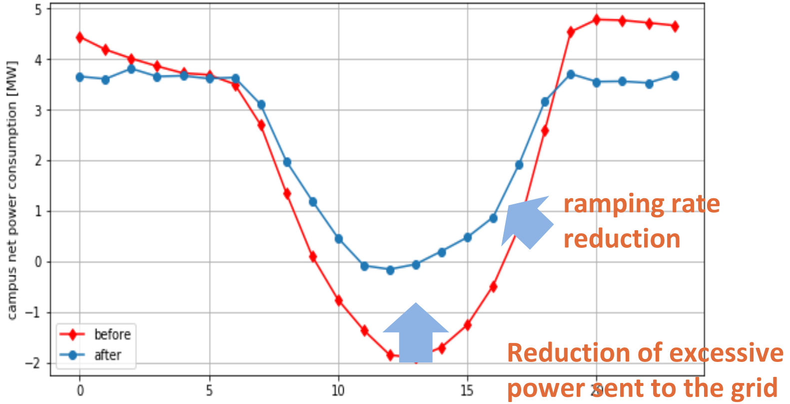
When the price rate is high




The single control deployment achieved a 5 MWh load shift (1.25 MW x 4 hours), which demonstrates great effectiveness

# Field test results with a carbon emission signal

**Experimental data: daily-averaged net power consumption profiles* (one week test period in May, before CFHub)**



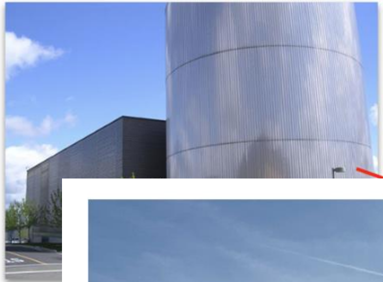

hour of day

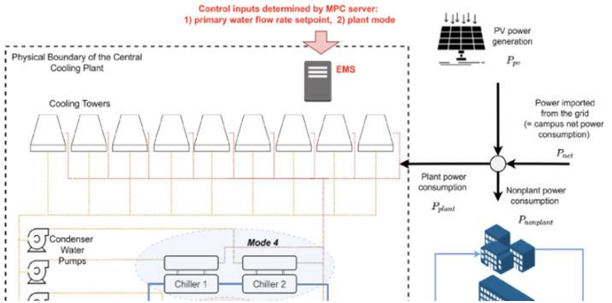
| Control | On-site Solar Self-Consumption [%] | Carbon Emission Savings [%] | Peak Demand Reduction [%] |
|---|---|---|---|
| Baseline | 72 | - | - |
| MPC | 99 | 10 | 10 ~ 15 |

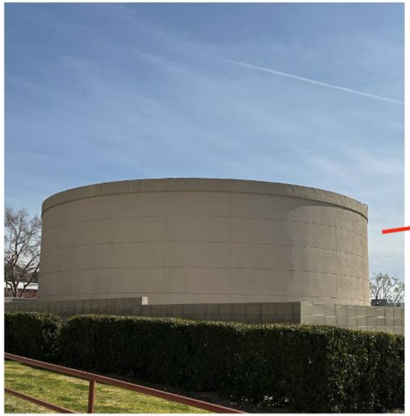
# Key Learnings: Challenges Identified

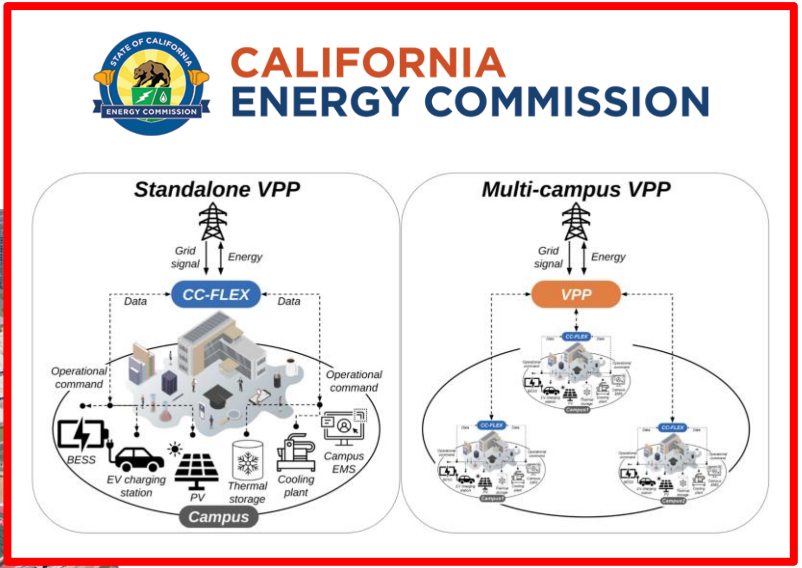
| Category | Challenge |
|---|---|
| Operation restriction | Potential **conflicts** between MPC decisions and EMS logic |
| Operation restriction & Safety | **Revising EMS logic** is practically difficult and it requires identifying potential conflicts after updates, convincing facility manager and operators to accept necessary changes of the EMS, and ensuring operational safety during the MPC demonstration |
| Safety | **Lack of liability** by MPC implementer for a potential operation failure during MPC implementation |
| Others | There are **many stakeholders** for a large plant operation including logic programmers, IT personnel, facility operators, and facility managers |
| Customer adoption | Facility operators are **not familiar** with an advanced control concept since it is not intuitive compared with rule-based control |
| Customer adoption | **Unclear value proposition** and/or **not enough incentives** |

# Is This Approach Scalable?







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# S4B Annual Meeting – Integration Thrust Area

**Presenter: Vishaldeep Sharma (PI)**

**Contributors:** Bo Shen, Praveen Cheekatamarla, Navin Kumar

**Stor4Build Annual Meeting**
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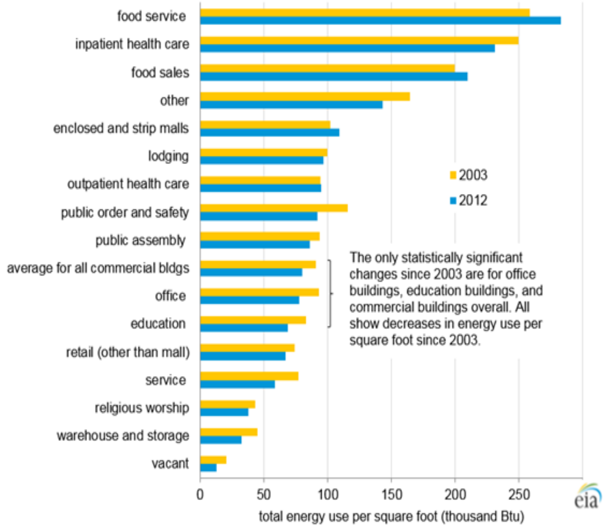
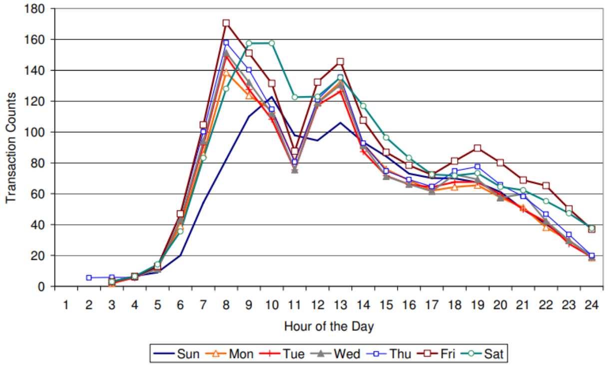
# Background

- **275,000** Fast food and Quick service restaurants (QSR)
- Smallest commercial buildings (2500-4500 $ft^2$)
- Most energy intensive buildings/$ft^2$
    - 24-hour operation
    - Product variation (Hot meals, Ice-creams, dairy frozen food)
    - Low waste heat potential
- **Walk-in Cooler/Freezer**
    - Transition to low GWP refrigerants
    - Current refrigerants – R404A (**GWP 3922**), R448A (**GWP 1273**)
    - Alternative refrigerants – $CO_2$ (A1), Propane (A3), R454A (A2L) and R454C (A2L)

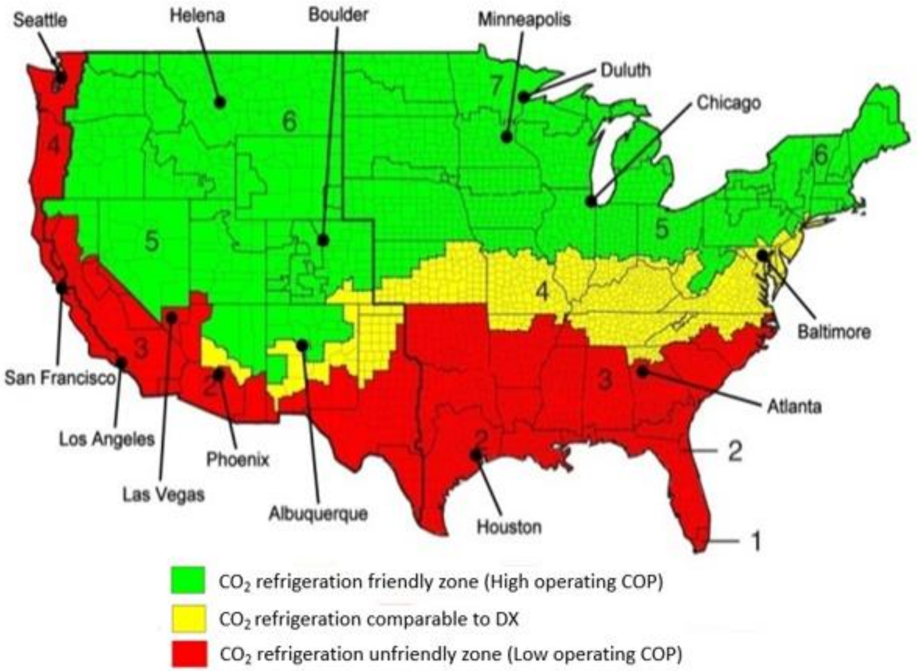



Source: U.S. Energy Information Administration, Commercial Buildings Energy Consumption Survey.



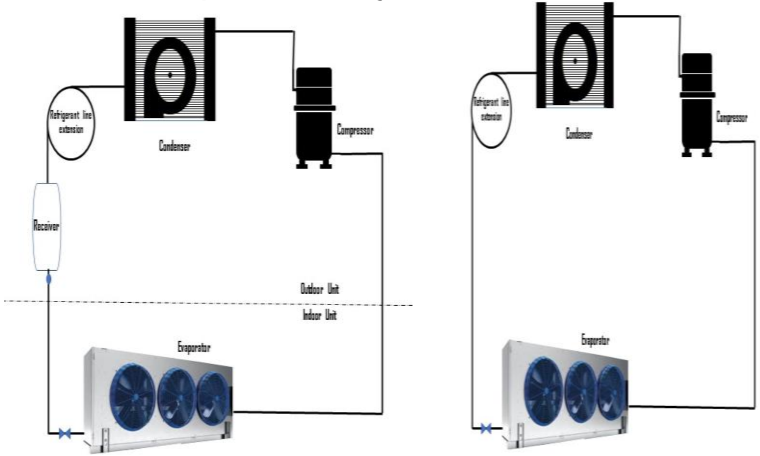
# Motivation

- Energy Efficient Solution for QSR
- $CO_2$ refrigeration system
    - High Pressure
    - Low critical temperature
    - Ambient temperature sensitivity
    - Booster system vs. DX system
- Flammable refrigerants
    - Charge limitation
    - Safety
- Resilience - Maintain cold chain
- Lower operating and food prices



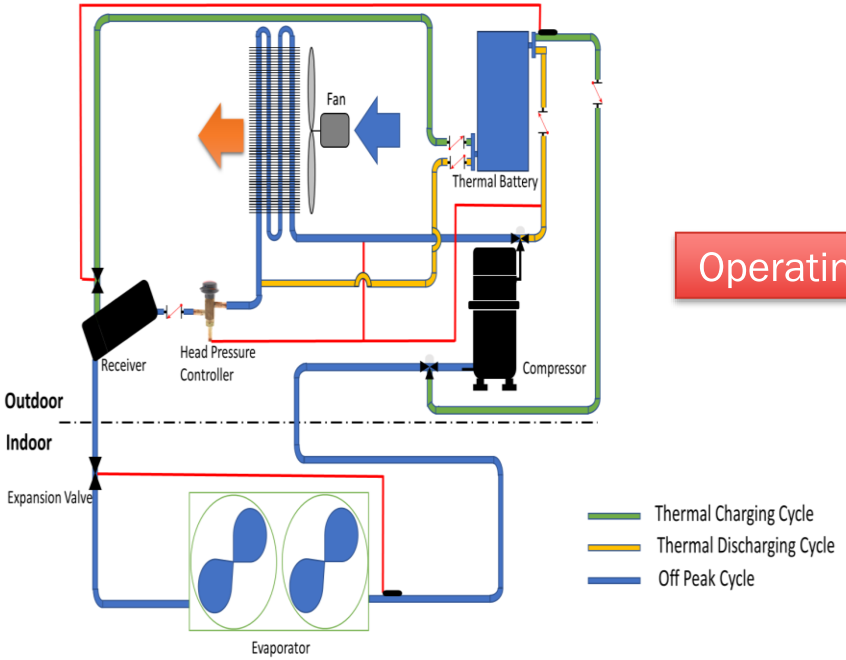
# Market Survey

Direct Expansion System

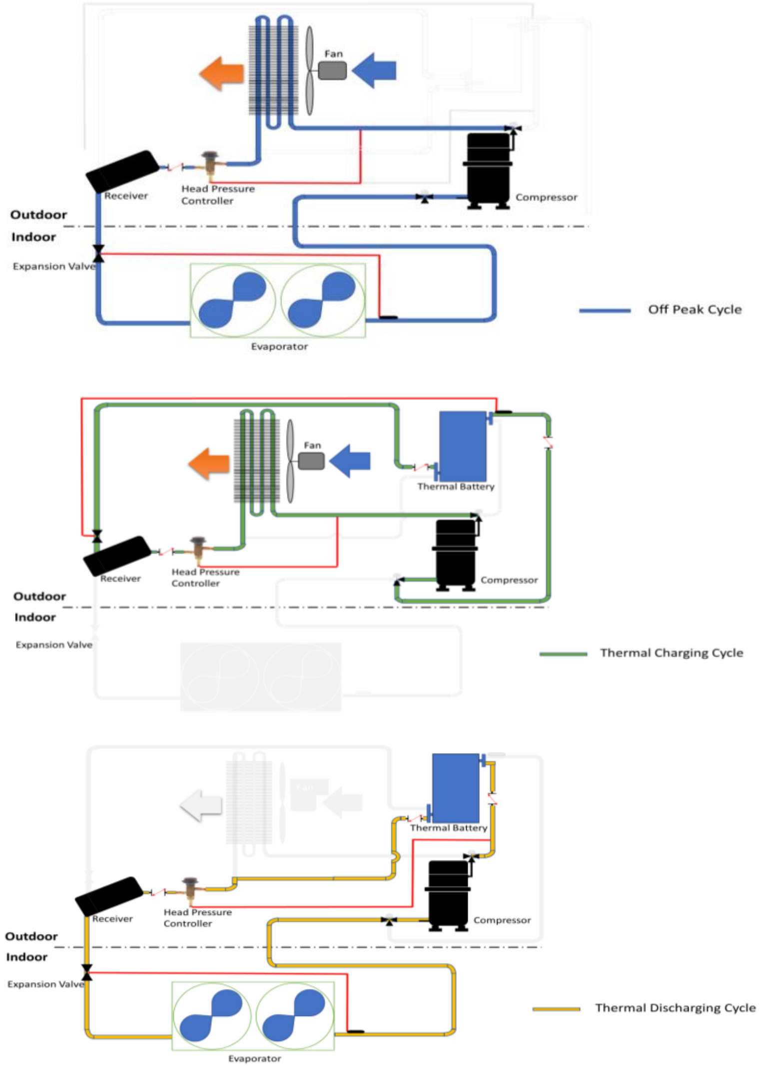



| | Receiver | | W/O Receiver | |
|---|---|---|---|---|
| Market Share | 90% | | 10% | |
| Refrigerant Charge | 11.1 lbs. | | 2 lbs. | |
| | Walk-in Cooler | Walk-in Freezer | Walk-in Cooler | Walk-in Freezer |
| Refrigerant Capacity (tons) | 0.5 | 5 | 0.5 | 0.3-0.5 |
| Temperature (°F) | 5 | -20 | 5 | -20 |
| Current Refrigerant | R404A, R448A and R449A | | | |

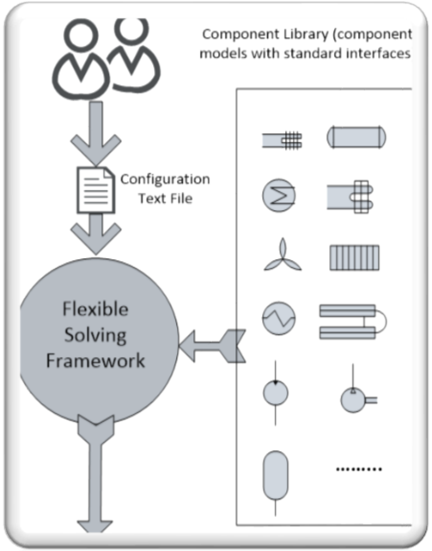
# Proposed Technology



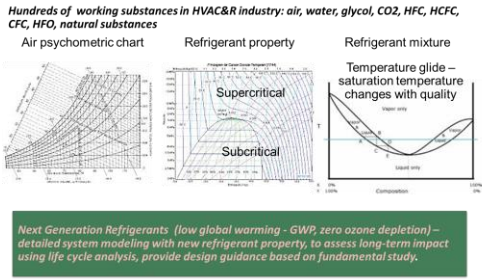

Operating Modes



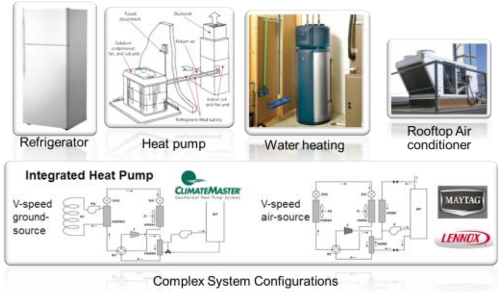
# HPDM: a component-based flexible modeling platform



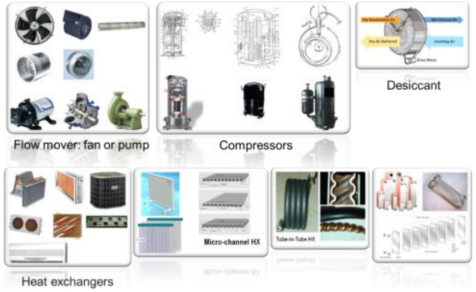

- ❑ Plug-&-Play
- ❑ Standard interface
- ❑ Automatically connect



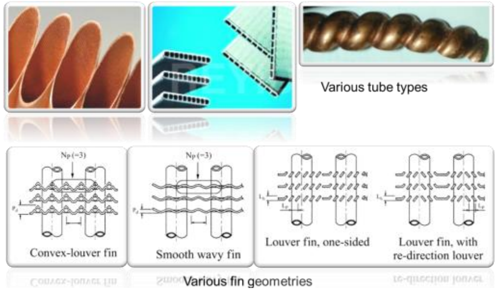

- ❑ **Universal working fluid property management**




- ❑ **Extensive applications and system configurations**

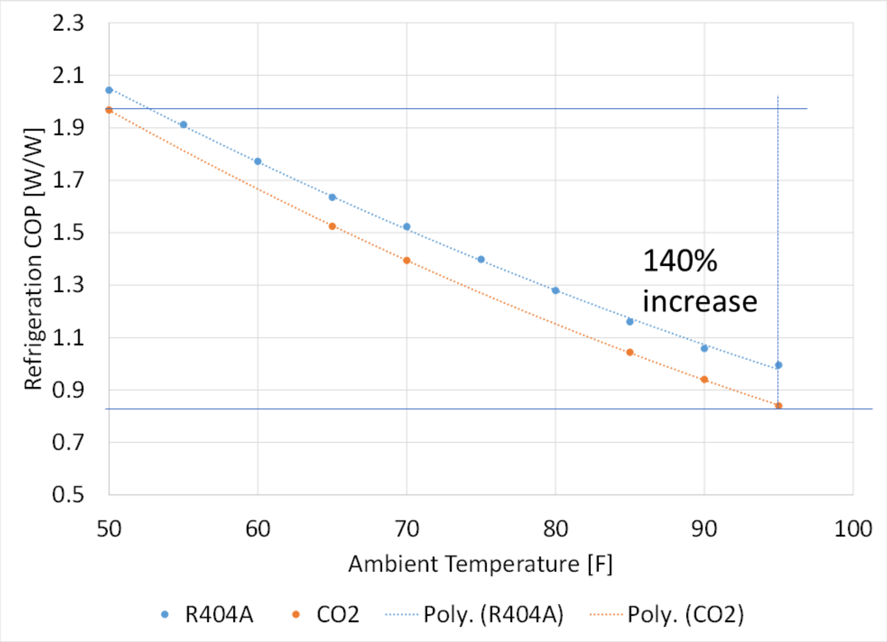



- ❑ **Numerous components**

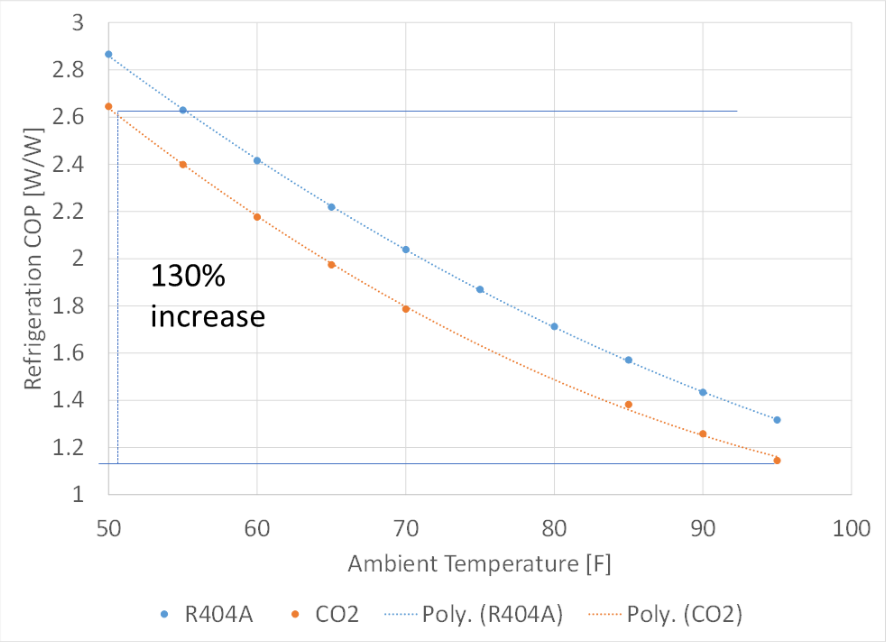



- ❑ **Plenty of tube and fin types**

# $CO_2$ vs. R404A




COP at -20°F, low temperature refrigeration , 3 tons DX system

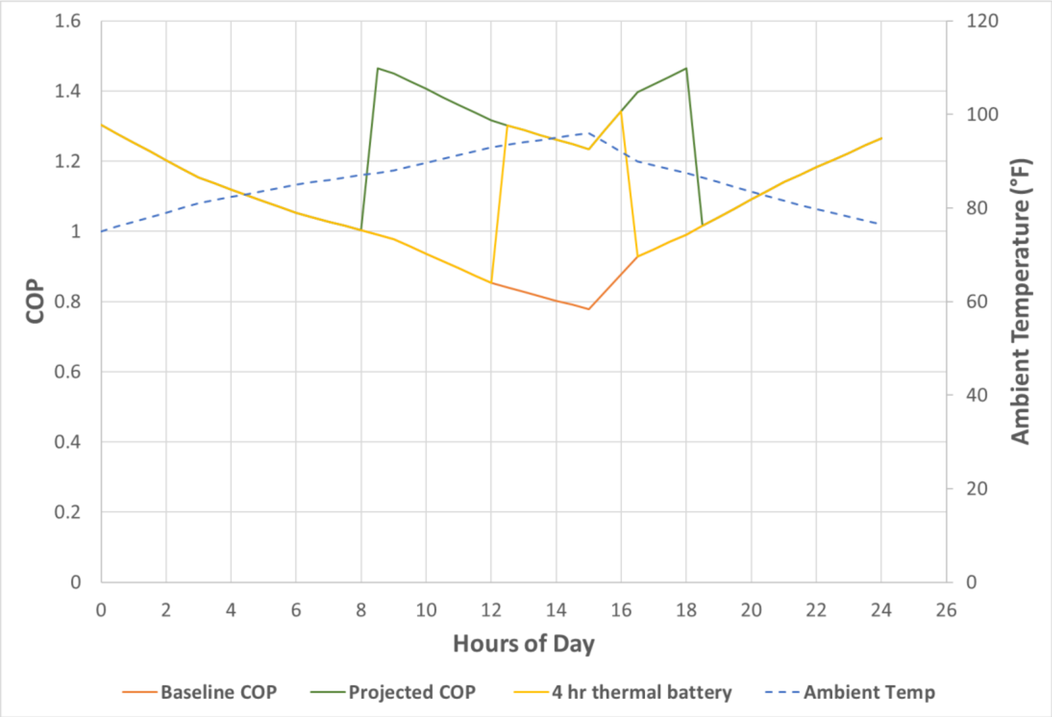



COP at 5°F, low temperature refrigeration , 4 tons DX system

Assume compressor isentropic efficiency at 70%, volumetric efficiency at 90%, varying the compressor speed to match the capacity

# Summer day - Knoxville

- Lower energy performance at higher ambient temperatures
- Utilization of stored energy to maintain optimal ambient temperature (condenser at 50 °F)
- Ability to maintain 30% - 40% higher COP



# DOE's Decarbonization Roadmap

## Cross-Cutting Goals

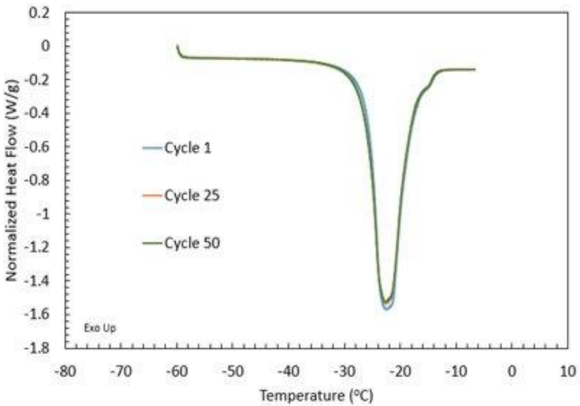
- **Affordability:** Utilizing low-cost modular and scalable thermal battery and modular integration technique to reduce the first cost of installation.
- **Resilience:** Thermal battery provides resilience for food storage during unpredicted power outages and environmental stress.
- **Equity:** Electricity for refrigeration is a major operating expense for food bank-related organizations. Thermal batteries could help reduce their operating costs.

## Strategic Objectives

- **EE**: Reduce on-site energy use with an optimized, highly efficient thermal battery
- **Transform the Grid Edge:** Provide ~2 - 4 peak-load shifting for refrigeration

## Next Steps

- Develop and complete modeling
- Reach-out to potential OEMs for CRADA partnership
- Develop thermal battery
- Integrate TES battery with full scale walk-in cooler for performance evaluation

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# Deployment of a Commercial Packaged Heat Pump and Compact Thermal Energy Storage for Small Buildings

## S4B Annual Meeting - Integration Thrust Area

**Presenter**: Spencer Dutton (PI)

**Contributors**: Marco Pritoni, Weiping Huang, Armando Casillas, Lazlo Paul, Daniel Sambor (Stanford)

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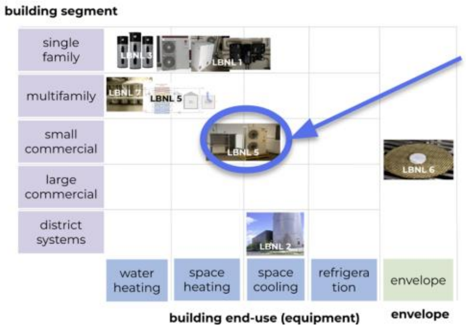
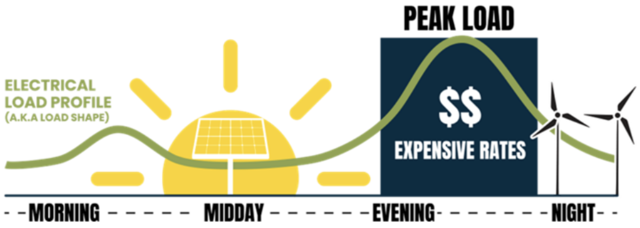



Deployment of a Commercial Packaged Heat Pump and Compact Thermal Energy Storage for Small Buildings

# CalFlexHub

- Identify, evaluate, develop, and demonstrate pre-commercial, load flexible technologies
- **Standardize the signals** used to communicate dynamic price and GHG information to devices

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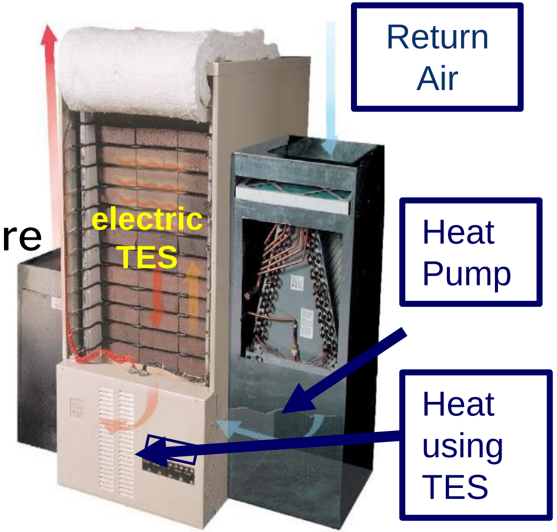
CRADA

# Current TES adoption in small commercial buildings is limited

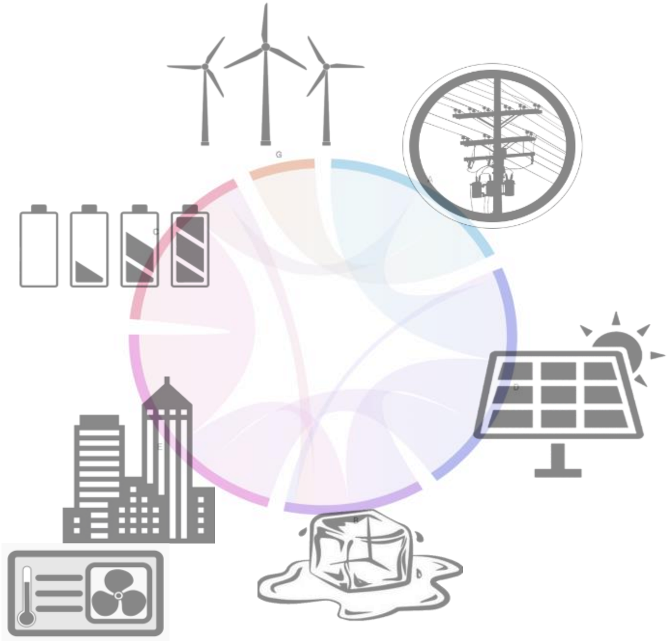
- HP+TES has a great potential to decarbonize : electrification + demand flexibility
- US commercial building HVAC market $40 billion in 2024, minimal HVAC+TES
  - TES for **large buildings** and campuses market available and cost effective.
  - Packaged HVAC with TES for **small buildings** exists, but with electric resistance.
    - iCorps (2019) analysis of **market opportunities** HVAC+TES:
      - Vertical Packaged Units, good first “minimum viable product”
        - very common, and existing systems inefficient
        - no TES weight issues if ground mounted
        - strong interest with facilities manager.
          - pathway to electrification without infrastructure upgrades
          - conditioning-as-a-service, costs shifted to operational

Vertical Packaged Unit



# New HP products have high carbon reduction potential

- New, low-GWP AWHP’s offer new opportunities to further reduce carbon emissions, but, current approaches are too expensive and not scalable:
  - Custom design and installation costly
  - Components currently low volume products
  - No smart controls for integrated system
  - May require panel/service upgrade



# We propose a new technology

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Key design characteristics:

- **Integrated components**, packaged system that can be mass manufactured like RTU or VPU.
- **Integrated controls** that communicates with dynamic pricing servers and weather service data to make operational decisions
- **Easy to install,** comes on the back of a truck, attach to air supply and power.
- **Modular TES**, tailored to meet climate & tariff environment
- **Easy to remove** for off-site maintenance

Blueprint strategic objectives met:

- **Transform the grid edge,** increases demand flexibility
- **Accelerate on-site emissions reductions,** shifting conditioning loads to align with renewables (demonstrated using DER micro-grid)

# Technology development timeline

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Lab lead

Industry lead

1. Develop models + develop system designs ---------------------->
2. Characterize component performance----------------------------->
3. Develop system with commercially available components ---->
4. Integrate smart controls to manage all components----------->
5. Deploy in the field, to demonstrate performance --------------->
6. Integrate system components into packaged design ---------->
7. Industrial design and cost compression----------------------------->
8. Commercialization and mass production--------------------------->

Complete

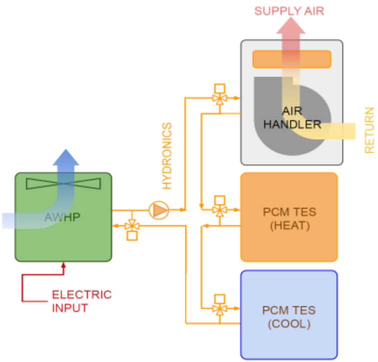
On going

Planned

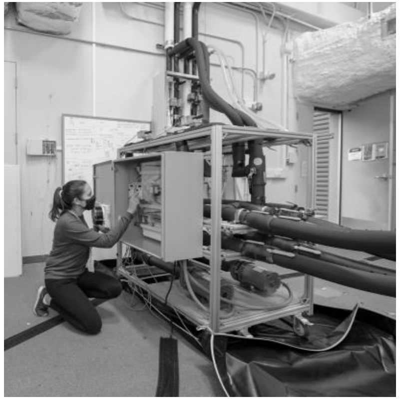
# Modeling and Lab R&D stages completed

| | |
|---|---|
| **Charging** | |
| Max HP power | 4.8kW_elc |
| Thermal energy stored (hot) | 4.5kWh_thm |
| COP charge | 3.5 |
| **Discharging** | |
| Discharge rate (max flow) | 2kW_thm |
| Discharge time | 2h |
| Power during discharge | 80W_elc |
| Peak load reduction | 98% |

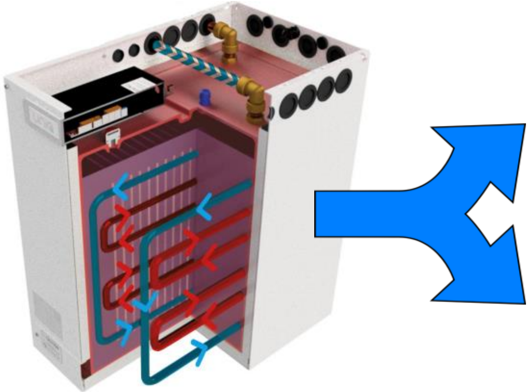
## Modelica based models, range of applications

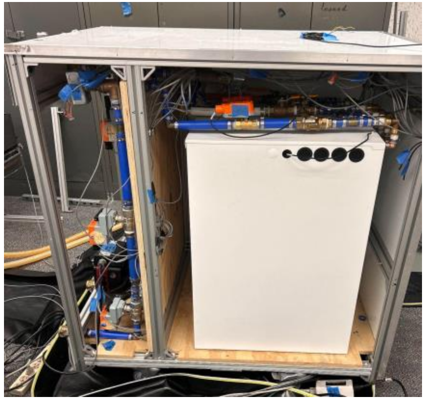



## FlexLab based component characterization



## Lab based integration testing





# Field deployment w/ Stanford University and DOD

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**New CRADA LBNL-Stanford**

- Two side-by-side US military forward operating bases. 20’ x 20‘ modular
- Ideal for comparing HVAC-TES with baseline all electric PTAC.
- Site includes DERs: solar, wind, electrochemical battery.

# Status update: HP+TES installed and undergoing commissioning

- Aermec AWHP, TES unit installed, commissioning August 2024


# Ongoing iterative R&D to reduce cost and improve performances

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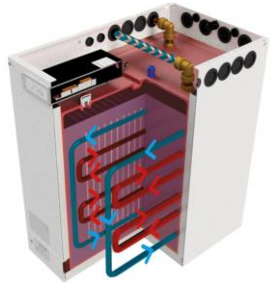

Low cost TES, polymer HX, Carbon foam etc

High energy density Thermochemical materials (TCM)

New low GWP units

Higher temperature

Reduced costs

Model based design

Dynamic pricing controls

Optimal controls

LBL focus: Integration and controls

# Acknowledgements

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# Thank You

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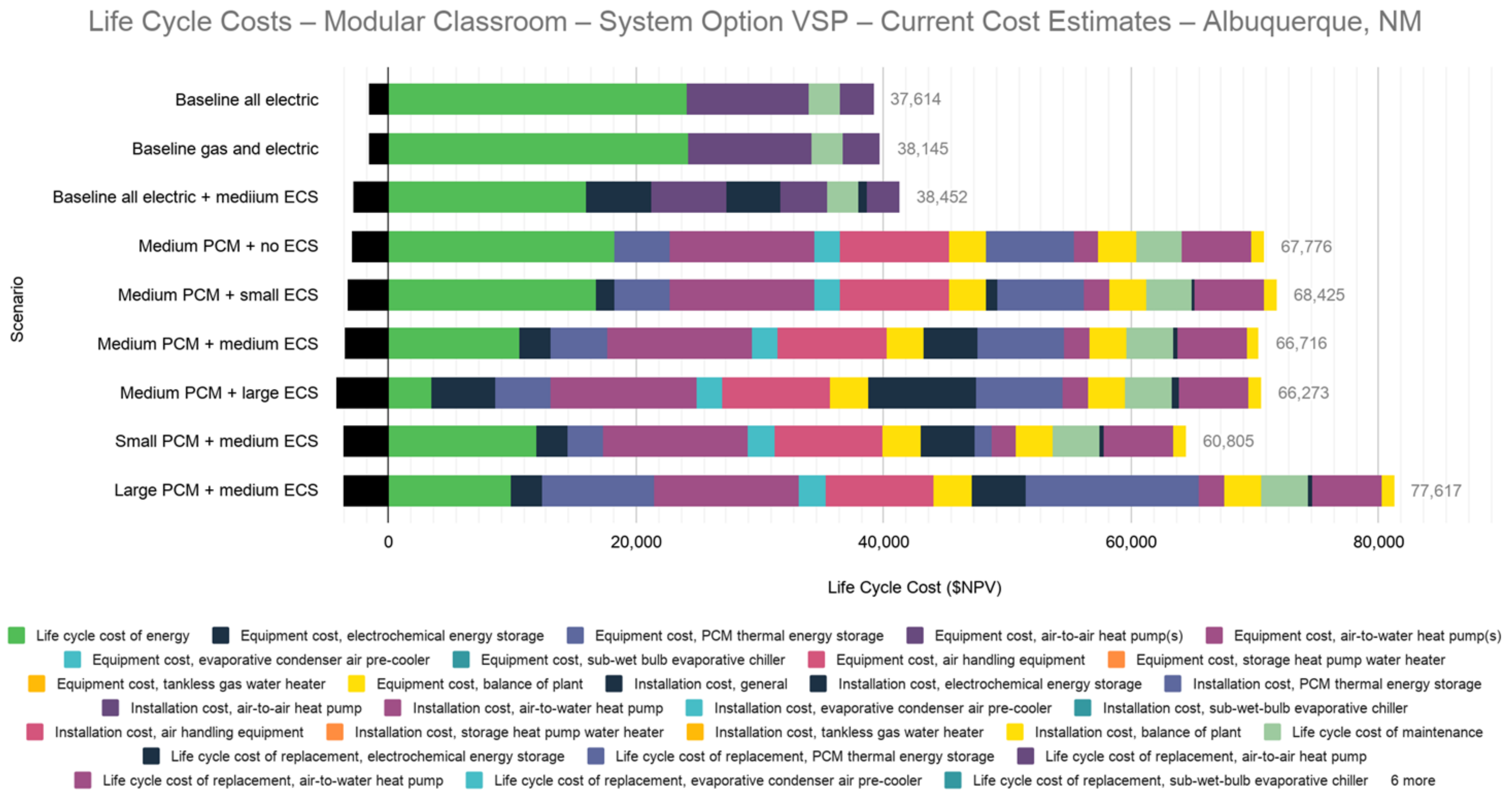

Life Cycle Costs – Modular Classroom – System Option VSP – Current Cost Estimates – Albuquerque, NM
Scenario
Baseline all electric
Baseline gas and electric
Baseline all electric + mediium ECS
Medium PCM + no ECS
Medium PCM + small ECS
Medium PCM + medium ECS
Medium PCM + large ECS
Small PCM + medium ECS
Large PCM + medium ECS
37,614
38,145
38,452
67,776
68,425
66,716
66,273
60,805
77,617
0
20,000
40,000
60,000
80,000
Life Cycle Cost ($NPV)
Life cycle cost of energy
Equipment cost, electrochemical energy storage
Equipment cost, PCM thermal energy storage
Equipment cost, air-to-air heat pump(s)
Equipment cost, air-to-water heat pump(s)
Equipment cost, evaporative condenser air pre-cooler
Equipment cost, sub-wet bulb evaporative chiller
Equipment cost, air handling equipment
Equipment cost, storage heat pump water heater
Equipment cost, tankless gas water heater
Equipment cost, balance of plant
Installation cost, general
Installation cost, electrochemical energy storage
Installation cost, PCM thermal energy storage
Installation cost, air-to-air heat pump
Installation cost, air-to-water heat pump
Installation cost, evaporative condenser air pre-cooler
Installation cost, sub-wet-bulb evaporative chiller
Installation cost, air handling equipment
Installation cost, storage heat pump water heater
Installation cost, tankless gas water heater
Installation cost, balance of plant
Life cycle cost of maintenance
Life cycle cost of replacement, electrochemical energy storage
Life cycle cost of replacement, PCM thermal energy storage
Life cycle cost of replacement, air-to-air heat pump
Life cycle cost of replacement, air-to-water heat pump
Life cycle cost of replacement, evaporative condenser air pre-cooler
Life cycle cost of replacement, sub-wet-bulb evaporative chiller
6 more