Electrification of Greenhouse Heating Systems

Final Report

ET25SWE0032

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Executive Summary

This report presents findings from a market study on the electrification of greenhouse heating systems in California. The California greenhouse sector plays a critical role in the state's agricultural economy and food system resilience. Controlled environment horticulture enables year-round domestic food production, reduces the distance between producers and consumers, and enhances climate resilience in the face of shifting weather patterns. Greenhouses represent a promising area for decarbonization because while they rely on gas-fired heating systems, they have relatively low heating temperature requirements—making them well suited to heat pump technology.

However, the sector faces challenges, such as high upfront costs, unfavorable energy prices, and limited grower experience with electrification technologies, as well as evolving policy landscapes and incentive structures. Furthermore, manufacturers, distributors, and contractors often lack comprehensive electrification solutions and face knowledge gaps. Additionally, many advanced products available in Europe and Asia are not yet accessible in the US market, creating additional barriers to adoption. This context underscores the need for targeted research and programmatic support to encourage greenhouse electrification.

This study initiates the assessment of technical, economic, and policy opportunities for replacing fossil-fuel-based heating with electric heat pump solutions in controlled environment horticulture greenhouses. Greenhouse heating represents a significant share of operating costs for growers, and electrification offers the potential to reduce greenhouse gas emissions and align agricultural operations with California's decarbonization goals.

Study Purpose

The team designed this study to characterize current greenhouse heating practices; identify typologies of greenhouses best suited for electrification; evaluate potential energy, demand, cost, and non-energy impacts; and recommend strategies for adoption. One of the study's core objectives was to ensure that findings are actionable and support the adoption of electrified greenhouse heating systems. To achieve this, the team collaborated with key stakeholders throughout the research process and will share key findings with program implementors to help translate results into actionable strategies for program administrators, regulators, and researchers, as well as savings estimates, targeting strategies, and pathways for future research. This approach was intended to support informed decision-making and accelerate implementation.

Key Findings in Favor of Electrification

- **California's greenhouse market offers large-scale electrification potential:**
  California has the largest greenhouse sector in the United States, with crops such as tomatoes, strawberries, cucumbers, herbs, lettuce, and peppers dominating production. Mid- to large-scale greenhouses with rigid plastic or glass coverings represent the highest potential for electrification due to their scale, envelope efficiency, and automation readiness.
- **Most process conditions fit within heat pump capabilities:**
  Typical crop setpoints for temperature, humidity, carbon dioxide, and lighting fall within

ranges compatible with heat pump performance. Greenhouses with moderate setpoints and rigid envelopes present potential near-term candidates for electrification.

- **Heat pumps and thermal energy storage create new technical and operational opportunities**:
  Heat pump technologies, including hybrid dual fuel and thermal energy storage systems, can potentially improve energy efficiency and provide additional co-benefits, such as waste cooling for offsetting cold storage energy use. Despite these benefits, which can be marketed to encourage adoption, the high first costs and operating costs associated with heat pumps will require utility energy program support to promote adoption.
- **Heating loads create a large lever for emissions reduction**:
  Heating can represent up to 80 percent of greenhouse energy use, with boilers and forced-air systems as the most common choices. Non-process loads, such as air infiltration and ventilation, play a critical role in determining system feasibility. A greenhouse's existing heating system and distribution types are key parameters that have an outsized influence on retrofit strategy, first cost to retrofit, and energy costs. Both hydronic and forced-air overhead unit heating systems provide pathways for electrification.
- **Non-energy impacts often drive the business case more than energy savings:**
  Non-energy impacts are the additional benefits or costs of energy efficiency and distributed energy resources beyond direct energy savings, affecting participants, utilities, and society. When installing energy efficiency measures in greenhouse operations, positive non-energy impacts often outweigh pure energy savings in importance, influencing profitability, sustainability, and community benefits across stakeholders. Owners and operators highlighted positive non-energy impacts of electrified heating, such as improved crop quality, yield gains, labor savings, and business model enablers like growing starts for other farms to transplant, which supports profitability and growth. Investor-owners emphasized system-level benefits, including carbon footprint reductions, job creation, food security, and economic value from power market arbitrage. Manufacturers and vendors focused on positive operational non-energy impacts, like disease prevention, humidity control, and labor efficiency, while acknowledging challenges like retrofit complexity and scaling risks.
- **Non-energy impacts value not currently recognized in evaluation frameworks and legislation:**
  Policy experts stressed that positive non-energy impacts—such as health benefits, rural economic development, and farm viability—are undervalued in current cost-effectiveness tests, further limiting the opportunity for decarbonization measures. Across all actors, non-energy impacts span yield, labor, resilience, risk management, and community impacts, underscoring the need for policies and programs to explicitly prioritize these dimensions. Regardless, in order to access these substantial benefits, the first cost barrier must be tackled.
- **Electrification has clear near-term, mid-term, and long-term targets**:
  The electrification strategy our team identified for greenhouses in California outlines three key typologies: near-term electrification targets, "prepare and improve" segments,

and long-term strategic buildouts. Near-term opportunities focus on high-tech food and berry greenhouses, medium-scale rigid-plastic facilities, and low-temperature propagation houses, where heat pumps and thermal energy storage systems can be deployed effectively, with attention to carbon dioxide enrichment and grid constraints. "Prepare and improve" segments, such as low-tech plastic-film houses and high-control cannabis facilities, emphasize efficiency upgrades and hybrid systems to enhance readiness for future electrification. Long-term strategies envision heat pump-centric campuses and integration of industrial waste heat utilization, offering innovative pathways for decarbonization. These typologies highlight the need for tailored approaches that balance technical feasibility, economic viability, and policy support to advance greenhouse electrification across diverse facility types.

Key Findings Against Electrification

- **High first costs and operating costs limit adoption without program support:**
  Despite the technical fit and non-energy benefits of heat pumps, high first costs and operating costs will require utility energy program support to promote adoption. In order to access substantial non-energy benefits, the first-cost barrier must be tackled through incentives, financing, and technical assistance.
- **Electricity prices and rate structures remain a major barrier:**
  California's policy environment is broadly supportive of electrification, but the cost of electricity relative to gas—referred to as the "spark spread"—poses significant economic challenges. Incentive structures remain complex, with custom incentives for greenhouse heat pumps available, but no deemed offerings currently in place. While federal programs such as the United States Department of Agriculture's Rural Energy for America Program grants and the Inflation Reduction Act tax credits can support adoption, they face future uncertainty due to potential shifts in federal policy priorities and political leadership.
- **Waste heat opportunities exist, but business models and regulations lag:**
  Manufacturers and policy experts see many potential external heat sources—such as industrial refrigeration, data centers, and municipal plants—as opportunities for greenhouse heating. However, California lacks the business models and regulatory structures (e.g., heat-network concessions, standardized "heat-as-a-service" contracts) that underpin the most successful European examples. Addressing these gaps could unlock significant decarbonization potential for the sector.
- **Cooling, dehumidification, and shared infrastructure remain underdeveloped opportunities:**
  Cooling in California greenhouses is primarily passive or evaporative, but opportunities exist to integrate heat pumps for both cooling and heating through shared infrastructure. Facilities with substantial refrigeration loads, such as facilities with cold storage walk-in coolers and those that relay on field heat removal practices, stand out as strong candidates for electrification. Additionally, California's reliance on water-intensive and humidity-intensive evaporative cooling methods may drive future interest in heat-pump-based cooling and dehumidification as water scarcity and disease pressures grow. This

intersection of cooling, dehumidification, and heating represents a significant but underdeveloped opportunity for decarbonization and improved resource efficiency.

- **At scale, combined heat and power systems remain a strong competitor and a likely component of hybrid pathways:**
  Combined heat and power systems offer the ability to simultaneously provide heat, power, and carbon dioxide, making them attractive to growers who prioritize operational flexibility and resilience. However, this creates a challenge for electrification programs, which must offer sufficient incentives to overcome the economic and operational benefits of combined heat and power. Current policies, which often require full fuel substitution to qualify for incentives, may need to evolve to support hybrid models that combine heat pumps with combined heat and power or other gas-based systems. Future research should explore comparative analyses of heat pump and combined heat and power design options to better understand how dual-fuel strategies can align with decarbonization goals.

Stakeholder engagement has been a central component of this study, ensuring that research findings and recommendations are both actionable and aligned with stakeholder needs. The project team collaborated with growers, equipment vendors, program administrators, and policymakers throughout the research process to gather insights, refine technical assumptions, and identify practical implementation barriers. These collaborative efforts not only shaped the development of findings but also supported the effective dissemination of results to accelerate the adoption of electrified greenhouse heating systems.

In sum, this report reflects the commitments outlined in the project plan by providing due diligence on literature review, market actor interviews, non-energy impact analysis, typology development, and early stakeholder engagement. The findings to date point to promising opportunities for greenhouse heating electrification in California while also highlighting the need for targeted program support, refined incentive structures, and continued outreach to ensure adoption at scale.

Abbreviations and Acronyms

Acronym	Meaning
ACM	Alternative Calculation Method
AESAP	Agriculture Energy Savings Action Plan
AWHP	Air-to-water heat pump
°C	Celsius
CARB	California Air Resources Board
CEA	Controlled environment agriculture
CEC	California Energy Commission
CEH	Controlled environment horticulture
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Coefficient of performance
CPUC	California Public Utilities Commission
DLI	Daily light integral
DR	Demand response
EE	Energy efficiency
ºF	Fahrenheit
HDD	Heating degree days
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
IDSM	Integrated demand-side management

Acronym	Meaning
IOU	Investor-owned utility
kBtuh	Thousand British thermal units per hour
kW	Kilowatt
LED	Light-emitting diode
MW	Megawatt
NEI	Non-energy impacts
NO_x	Nitrogen oxides
OAT	Outdoor air temperature
PAC	Program Administrator Cost Test
ppm	Parts per million
PG&E	Pacific Gas & Electric
PV	Photovoltaics
REAP	Rural Energy for America Program
RII	Resource Innovation Institute
SDG&E	San Diego Gas & Electric
SGIP	Self-Generation Incentive Program
TES	Thermal energy storage
TRC	Total Resource Cost
UC Davis	University of California, Davis
UK	United Kingdom
USDA	United States Department of Agriculture
VG3	USDA Virtual Grower 3

Acronym	Meaning
WH	Water heating

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Introduction

This report presents the findings of a market study on the electrification of greenhouse heating systems in California. It summarizes insights from the literature review, market actor interviews, energy analysis, non-energy impacts (NEI) analysis, cost estimates, and greenhouse typology recommendations, as well as provides recommendations for future research and program design. Together, these results help illuminate market trends, technical opportunities, and barriers to market adoption.

Report Structure

- **Background:** Overview of controlled environment horticulture, greenhouse heating needs, and the current market context.
- **Objectives:** Goals of this market study and expected deliverables.
- **Methodology and Approach**: Research methods employed to date, including literature review and interview strategies.
- **Findings:** Summary of findings from research tasks.

Background

Controlled environment horticulture (CEH) is an increasingly important energy end use in California, providing year-round domestic food production, reducing the distance between producers and consumers, and improving the resilience of the food system against climate change. Within CEH, greenhouse operations represent a particularly promising area for decarbonization. While most California greenhouses do not require vapor compression cooling, many have heating loads that are currently met by fossil-fuel-based systems. These systems have historically been the standard approach, but they present a clear opportunity for electrification. The temperatures required for greenhouse heating are relatively low compared to other process loads, do not require steam, and can be readily served by existing heat pump technology.

California's policy landscape further amplifies the importance of exploring electrification pathways for greenhouse heating. The state has established ambitious decarbonization goals, and agriculture remains a cornerstone of the state's economy. Together, these forces create strong drivers for programs and policies that can support the adoption of decarbonized heating solutions—but there are significant barriers.

High first costs for heat pump systems, uncertainty around incentive structures (particularly those that derate incentives in the presence of self-generation), and limited experience among growers and vendors all hinder wider adoption. Additionally, the high cost of electricity relative to natural gas (or spark spread) in California further exacerbates operating cost concerns for growers, making the transition to electrified heating systems less economically attractive without targeted incentives or cost-reduction strategies.

The greenhouse market is also evolving in ways that reinforce the urgency of this research. Greenhouse adoption has expanded as growers pursue year-round productivity and climate

resilience in response to shifting weather patterns. Traditionally, fossil fuel heating has been the dominant solution, but recent technological improvements in electric heating and heat pump systems have created new opportunities. Literature reviews and prior studies highlight these opportunities while also exposing gaps. For example, the United States Department of Agriculture's (USDA's) Virtual Grower 3 modeling software provides a valuable platform for simulating greenhouse operations but has limitations that restrict its usefulness for evaluating heat pump strategies or dual-fuel applications (USDA ARS 2016).

Broader economic, technological, and regulatory contexts also shape the potential for electrification in this sector. Economically, the high spark spread—the ratio of electricity prices to natural gas prices—poses a significant challenge for electrification, as electricity remains substantially more expensive than gas in California. Technological advances in heat pump efficiency and system integration expand the range of feasible electrification strategies. On the regulatory side, California's agricultural energy efficiency initiatives, such as the Agriculture Energy Savings Action Plan (AESAP), are beginning to recognize the potential for decarbonization in controlled environment agriculture (CEA), though existing incentive frameworks often lag behind market needs.

In sum, the greenhouse heating market in California stands at a transitional moment. Historical reliance on fossil fuels is being challenged by both state-level climate policy and technological progress in heat pump systems. However, due to high first costs and operating costs, adoption is far from assured, and targeted research is needed to better understand market actors, technical pathways, and policy levers that can accelerate the shift toward electrified heating. This project builds on the available literature and contextual factors and moves further by engaging directly with growers, vendors, and experts to identify practical strategies for implementation of heat pump systems in the greenhouse heating market.

Objectives

The market study has been designed to investigate and assess opportunities for greenhouse heating electrification in California.

Research Questions

- What are the technical and economic opportunities for electrifying greenhouse heating using heat pumps?
- What are the market barriers to adoption, and how can energy efficiency and decarbonization programs support this sector effectively?

Goals of the Study

- Characterize current greenhouse heating practices and system parameters.
- Identify target greenhouse typologies for electrification along with suitable heat pump strategies.
- Quantify energy, demand, cost, and non-energy impacts of electrification scenarios.

- Assess market-ready strategies, including full electrification, thermal energy storage (TES), and dual-fuel options. We also refer to the dual-fuel option as a hybrid system throughout this report.
- Evaluate potential end use types for waste cooling.

Desired Outcomes and Deliverables

- **Preliminary Findings Report**, which included initial findings from the literature review and plans for the market actor interviews.
- **Draft Report**, which includes all sections of the Preliminary Findings Report, plus final results from the interviews, non-energy impact analysis, target greenhouse typologies, and recommendations for next steps.
- **Final Report** (this document), which includes all sections of the Draft Report, plus final results from the energy analysis, first cost analysis, and recommendations for future research.

Targeting for Technology Transfer and Recommendations

- **Program administrators** (e.g., AESAP) to inform custom incentive offerings.
- **Policymakers and regulators** to refine incentive structures, particularly for dual-fuel and self-generation cases.
- **Growers and greenhouse operators** to increase awareness of electrification strategies and non-energy impacts.

The project team will complete outreach for report dissemination through program channels, industry partnerships, and future field demonstration efforts.

Methodology and Approach

The project employs a mixed-methods approach that integrates literature review, market actor interviews, and energy analysis supported by energy analysis tools. Together, these methods provide both qualitative and quantitative insights into the opportunities and challenges of electrifying greenhouse heating in California.

This report documents our approach and how it informs forthcoming study elements. The project team began with a comprehensive review of existing literature, drawing on academic studies, industry reports, and utility program evaluations. This review provided a foundation for identifying key trends in greenhouse parameters affecting heating technologies, adoption drivers, and barriers to electrification. Beyond establishing this knowledge base, the literature review was instrumental in shaping the project team's next steps: informing the formulation of target greenhouse typologies, which are categories of greenhouse operations that represent the most promising candidates for electrifying their heating systems. These typologies reflect factors such as greenhouse size and type, crop type, climate zone, and existing heating infrastructure.

The literature review also guided the design of the interview guides. By synthesizing recurring themes and gaps identified in existing studies, the project team developed tailored interview questions for different market actors, including greenhouse owners and operations, equipment manufacturers and vendors, subject matter experts, utility program representatives, and policymakers.

These interviews served multiple purposes. First, they helped validate and refine the greenhouse typologies, ensuring that the categories identified during the literature review are practical and aligned with market realities. Second, they provided insight into the decision-making processes, barriers, and motivations of each actor within the greenhouse ecosystem. Finally, the project team used the interviews to refine key assumptions in the non-energy analysis and energy analysis portions of the project, particularly around baseline heating practices, operating schedules, equipment performance, and additional NEIs growers highly prioritize.

In this way, the research process is highly iterative: the literature review established initial typologies and informed interview design; stakeholder interviews validated and sharpened those typologies while also contributing critical data to improve the accuracy of the energy and non-energy impact analyses; and the combination of methods will ensure that the findings are robust, actionable, and grounded in both existing knowledge and the practical experiences of California's greenhouse industry.

The team identified and quantified NEIs primarily through market actor interviews, supplemented by insights from the literature review. Interview guides include targeted questions to elicit growers' and other stakeholders' perspectives on non-energy outcomes (positive and negative) associated with greenhouse heating strategies (e.g., crop yield and quality, plant health, labor requirements, operational flexibility, comfort and safety, noise, maintenance burden, and perceived risk or resilience benefits). During interviews, respondents qualitatively described the most important non-energy outcomes they experienced or anticipate when considering a transition from fossil fuel heating to heat pump–based systems, and interviewers probed where feasible for semi-quantitative or quantitative information (such as frequency of issues, magnitude of improvements, changes in

labor hours, or avoided product loss) and for the relative importance of these NEIs compared to energy cost savings. The project team systematically coded and aggregated responses to identify common NEI categories, their direction (benefit or cost), and their relative importance across greenhouse types and operating models. These NEI characteristics both inform the non-energy analysis (by indicating which NEIs are most material to growers and how they may influence adoption decisions) and help refine and prioritize target greenhouse typologies for program design. For example, typologies where growers place a high value on improved temperature uniformity, reduced on-site combustion, or lower maintenance burden may be especially strong candidates for electrification programs, even when pure energy cost metrics are marginal. By linking NEI profiles to specific greenhouse typologies, the study provides program administrators with actionable guidance on which segments are most likely to respond to electrification offerings that explicitly recognize and communicate these non-energy benefits.

For the energy analysis, the team applied USDA's Virtual Grower 3 (USDA ARS 2016) to estimate baseline energy consumption under conventional fossil fuel systems across all 16 of California's climate zones, and to compare against measure cases involving heat pumps. Additionally, the project team used supplemental spreadsheet analysis to address gaps in the tool's capabilities, which provided estimates of gas consumption, electric demand, annual energy use, and on-bill cost impacts, offering an initial framework for assessing the technical and economic feasibility of greenhouse electrification.

For the first-cost analysis, the team gathered equipment costs for suitable heat pump strategies from literature review, subject matter experts, and vendors. First cost is a substantial barrier for this market segment, and the project team will reference equipment costs when discussing the feasibility of different heat pump strategies.

This integrated project approach aims to create a comprehensive understanding of the greenhouse heating market and the practical strategies available for decarbonization.

Findings

The findings from this project draw on literature reviews, market actor interviews, non-energy impact analysis, and target greenhouse typologies, as well as planning for stakeholder engagement.

The first section reviews the technical literature on greenhouse operations, including segmentation of the California market, key process parameters for crop production, and the energy implications of process and non-process loads. It also describes the potential implications for utility programs relevant to each topic, and includes a review of the policy literature to identify regulatory drivers, incentive structures, and decarbonization goals that shape the adoption of electrified heating technologies.

In the second section, the project team presents findings from market actor interviews and the non-energy impact analysis; we then identify promising greenhouse typologies for electrification. Finally, we describe stakeholder feedback throughout stages of this research. Taken together, these findings establish a technical, policy, and market context that will ground the final phases of this research.

Technical Literature Review

Market Segmentation of Greenhouses by Crop and Greenhouse Type

California is ranked number one in the nation for greenhouse agricultural products sold, demonstrating a massive opportunity to enhance greenhouse operations (USDA SS 2022a). While some California greenhouses grow floriculture and nursery products, nutritious crops are a staple of greenhouse production. According to the USDA 2019 Horticulture Specialties census and verified by in-house program implementation staff, the food crops most commonly grown in greenhouses (also referred to as "under protection") in California include tomatoes, herbs, cucumbers, lettuce, peppers, and strawberries (USDA SS 2019a, Table 14).

Item	Operations	Area under protection (1,000 square feet)
Food crops grown under protection and sold, total	2,994	88,943
Cucumbers	1,003	6,337
Herbs, cut fresh	700	10,685
Lettuce, all	1,042	5,531
Peppers, all (excluding ornamentals)	745	2,481
Strawberries	161	659
Tomatoes	2,205	52,576
Other food crops grown under protection and sold	1,005	10,674

Figure 1: Food crops grown under protection and sold.

Source: USDA 2019, Table 15.

As shown in Figure 1, tomatoes—primarily grown in the Southern, Central Coast, and Sacramento regions of the state—are the most common nutritious food crop grown in California (USDA SS 2022c). While strawberries currently represent a small portion of greenhouse production, berries as a broader category are a fast-growing segment, enabling year-round harvests; strawberries are primarily grown under protection in the Central Coast (Watsonville and Santa Maria) and Southern regions (Oxnard, winter production) (Kubota 2019).

Production area for each crop type varies widely throughout California from under 999 square feet to over 40,000 square feet. While Figure 1 comes from the 2019 USDA Census of Horticulture Specialties, the comprehensive USDA's 2022 Census of Agriculture reported approximately 11,500 total greenhouse farms growing vegetables and fresh cut herbs. Of this total, roughly one-third (37 percent) are under 1,000 square feet, half (51 percent) are between 1,000 and 9,999 square feet, and 12 percent are over 10,000 square feet (USDA SS 2022b, Table 39; USDA SS 2019e, Appendix B). A breakout of the number of farms and sizes in square feet is available in Figure 2 below.

Crop		Under glass or other protection	
		Farms	Square feet
FOOD CROPS GROWN UNDER GLASS OR OTHER PROTECTION			
Total greenhouse vegetables and fresh cut herbs	2022	11,465	133,379,301
	2017	10,849	112,564,105
2022 farms by area:			
1 to 999 square feet		4,197	1,388,402
1,000 to 1,999 square feet		1,661	2,269,373
2,000 to 2,999 square feet		1,509	3,598,981
3,000 to 3,999 square feet		860	2,823,958
4,000 to 5,999 square feet		1,009	4,779,238
6,000 to 9,999 square feet		828	6,202,283
10,000 or more square feet		1,401	112,317,066
10,000 to 19,999 square feet		721	9,641,773
20,000 to 39,999 square feet		328	8,687,999
40,000 or more square feet		352	93,987,294
Greenhouse tomatoes	2022	8,578	68,430,394
	2017	7,974	63,929,576
2022 farms by area:			
1 to 999 square feet		3,904	1,234,805
1,000 to 1,999 square feet		1,343	1,799,826
2,000 to 2,999 square feet		1,042	2,482,319
3,000 to 3,999 square feet		586	1,900,177
4,000 to 5,999 square feet		574	2,725,447
6,000 to 9,999 square feet		453	3,338,138
10,000 or more square feet		676	54,949,682
10,000 to 19,999 square feet		386	4,963,785
20,000 to 39,999 square feet		177	4,588,404
40,000 or more square feet		113	45,397,493

Figure 2: Census of Agriculture: Food crops grown under glass or other protection in the United States.

Source: USDA SS 2022b, Table 39.

To further characterize California greenhouses, the project team considered the most common covering types: plastic film covering, rigid plastic, and glass. Understanding the dimensions for these covering types is key to identifying greenhouse archetypes with the greatest potential for electrification. Greenhouses with rigid plastic or glass coverings typically represent higher-tech, well-sealed, actively heated operations, making them more viable candidates for electrification. In contrast, plastic film operations dominate the market but are often lower-cost structures with high infiltration rates and limited or no active heating, making them more challenging and less cost effective to decarbonize due to high first costs and overall energy costs.

According to the 2017 USDA Census of Agriculture data, most California greenhouses have a plastic film covering (USDA SS 2019c, Table 38). However, California still has the highest potential for high-tech greenhouses in the nation, even when limiting consideration to the number of greenhouses in California that use only rigid plastic and glass coverings (USDA SS 2019c, Table 38). The breakout in Figure 3 shows 314 operations in California with rigid plastic and 87 with glass coverings.

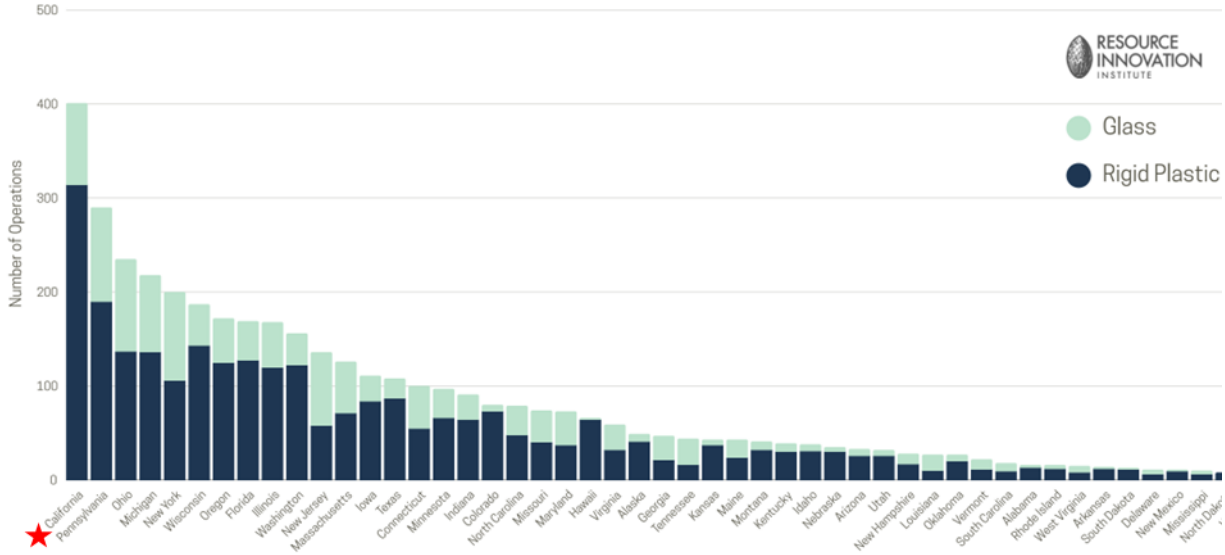

Figure 3: Greenhouse covering type by state.

Source: Azzaretti and Carleton 2024.

While Figure 3 does not include the 579 operations in California with plastic film coverings, the underlying dataset indicates that plastic film accounts for roughly 92 million square feet of greenhouse area statewide; more than twice the combined area of rigid plastic (35 million square feet) and glass (18 million square feet) (Azzaretti and Carleton 2024). Finally, it is worth noting that the 2019 Census of Horticulture Specialties reports significantly fewer greenhouse operations by covering type than the more recent 2022 Census of Agriculture, underscoring the importance of reconciling data sources when assessing the California greenhouse market.

Implications for Programs

Program designers should prioritize greenhouses based on crop type, greenhouse size, and covering type, as these factors strongly influence heating demand, retrofit feasibility, and energy savings potential.

CROP TYPE

- Growers who want to grow high value crops that require heating—and in some cases, cooling—for year-round production, such as tomatoes and strawberries, may benefit from heat pumps, although vapor compression cooling is not currently common in this application.

SYSTEM REQUIREMENTS

- Important equipment selection criteria for owners are controllability, performance, reliability, and cost (first cost, then energy cost).

EXISTING HEATING TYPE

- A greenhouse's existing heating system and distribution types are key parameters that have an outsized influence on retrofit strategy, first cost to retrofit, and energy costs. Overhead unit heaters were very common in a survey of existing equipment type, followed by radiant heating and underfloor/under-bench heating.
- Overhead unit heaters may be easily replaced with air-to-air heat pumps, and hydronic systems could be retrofitted to air-to-water heat pumps (AWHPs) if the owner prefers to keep the existing heating distribution system.

GREENHOUSE SIZE AND USE OF ENERGY CURTAINS

- Small operations may face challenges in realizing specific positive non-energy impacts, such as consistent crop quality, improved air circulation, and precise environmental control, as they commonly lack energy curtains. However, their lower heating loads make electrified systems more affordable and easier to implement, even if some NEIs are less pronounced compared to larger greenhouses with energy curtains.
- Mid- to large-scale greenhouses offer economies of scale and more commonly use energy curtains, making electrification more cost effective. These operations are better suited for centralized boiler or hydronic heat pump retrofits, where the heat source (e.g., a gas boiler) is replaced with an AWHP while retaining the existing hydronic distribution system. This approach minimizes disruption and leverages existing infrastructure for electrification.

COVERING TYPE

- Rigid plastic or glass-covered greenhouses are particularly promising candidates for heat pump retrofits because they have better envelope efficiency and lower heat losses.
- Plastic film greenhouses may also be eligible, but programs should carefully evaluate envelope condition and heating requirements.

REGIONAL CONSIDERATIONS

- Greenhouses in California's Central Coast (Climate Zone 3), Sacramento (Climate Zone 12), and Southern regions (Climate Zone 6) represent the densest clusters of greenhouse food crop production and therefore, the largest potential program impact.

By incorporating these factors into program targeting, energy efficiency initiatives can maximize adoption rates of greenhouse heat pump systems, optimize system performance, and ensure cost-effective electrification of greenhouse heating.

Greenhouse Process Parameters

To foster ideal growth conditions for greenhouse crops, it is important to maintain process parameters, including temperature, relative humidity, carbon dioxide (CO_2) levels, water consumption, nutrient levels, ventilation rates, and daily light integral (DLI)[1] targets. A general greenhouse production article by the University of California, Davis (UC Davis) recommends that

[1] Daily light integral (DLI) refers to the total amount of photosynthetically active radiation that plants receive over a 24-hour period, measured in moles of light per square meter per day (mol/m^2/day). It is a critical parameter for optimizing plant growth and productivity in greenhouses.

growers set relative humidity below 85 percent to prevent disease, and states that humidity control is achieved by a combination of heating, fans (likely to mix air within the greenhouse), and ventilation (University of California N.D.). Both UC Davis and Resource Innovation Institute (RII) specified process parameters by crop type, which are broken out in Error! Reference source not found. and Figure 5 below.

Crop Type	Category	Target Temperature Range10 (°F)	Target Humidity Range (%)
Cucumbers[11]	Cold-sensitive	65 - 80	60 - 70%
Tomatoes[12]	Cold-sensitive	64 - 81	60 - 90%
Peppers[13]	Cold-sensitive	65 - 85	60 - 90%
Strawberries[14]	Cold-temperate	50 - 77	40 - 95%
Greens[15]	Cold-tolerant	50 - 65	50 - 70%
Herbs & Microgreens[16]	Cold-tolerant	60 - 70	40 - 60%
Mushrooms[17]	Cold-tolerant	50 - 68	75 - 95%

Figure 4: Ranges of horticultural environmental conditions by crop type.

Source: Schimelpfenig 2022, Table 3.

Crop Type	DLI Target[24] (mol/(m2 day)	Horticultural Lighting Application
Cucumbers	15 - 30	Medium-High
Tomatoes	20 - 30	High
Peppers	20 - 30	High
Greens	12 - 17	Medium
Herbs & Microgreens	12	Low-Medium
Strawberries	17 - 20	Medium
Mushrooms	2 - 3	Low

Figure 5: Crop DLI target and lighting application amount.

Source: Schimelpfenig 2022, Table 5. Note: Range 10 acknowledges that during early stages of propagation, temperature and humidity targets may be higher. Some crops may need swings in temperature to trigger flowering/fruiting.

For tomatoes, Schimelpfenig listed the target temperature range as 64 degrees Fahrenheit (°F) to 81°F, with a relative humidity range of 60 to 90 percent and a DLI target of 20 to 30 moles of light

per square meter per day (Schimelpfenig 2022). UC Davis has slightly different temperature recommendations, with a daytime temperature range of 75°F to 80°F and a nighttime temperature set above 60°F (University of California N.D.). Temperatures above 85ºF are not recommended due to negative impacts on the successful development of fruit from flowers (fruit set) and the red color development processes (University of California N.D.).

Another main process parameter for greenhouses to maintain optimal plant health is CO_2 concentration. The USDA cites 800 parts per million (ppm) to 1,000 ppm as the optimal concentration of CO_2 for greenhouse plants, although ideal CO_2 levels vary based on the growth stage of the plant and by crop type (USDA AMS 2023). Many greenhouses that use natural gas for heating also use combustion gas for CO_2 enrichment, capturing the relatively clean exhaust to boost crop yields. This practice provides a low-cost CO_2 source but creates a dependency on combustion-based heating systems. Electrified systems, such as heat pumps or electric boilers, eliminate that CO_2 co-benefit, meaning growers would need to purchase bottled CO_2 or install separate generation systems—an important consideration when assessing the full cost and feasibility of greenhouse electrification.

Implications for Programs

Programs seeking to promote electrification should consider greenhouse operational and environmental parameters that influence heating demand and compatibility with heat pump technologies. Key parameters include temperature, relative humidity, CO_2 concentration, crop growth stage requirements, and supplemental lighting practices.

TEMPERATURE AND HUMIDITY SETPOINTS

- Greenhouse temperature setpoints are generally well within the capabilities of commercially available heat pumps.
- Greenhouses typically rely on ventilation or heating for humidity control, which may drive heating loads beyond what is strictly needed for temperature control. Heat pumps may be well suited to provide dehumidification with vapor compression cooling.

SUPPLEMENTAL LIGHTING PRACTICES

- **Presence of supplemental lighting:** Greenhouses without supplemental lighting tend to have more heating-dominated load profiles and simpler electric infrastructure, making them relatively straightforward candidates for heat pump retrofits (for example, many medium-scale rigid-plastic houses and propagation houses). Facilities with extensive supplemental lighting—such as high-tech food and berry houses and high-control cannabis/CEA facilities—often face tighter electric-capacity constraints, which can limit how much heating can be electrified without service upgrades.
- **Interaction with heating loads:** Supplemental lighting increases internal heat gains during lighted periods, which can reduce space-heating needs but may increase cooling or dehumidification needs. In heavily lighted facilities, electrification benefits may appear as a mix of reduced gas heating and improved cooling/dehumidification efficiency, rather than purely as heating savings.
- **Lighting schedules and screening:** Lighting schedules (e.g., primarily daytime vs. nighttime operation) affect when heating is needed and how well heat pumps align with

grid conditions. As a practical screening step, programs can use the presence of supplemental lighting, its schedule, and available electric capacity to distinguish greenhouses suited for deeper electrification (limited/no supplemental lighting and adequate headroom) from those better served by dual-fuel strategies in the near term.

CO_2 CONCENTRATION AND GROWTH STAGE

- Facilities that inject CO_2 to support vegetative or flowering growth stages may be more inclined to control humidity via heating so as not to dilute the injected CO_2.
- Greenhouses with highly variable CO_2 requirements may require adaptive controls to optimize electrified heating performance.

PROGRAM TARGET SUMMARY

- **High-priority targets***:* Greenhouses with moderate temperature and humidity requirements, and stable CO_2 management. These facilities provide predictable heating loads and maximize the energy and cost savings achievable with heat pump electrification.
- **Secondary targets:** Facilities with more variable environmental parameters may still be candidates, but programs should consider hybrid systems, such as combining heat pumps with supplemental heating strategies, to ensure adequate crop growth conditions.

By prioritizing facilities based on these process parameters, programs can identify greenhouses where electrification offers the greatest technical and economic feasibility, while supporting optimal crop production and operational reliability.

Greenhouse Process and Non-Process Loads

Energy usage, especially heating and lighting, is a main expense for greenhouse operations, also referred to as controlled environment agriculture (CEA). The CEA and Greenhouse Heating, Ventilation, and Air Conditioning (HVAC) Market and Technology Study by Southern California Gas Company, along with an ICF study, found that for CEA facilities, energy accounts for up to 60 percent of operating costs and heating can be a top-three operating cost (ICF 2023).

The University of Wisconsin-Madison Cooperative Extension similarly indicated that greenhouse heating and electricity can account for 70 percent to 80 percent and 10 percent to 15 percent of total energy consumption, respectively (Sanford 2011). While the 2019 Greenhouse Energy Profile Study from the Posterity Group focused on Ontario's greenhouse sector, its findings align with trends observed in California, where natural gas remains the dominant energy source for heating, and electricity is primarily used for lighting and auxiliary systems. These parallels suggest that insights

from Ontario's greenhouse sector may be applicable to California, particularly for vegetable sub-sectors, as shown in Figure 6 below.

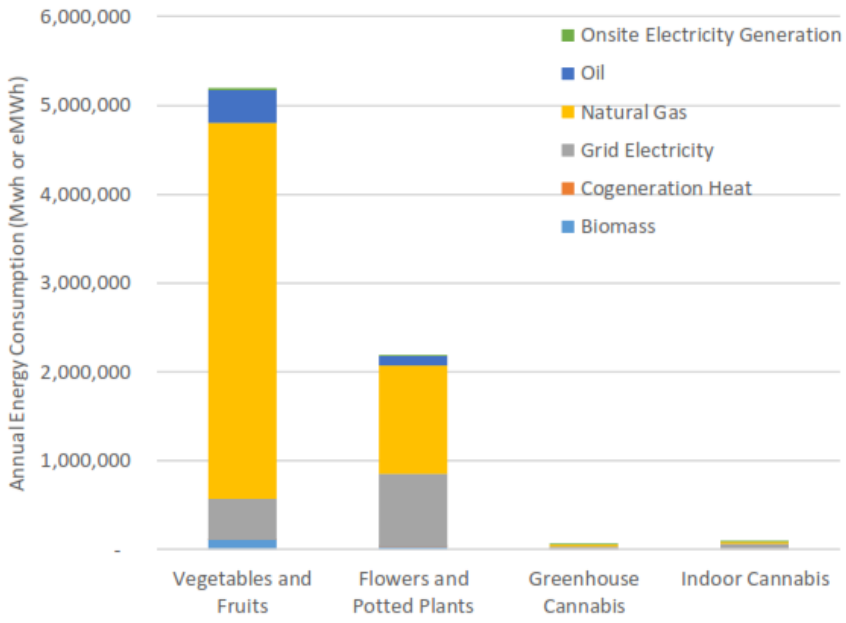

Figure 6: Energy consumption by sub-sector and fuel in Ontario, Canada.

Source: Posterity Group, 2019.

For process load end uses by energy source, the 2019 Greenhouse Energy Profile Study found that greenhouses' main energy source (natural gas) primarily fueled heating systems, as well as minimal amounts of cogeneration, as shown below in Figure 7.

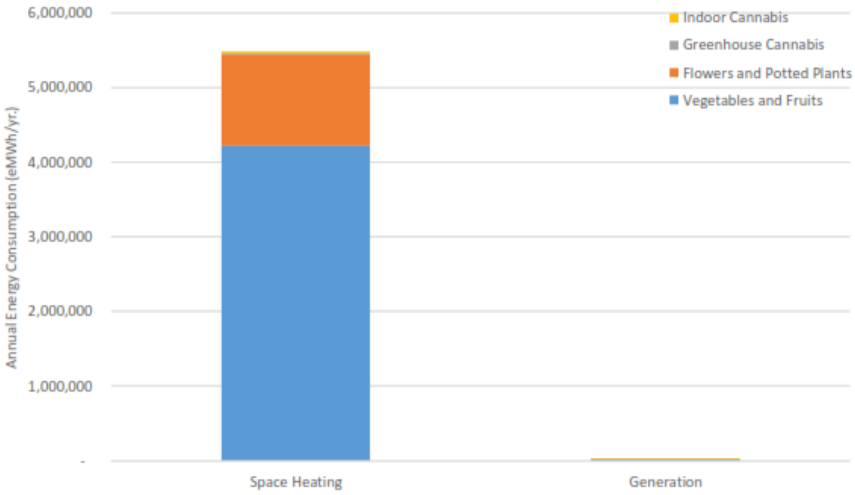

Figure 7: Natural gas consumption by end use and sub-sector.

Source: Posterity Group, 2019.

Electricity use—while considerably lower than natural gas consumption—powers a larger variety of process load end uses, including lighting, pumping, heating, cooling, and others shown in Figure 8. Electricity end-use intensity varies across the greenhouse subsectors, as well as between lit and unlit facilities. The Posterity Group's 2019 report found that a lit vegetable greenhouse consumes 10 times as much electricity as an unlit vegetable greenhouse, with essentially all the additional electricity used for lighting. A lit florticulture greenhouse consumes 4 times as much electricity as an unlit vegetable greenhouse, while indoor cannabis facilities use almost 3.5 times more electricity per square foot than lit vegetable greenhouses. Additionally, indoor cannabis facilities use 1.4 times more electricity than cannabis produced in greenhouses.

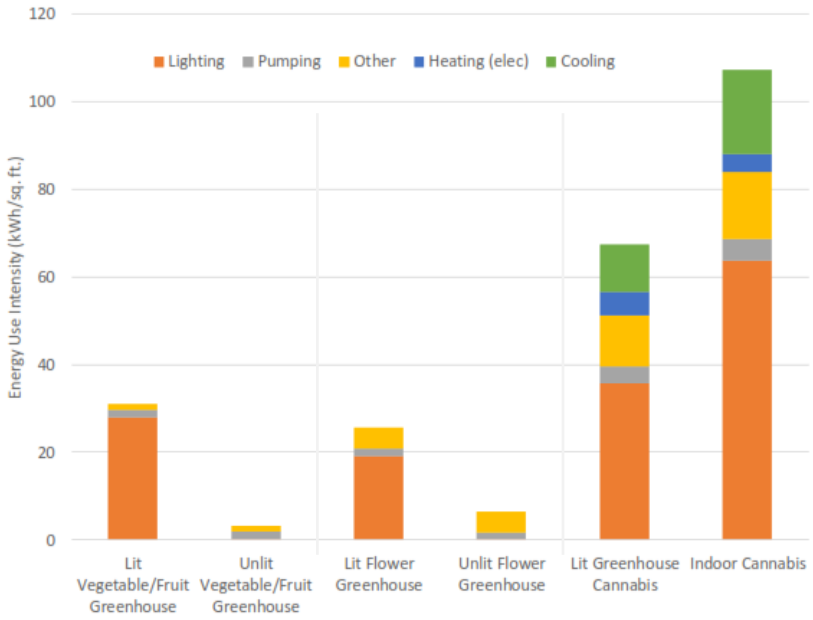

Figure 8: Electricity end-use process loads by facility type.

Source: Posterity Group, 2019

Since heating is the dominant process load, the remainder of this section will focus on considerations that affect gas usage.

Annual natural gas energy usage for greenhouses ranges from 1.7 therms per square foot for double-wall coverings to 3.1 therms per square foot for single-wall coverings (ICF 2023). Figure 9—which represents data from two facilities—shows that the average annual heating usage for CEA facilities was nearly 400,000 therms. One of these sites produces leafy greens and is approximately 680,000 square feet (ICF 2023).

CEA Farm Type	Average Annual Therms for Heating	Facility Count
Vegetable	389,916	2
Cannabis	374,415	8
Orchid	160,247	8
Nursery	83,648	50
Floriculture	73,903	24
CEA WEIGHTED CUSTOMER AVERAGE	**119,709**	**92**

Figure 9: Annual therms for heating in California by CEA farm type.

Source: ICF 2023, Table 2

The Appropriate Technology Transfer for Rural Areas found that forced hot air units are the most common heating equipment in CEA facilities. This equipment is desirable because these units "are relatively inexpensive, can be sized easily to the amount of heated space, and are simple to install" (Greer et al. 2023). Additional forced hot air units can be installed if a greenhouse operation expands, and can also be ducted for tabletop heating (Greer et al. 2023). Additionally, an RII report lists unit heaters as common, as well as hot water systems with floor heating, bench heating, root zone heating, or hydronic unit heaters, as illustrated in Figure 10 (Schimelpfenig 2022).

HVAC System Type	Facility Type: Ventilated Greenhouse	Facility Type: Sealed Greenhouse
Heating	Unit heaters Hot water systems: boilers connected to radiant warm-floor slab heating or bench heating, hydronic unit heaters, root zone heating Biomass heating, furnaces	Hot water systems, geothermal heat exchange systems, air to air heat exchangers, fan coil units, electric resistance systems, latent heat converters
Ventilation	Natural ventilation - ridge vents, gutter vents, side wall vents, open-roof, retractable roof, powered fan systems for ventilation and exhaust	100% recirculating systems, no air exchange with outside
Airflow	Horizontal airflow fans (HAF)	Vertical air fans, destratification fans, air handling units
Cooling	Evaporative fan-and-pad, fogging or misting for cooling and humidifying, chillers[20]	High-pressure fogging or misting for cooling and humidifying, integrated cooling & dehumidification
Humidity management	Exhaust fans, wood-fired heating, sometimes plug-in dehu units	Central dehumidification system

Figure 10: Typical HVAC systems by greenhouse facility type.

Source: Schimelpfenig 2022, Table 4.

Implications for Programs

Heating in greenhouses is commonly provided by boilers or forced-air systems, and each system presents distinct opportunities and challenges for electrification.

BOILERS

Boiler systems are generally found in mid- to large-scale greenhouses with centralized heating plants. These facilities are strong candidates for heat pump electrification because:

- Hydronic distribution systems integrate well with AWHPs.
- Existing modular or zoned heating infrastructure can accommodate phased retrofits, making installation less disruptive.
- Peak heating loads are typically more predictable, improving the efficiency and cost effectiveness of heat pump solutions.

Challenges for boiler electrification include:

- Retrofitting low-temperature heat pump systems into high-temperature boiler networks may require supplemental piping or heat emitters.
- Large, highly insulated spaces may require careful system sizing to meet crop-specific temperature setpoints.

FORCED-AIR SYSTEMS

Forced-air heating units are small, cheap, and easy to deploy plug-in units. They are common in small- and medium-sized greenhouses due to low upfront costs, ease of installation, and versatility. These facilities can also be good candidates for electrification, especially when:

- The greenhouse is in a mild climate where peak heating loads are manageable.
- The facility has moderate envelope efficiency (low infiltration, well-maintained coverings) to reduce unpredictable heat loss.
- Operators are open to adopting hybrid or supplemental strategies, such as combining heat pumps with small electric boosters or thermal storage to meet peak demand.

Challenges for forced-air electrification include:

- Air-source heat pumps may struggle to meet high peak loads during cold periods without supplemental heating.

NON-PROCESS LOADS

Non-process loads, particularly air infiltration and ventilation losses, significantly impact heating demand and system sizing. Unlike process loads directly tied to plant growth parameters (e.g., temperature, humidity, and CO_2 concentration), these non-process loads stem from the physical characteristics of the greenhouse envelope and its auxiliary systems. Greenhouses with tight envelopes, functioning energy curtains, and controlled ventilation are stronger candidates for electrification, as they reduce the first costs and operating costs associated.

Envelope performance is a major determinant of heating demand. Greenhouses with single-layer coverings, damaged seals, or frequent door openings can experience substantial infiltration losses, forcing heating systems to operate longer and at higher capacity. Energy curtains, double-layer poly coverings, and vestibules have been shown to reduce heating loads, improving the viability of lower-capacity heat pump systems. Greenhouses with tight envelopes and effective energy curtains are therefore stronger candidates for electrification, as reduced heat loss helps keep electric heating systems within feasible size and cost thresholds.

Ventilation systems, including both passive vents and active exhaust fans, play a dual role in energy performance. While they are essential for maintaining temperature, humidity, and CO_2 levels, uncontrolled ventilation can lead to major heating penalties. Automated vent control systems, variable-speed fans, and integrated climate management systems can reduce unnecessary air exchange, thus improving energy efficiency and stabilizing indoor conditions. Electrified greenhouses that optimize ventilation strategies may be able to reduce heating loads enough to offset part of the added cost of electric heating.

Lighting and internal heat gains also influence heating demand. High-intensity discharge lamps, which are still common in older facilities, provide significant waste heat that offsets some space heating requirements. As growers switch to more efficient light-emitting diode (LED) lighting, this internal heat contribution decreases, increasing the need for supplemental heating. Electrification programs should account for these interactive effects, as greenhouses undergoing LED retrofits may experience rising heating loads that make heat pump adoption more attractive, or necessary, to maintain overall crop performance.

Operational factors such as irrigation timing, shade or energy curtain control, and occupant behavior also contribute to non-process loads. For instance, frequent misting or irrigation increases humidity and latent heat load, while improper shading control can lead to temperature fluctuations that increase heating demand.

PROGRAM TARGET SUMMARY

Successful electrification strategies should target greenhouse operations where both heating system type and non-process load conditions support efficient, cost-effective performance. Non-process loads—such as air infiltration, ventilation, and heat loss through greenhouse coverings—strongly influence the feasibility and cost effectiveness of electrification. Greenhouses with tighter envelopes, functional energy curtains, and controlled ventilation present lower heating demands, reducing both the first cost and operating cost of electrified systems.

Programs aiming to advance greenhouse electrification should therefore target operations that:

- Have modern or well-maintained structures, particularly those with rigid or double-wall coverings that limit infiltration and heat loss.
- Use energy curtains or other thermal retention strategies that moderate nighttime temperature swings and reduce peak heating demand.
- Employ controlled ventilation and automated environmental controls that balance air exchange with heating efficiency.
- Are not heavily reliant on combustion-based CO_2 enrichment, as these facilities would require additional strategies to maintain CO_2 levels after electrification.
- Have smaller air volumes per unit of growing area or use partitioning or energy curtains to reduce the total conditioned space, further improving heat pump viability.

By focusing on facilities with efficient envelopes and well-managed non-process loads, programs can identify the most viable candidates for heat pump deployment: greenhouses where electrification is both technically achievable and economically attractive. These envelope characteristics also define

key target greenhouse typologies for future program design and modeling of greenhouse electrification potential.

Policy Literature Review

Owning and operating greenhouses in California requires a clear understanding of the local, state, and federal policy landscape, as it differs from standard commercial building policy. California does not mandate heat pump use in greenhouses, but a combination of energy codes, air quality regulations, and financial incentives are creating a strong push toward heat pump technology:

- **Title 24, Part 6 (California Energy Code):** The 2025 energy code includes specific requirements for CEH operations (CEC 2025, Section 120.6(h)). For indoor growing,[2] dehumidification systems must comply with one of four options. For all conditioned greenhouses, space conditioning installations must comply with mandatory requirements under covered processes (e.g., boilers and steam traps).
- **California Air Resources Board (CARB)**: While greenhouse heating is not a primary target, broader air quality regulations from CARB can still influence technology choices. For example, boiler heating systems are subject to local nitrogen oxide (NO_x) emission limits and larger facilities may be subject to CARB's Cap-and-Invest program, formerly known as the Cap-and-Trade program (CARB N.D.).

Several state and federal programs can make heat pump retrofits and installations economically attractive for greenhouse operators.

- **Statewide utility programs:** These programs provide prescriptive and custom incentives for CEH energy efficiency and fuel substitution measures. While prescriptive rebates for greenhouse heat pumps are not currently offered, custom incentives can be secured based on site-specific energy savings. For investor-owned utilities (IOUs), the California Public Utilities Commission (CPUC) provides specific guidelines for incentivizing fuel substitution measures. Fuel-switching measures involving non-utility fuels, such as propane or fuel oil, are outside the scope of the Fuel Substitution Decision (CPUC 2019, D.19-08-009) and are not eligible for IOU incentives. Onsite electricity generation can accelerate heat pump payback periods by lowering operational costs. While these on-site generation projects have historically been eligible for the statewide Self-Generation Incentive Program (SGIP), on-site generation projects do not qualify for traditional energy efficiency (EE) incentives. Furthermore, addressing the demand impacts of heat pumps is critical for maintaining grid capacity as the state continues its electrification efforts.

  California's demand-side management framework historically separates funding through distinct regulatory proceedings and budget rules at the CPUC for EE, demand response (DR), and SGIP programs rather than a single unified policy and program delivery mechanism. These operational silos stem from separate statutory mandates and distinct

[2] Indoor growing is a type of CEH space in a building with a skylight roof ratio less than 50 percent. Growing plants in a warehouse with or without skylights is an example of indoor growing.

utility program administration rules. Each category maintains separate rules, compliance metrics, and application processes, which creates structural barriers in co-marketing or combining customer incentives across these traditional programmatic lines.

Integrated demand-side management (IDSM) is a strategic approach designed to combine multiple customer-side energy resources. In 2007, the CPUC formally launched IDSM under Decision 07-10-032, instructing IOUs to combine EE, DR, advanced metering, and self-generation into a cohesive strategy. In 2018, the CPUC recognized massive administrative silos persisted, so CPUC staff redirected specific IDSM funding to target low-cost, high-value "EE-DR integration" within the rolling EE portfolios.

While focused IDSM initiatives remain active, standard EE program funding is currently limited to supporting energy efficiency upgrades, electrification projects, and permanent load management measures. Although EE frameworks are authorized to supply technical guidance for DR and self-generation measures, they are prohibited from issuing upfront capital or performance-based incentives for these supply-side technologies. Because self-generation oversight and budgets are kept entirely separate, utilities cannot bundle multi-resource "electrification-SGIP" packages—such as pairing agricultural greenhouse heat pump conversions with behind-the-meter solar arrays—under a single, streamlined IDSM incentive. Onsite generation technologies currently eligible for SGIP incentives include photovoltaics, electrochemical and thermal energy storage, wind turbines, and combined heat and power (CHP) using biogas or hydrogen. Integrating generation technologies into EE program offerings could provide more streamlined, efficient, and comprehensive IDSM solutions for customers facing the technical and economic challenges of electrifying greenhouse heating systems.

- **Federal programs:** The USDA Rural Energy for America Program (REAP) offers grants and loan guarantees for renewable energy systems and energy efficiency improvements for rural businesses, including greenhouses (USDA RD N.D.). Air-source heat pumps qualify as high efficiency HVAC systems under the program's Energy Efficiency Improvements projects. Meanwhile, geothermal heat pumps are eligible for the Renewable Energy Systems category because they draw energy from the Earth; while this program is currently not accepting grant applications, loans are still available (USDA RD N.D.).

There are numerous states across the country that support fuel substitution or switching through guidelines and fuel-neutral goals, California being one of them.[3] These states may offer new policy ideas for targeting, supporting, and incentivizing heat pump adoption in the CEH sector. Unfortunately, federal funding and tax incentives may be a less reliable market driver moving forward, given the current presidential administration's dismantling of past and existing

[3] Other states include Alaska, Oregon, Colorado, Minnesota, Wisconsin, Illinois, Tennessee, New York, Vermont, Massachusetts, Connecticut, and New Jersey.

environmental and energy programs. For example, USDA REAP is not currently accepting grant applications.

Implications for Program Design

The policy landscape highlights both opportunities and constraints for rolling out greenhouse electrification programs. To effectively leverage this information, programs should consider the following actions:

- **Clarify fuel eligibility early.** Many greenhouses currently rely on delivered fuels, such as propane or fuel oil, which are excluded from IOU fuel substitution incentives under CPUC Decision D.19-08-009. Before investing in outreach, programs should confirm whether these facilities can be eligible for support for electrification. Parallel pilots or non-IOU funding sources may be needed to reach this segment equitably.
- **Revisit avoided cost treatment.** For greenhouses using delivered fuels, avoided gas infrastructure costs will not apply. Programs should evaluate how this affects cost-effectiveness tests and whether greenhouse gas benefits or equity considerations can serve as alternative sources of program value. Pilot programs could help test methodologies for quantifying benefits when infrastructure-related avoided costs are not relevant.
- **Develop deemed or hybrid offerings.** Current reliance on custom projects creates barriers to participation in a sector dominated by small and medium growers. Programs should explore deemed savings approaches, or hybrid deemed-custom methods, to streamline participation while still capturing site-specific performance data. The majority of greenhouse projects are currently incentivized with deemed rebates (i.e., LED lighting, heat curtains, pipe insulation, condensing boilers); however, there currently is no deemed offering for greenhouse heat pump installations.
- **Position incentives alongside state and federal programs.** Inflation Reduction Act federal tax credits and USDA REAP grants can substantially reduce upfront costs. Programs should provide technical assistance to help growers layer incentives across sources and design program rules to complement, not duplicate, federal offerings.
- **Integrate equity and market development goals.** Many greenhouse operations are located in hard-to-reach or disadvantaged community areas. Framing program benefits around supporting local economies through equity and resilience—in addition to avoided costs—can provide justification for pilots and targeted outreach efforts.
- **Alignment with broader CARB and CPUC directions.** While CARB's Scoping Plan is more focused on transportation, its inclusion of agriculture in the state's long-term climate goals means CEH will increasingly face scrutiny. Programs that anticipate this trend by piloting electrification and efficiency now can help shape future policy directions and establish leadership.

Stakeholder Feedback

Stakeholder feedback was a core input to every major element of this research, including the technical literature review, policy and program scan, market actor interviews, and energy analysis. The project team engaged a diverse set of stakeholders including policy and program administrators, implementers, technical experts, manufacturers, vendors, and greenhouse operators, to ensure findings were relevant, actionable, and grounded in real-world conditions.

Through structured interviews, email correspondence, and data sharing, stakeholders helped validate where technical and policy findings aligned with field experience and where important gaps remained. Their input informed the refinement of greenhouse typologies, adjustment of energy analysis assumptions, development of electrification archetypes, and identification of program design and technology transfer opportunities.

Engagement evolved over the course of the project. Early outreach focused on policy and program stakeholders to understand existing decarbonization efforts, policy alignment, market barriers, and opportunities for integration. Later engagement expanded to manufacturers, vendors, and greenhouse operators to test technical assumptions and assess implementation challenges, such as heating system performance, product availability, market readiness, and grid capacity constraints.

In addition to informing the research, stakeholder engagement also supported dissemination of findings and recommendations back to these groups. By maintaining open communication and tailoring recommendations to stakeholder needs, the project aimed to accelerate adoption of electrified greenhouse heating systems and support California's broader decarbonization goals.

Market Actor Interviews

To complement the technical literature review, TRC conducted a series of structured interviews with key market actors to better understand opportunities and barriers for electrified greenhouse heating in California. These interviews provided qualitative insights into how process parameters, operational practices, and market conditions influenced the feasibility and attractiveness of heat pump and electric boiler adoption. These findings directly inform the energy modeling and program design considerations developed later in this study.

Research Sample

The project's research sample captured perspectives from multiple points along the greenhouse heating value chain. The project team conducted a total of 14 interviews across the following groups:

- **Greenhouse owners and operators** (six interviews): These conversations provided firsthand accounts of operational practices, decision-making around heating and cooling, and real-world constraints that shape adoption of electrified systems.
    - O1: A small farm store/greenhouse that worked with a designer to install a dual-fuel hydronic heat pump and boiler system with self-generation located in East Canon, Connecticut.

    - O2: A small, fifth-generation organic vegetable farmer using greenhouses for transplants and winter crops with a geothermal heat pump and solar located in Petosky, Michigan.
    - O3: A large, multisite cannabis operator managing complex Dutch-style boiler and CO_2 systems in Carpinteria, California.
    - O4: An institutional investor structuring large glasshouse sites around heat pumps and CHP located around East Anglia, United Kingdom (UK).
    - O5: A greenhouse salad greens grower at a technology-forward startup planning CHP-driven greenhouses near Hollister, California and Pescadero, California.
    - O6: A large greenhouse nursery provider using gas-fired unit heaters located in Perris, California, as well as other facilities throughout California.
- **Heat pump and equipment vendors** (three interviews): Vendors offered insights into the technologies currently marketed to greenhouses, customer drivers, and technical challenges with integrating heat pumps or electric boilers into existing infrastructure.
    - M1: A California-based company that provides turnkey greenhouse construction and retrofits.
    - M2: A California-based greenhouse heating system design and manufacturing company.
    - M3: A European-based industrial heat pump manufacturer.
- **Subject matter experts and program staff** (three interviews): These interviews added perspective on broader market trends, technical considerations across different greenhouse types, and lessons learned from prior efficiency or electrification efforts.
    - SME1: An agricultural sector energy efficiency utility program lead focused on trade ally and CEA partnerships around greenhouse heating.
    - SME2: A clean energy consultant firm that brings long-term, multi-program experience (since 2011), conducting audits, site visits, measure development, and program implementation across IOU and third-party agricultural programs, especially related to greenhouse lighting and heating.
    - SME3: A California-based consultant deeply embedded in greenhouse design and operations.
- **Policy makers** (two interviews): Engaging with regulators and agencies helped situate greenhouse electrification within the current and emerging policy landscape.
    - P1: A California energy policymaker.
    - P2: A California utility energy efficiency policy expert.

One owner-operator interview (O6) was conducted onsite at a greenhouse that uses gas heating. This interview did not follow the same formal structure as our remote interviews; rather, it was a more informal site walk-through to understand the existing heating system. Very early in the visit, after seeing the unit heater system and asking initial questions, it became clear that:

- The grower faced substantial financial barriers to upgrading from unit heaters to a hydronic distribution system, in addition to the cost of electrifying their heating system.
- They were not convinced that an electrified air-to-air system would perform as effectively for their operation.

Because of this, we focused the remainder of the visit on clarifying those barriers and decision drivers rather than running through the full scripted interview. This onsite perspective was nonetheless extremely valuable: It reinforced that starting with unit-heated sites would impose an additional financial burden (conversion to hydronic plus electrification), and it helped us prioritize greenhouses with existing hot water (hydronic) distribution systems as the higher-value near-term retrofit candidates for heat pump electrification in California.

Recruiting Strategy

The project team identified participants through TRC's existing industry networks (convenience sampling), outreach to California greenhouse associations (purposive sampling), and referrals from early interviewees (snowball sampling). Through speaking with vendors and subject matter experts, we connected with contacts from equipment manufacturers, distributors, and utility program partners. The team selected policymakers based on their active involvement in greenhouse energy policy, electrification, or self-generation regulation. To encourage participation, the project team offered a financial incentive, as well as emphasizing the role of this research in shaping future incentive programs and ensuring the program design reflects growers' needs.

Interview Topics

The project team structured interview guides to align with the project's research objectives while tailoring questions to each market actor group. Core themes included the following:

- **Process parameters and greenhouse design factors.** Exploring heating setpoints, hot water delivery temperatures, humidity control strategies, crop mix, partitioning, and the role of supplemental lighting. These operational details are critical inputs for modeling and for determining which greenhouse typologies are best suited for electrification.
- **Existing heating and cooling systems.** Assessing types of distribution systems (e.g., forced air, hot water, root zone), heating plant type, age, and maintenance practices, as well as any integration with thermal energy storage (TES), waste heat recovery, or potential/existing cooling end uses.
- **Adoption drivers and barriers.** Understanding how growers weigh crop needs, capital investment, and energy costs, to inform their interest in heat pumps, as well as vendor views on what makes electrified systems viable or challenging.
- **Non-energy impacts (NEIs)**. Probing for both positive and negative effects on crop quality, yield, resilience, and business outcomes that could impact the value proposition of electrified systems.
- **Policy and self-generation.** Examining how renewable energy integration, spark spread considerations, and local regulations shape decision-making.
- **Market outlook.** Gathering perspectives on which segments—by crop type, greenhouse design, or region—are most likely to adopt electrified heating in the near term.

The project team designed the interview questions with a flexible structure to enable interviewers to probe deeper into technical or operational issues where respondents have direct experience. Findings from these conversations were synthesized to highlight common themes, segment-specific

opportunities, target greenhouse typologies, and to create actionable recommendations for California programs.

Market Actor Interview Results

The following sections present findings from interviews across all market actor types presented by research theme.

Process Parameters That Impact Heat Pump Type and Energy Use

Across all market actors, a consistent message emerges: Process conditions and climate, not just nameplate capacity, determine whether heat pumps make sense in greenhouses. From the owner-operator side, the Connecticut designer (O1) and the Michigan geothermal farmer (O2) sit firmly in the low-design temperature, long-run regime where heat pumps are most effective. O1 worked with a designer on a new construction with AWHPs feeding radiant slabs and low-temperature fan coils, deliberately targeting water temperatures around 90°F to 95°F with a small Delta T (i.e., change in temperature) of 10°F to 15°F to keep coefficient of performance (COP) high. O2 operates a horizontal geothermal field tied to a heated concrete floor, with a storage tank typically in the mid-90s°F and floor setpoints ranging from the mid-60s°F for brassicas to 80°F to 85°F for tomatoes and peppers. These systems run for long hours, at modest temperatures, and in stable propagation environment—exactly the conditions that make geothermal heat pumps and AWHPs efficient.

By contrast, the California cannabis operator (O3), the UK investor (O4), and the California nursery supply (O6) operate at much larger scales and under different constraints. O3 uses large Dutch hot water boilers with minimum pipe temperatures in the high-80s°F to mid-90s°F—or 28 degrees Celsius (°C) to 35°C—that occasionally rise to 130°F (55°C) in very cold weather. He stresses that, in a well-insulated controlled environment, 180°F water is simply unnecessary; however, he also points out that retrofits would impose water quality and potentially scaling issues on heat pumps, and that electrifying his load would require multi-megawatt (MW) electrical service that the utility cannot currently supply.

O4's UK glasshouses are explicitly designed around low-temperature heat networks (110°F). Industrial heat pumps—on the order of 5 MW to 6 MW each—deliver supply temperatures that keep the loop efficient, with gas CHP serving as a peaking and resilience resource. O6's California glasshouses relied on inexpensive unit heaters, and O6 was hesitant to explore electrification further when faced with substantial financial barriers to upgrade to a hydronic distribution system, in addition to the cost of electrifying their heating system.

The California greenhouse leafy greens grower (O5) adds a third pattern: a model where lighting load, cooling needs, and grid capacity become key process parameters. At their sites, large LED loads at night, meaningful cooling and dehumidification challenges, and tight utility interconnection constraints all shape what is possible. Even though they are planning hydronic distribution at one site, O5's core decision variables are:

- Can the grid deliver the power we'd need for heat pumps and LEDs together?
- What does the total cost of implementation look like under current rates and demand charges?

Those factors pushed them toward gas CHP as the main heat and power source, even though they are climate-conscious and technically literate.

Manufacturers and vendors map these stories into two broad heat pump regimes:

- Low-temperature AWHP/water-source heat pump (90°F to 120°F supply) serving slabs, root-zone circuits, and large coils in well-insulated structures with long runtimes.
- High-temperature industrial heat pumps (150°F to 190°F) where pressures, materials, and COP penalties make systems expensive and policy-dependent.

Program staff, CEA consultants, and policy experts emphasize that factors such as humidity and vapor pressure deficit targets, dehumidification strategies, rate structures, and demand charges significantly influence the selection and operation of process parameters. For example, cannabis greenhouses run very dry, with substantial simultaneous heating and dehumidification, but that is less common for other crops; rate design and large spark spread gaps can make or break heat pump economics, even where temperatures and loads look heat-pump-friendly.

Overall, the interviews suggest: heat pumps work best where temperatures are low (120°F or below), runtimes are long, thermal mass is high (water, phase change material, or geothermal), and the grid and rates are favorable to fuel switching by not imposing additional costs. Where electric capacity is constrained, lighting loads are huge, or high temperatures and rapid ramping are needed, operators tend to stay with boilers or CHP, at least under current conditions.

Existing Heating Distribution System Types

Most actor groups treat distribution system type, either hydronic or forced air, as a major determinant of performance and electrification potential, but one owner-operator explicitly challenges that framing.

Program staff and vendors say California still has a large base of overhead gas unit heaters blowing hot air into relatively leaky structures, especially in floriculture and nurseries. These are cheap, familiar, and easy to install, but hard to adapt to low-temperature operation or TES, and often deliver poor vertical temperature consistency. At the other end are hydronic systems: hot water boilers with pipe rails, in-slab circuits, and (sometimes) root-zone loops that are inherently more compatible with low-temperature sources, such as heat pumps or CHP.

Owner-operators span this spectrum:

- O2 uses in-slab crosslinked polyethylene, or PEX, to heat the root zone, letting air temperature “float” lower.
- O3 runs a classic Dutch hydronic system with pipe rails that double as labor-saving tracks.
- O4 ties their sites into a low-temperature, district-style hydronic network serving large glasshouse blocks.
- O1 works in mixed systems (floor heat, fan coils, occasional propane unit heaters) and deliberately steers heat pump projects toward slab or low-temperature hydronics (running at 90°F to 120°F instead of the traditional 180°F) to keep COP high.
- O6 runs cheap, gas-fired unit heaters and is concerned with keeping first costs low.

- O5, however, is less convinced that distribution type is the primary bottleneck. In their view, you can usually design the distribution (air or water) to work with whatever efficient supply you choose; the more decisive constraints are fuel economics, grid capacity, and overall system integration. For their planned CHP-based site, they are happy to use hydronic distribution under and around modular production units, but they see that as a design detail that follows from the CHP decision, not as the driver of it.

Policy experts and program implementers see this distribution picture as a segmentation tool:

- **Boiler + hydronic + curtains** tend to signal a higher-tech, higher-sophistication grower who might be open to phased electrification or hybrid heat pump/boiler designs.
- **Unit heaters + poly hoops + limited controls** signal a cost-driven producer for whom even efficiency upgrades are a stretch, let alone a heat-pump-based conversion.

Any strategy to scale greenhouse electrification in California will need to start from where the distribution systems are, not where designers wish they were. Manufacturers and policy experts mostly align with the "distribution is important" view, but O5's perspective is a useful corrective: Hardware choices on the load side are only one part of the story. For many California growers, especially those with big lighting loads or capacity constrained electrical distribution networks, the decision to electrify, stay on gas, or adopt CHP is dominated by power availability, rate design, and capital constraints. Distribution then becomes a question of optimizing within that higher-level choice.

Thus, for many market actors, distribution is a strong predictor of where heat pumps and TES can fit (hydronic houses vs. unit heaters). For at least one sophisticated operator (O5), supply-side constraints and economics dominate, and distribution is something they are confident they can adapt once they choose the heat and power source.

Thermal Energy Storage (TES) Capacity

TES shows up as a topic across interviews; it may consist of dispatchable energy stored in tanks or storage as thermal mass in slabs, in-ground loops, and via custom operating strategies. Among owner-operators:

- O2 has both short-term slab storage (the floor and structure ride through outages for days) and seasonal storage in a horizontal geothermal field that is cooled in winter by greenhouse heating and warmed in summer by refrigeration and field heat removal.
- O3 uses a large, insulated hot-water tank charged in the daytime while capturing CO_2, then discharged at night to meet heating needs and allow smaller boiler capacity.
- O4 uses a two-tier TES architecture at district scale: a big, low-temperature tank for industrial heat pumps and a smaller, high-temperature tank for CHP, which provides flexibility for peaks and energy trading.
- O1 relies on the inherent mass of slabs, benches, and soil, and has separate experience using tanks for TOU shifting with heat pumps in other building types.
- O5 does not emphasize a big, dedicated TES vessel, but does describe operational and structural storage: hydronic systems and greenhouse mass allowing time-shifting of CHP output relative to instantaneous heat demand, and careful scheduling of lighting and

other loads to align with generation. In their framing, TES is less a single piece of equipment and more a combination of water volume, building mass, and runtime strategy.

Vendors and program staff see TES as a key enabler for heat pumps and CHP, smoothing loads, mitigating demand charges, and aligning operation with photovoltaics (PV) or low-carbon hours. Policy experts note that TES's value is often under-recognized in existing cost-effectiveness frameworks. California policymakers are currently exploring ways to expand IDSM toward more permanent and dynamic load-shifting initiatives. Given that energy efficiency, demand response, and distributed energy resources have historically been managed in silos, these efforts remain in the preliminary stages, presenting an ideal opportunity to share this research with statewide stakeholders.

The shared takeaway is that where some form of TES is present—whether slab, tank, ground loop, or well-designed runtime alignment—heat pump and CHP options become much more flexible and grid-friendly. Where TES is absent and loads must be met "in real time," both heat pump sizing and grid impacts are harder to manage.

Waste Process Heat Stream and Other Potential Heat Sources

Waste heat and unconventional heat sources came up repeatedly, but with very different levels of maturity and policy support. On the most advanced end, O4's UK sites are explicitly built around waste heat from wastewater treatment plants, lifted by large industrial heat pumps into a low-temperature heat network serving big vine-crop glasshouses. The greenhouse is intentionally placed at the end of the line to extract as much remaining available energy as possible, with policy (e.g., renewable heat incentives) making the economics work.

In California, O3 champions CHP as an underused opportunity, pointing to the Dutch model where grower-owned cogeneration fleets simultaneously provide heat, CO_2, and high-value power to the grid. They argue that, if California's rules allowed similar relationships with utilities, CHP waste heat could displace traditional boiler use while supporting grid reliability. The point raised by O3 regarding the potential of CHP systems to provide heat, CO_2, and power while supporting grid reliability is compelling, particularly when considering the high efficiency of heat-led CHP systems. However, California's current regulatory and policy framework presents significant barriers to this approach.

For CHP to achieve its full potential, it must operate in a heat-led mode, where electrical output is modulated to match heat demand, ensuring that all available energy is used. While highly efficient, this approach is consistently rejected by IOUs—with implied support from the CPUC—due to the tension between the flexibility required for IDSM and the rigid, categorical design of existing program incentives. These incentives are primarily structured to improve compliance and accounting rather than to adapt to the dynamic market needs necessary for achieving California's energy and decarbonization goals.

O5 is actively designing something along these lines for a CEA leafy greens site: a gas CHP sized to serve large LED loads and produce hot water for hydronic distribution under and around the grow modules, with a clear eye toward potential CO_2 capture for crop enrichment. In their concept, electricity for lighting is the primary product and hot water and CO_2 are "waste" streams that become

valuable inputs to the greenhouse. From a thermal perspective, this is a deliberate waste-heat utilization strategy, even if the formal policy has not framed it as such.

At smaller scales, O1 has a methane digester but currently uses the biogas in a relatively simple way (flare/co-burn rather than fully integrated greenhouse heat recovery), underscoring common "last-mile" integration challenges. O2's system doesn't use external waste heat; it effectively treats refrigeration heat and field heat rejection[4] as a seasonal load into the ground loop.

Manufacturers and policy experts see many potential external sources (e.g., industrial refrigeration, data centers, municipal plants) but note that California lacks the business models and regulatory structures (e.g., heat-network concessions, standardized "heat-as-a-service" contracts) that underpin the most successful European examples.

The broader takeaway is that waste heat, combined with heat pump or CHP systems, represents a significant technical opportunity for reducing the carbon intensity of greenhouse heating, but one that is highly contingent on local infrastructure, ownership boundaries, and policy. When waste heat is derived from fossil-fuel-based processes, including CHP, it does not constitute a zero-carbon solution; however, compared to conventional standalone fossil boilers, appropriately sized and heat-led CHP or waste-heat recovery can still deliver meaningful, near-term emissions reductions and efficiency gains. In this sense, waste-heat utilization can serve as an incremental step toward decarbonization; especially when paired with strategies such as progressive grid decarbonization, fuel switching over time, and eventual integration with low- or zero-carbon heat sources (e.g., heat pumps on a decarbonized grid). Realizing this potential in California will require deliberate policy innovation and the development of business models that align with the state's energy goals. Lessons from successful European examples, such as O4's UK site, demonstrate what is possible with strong policy support and market alignment. Without similar frameworks, California risks missing out on one of the most impactful pathways for lower-carbon greenhouse heating.

In short, waste heat is one of the biggest technical levers for lower-carbon greenhouse heating in the near to medium term, but it will require deliberate policy and business model innovation in California to move from isolated pilots to mainstream practice and to ensure that incremental gains are aligned with longer-term decarbonization trajectories.

Existing Onsite Cooling and Potential Use of "Waste Cooling"

The section below evaluates potential end use types for waste cooling. Cooling appears both as greenhouse climate control, cold storage, and as post-harvest or process cooling, with different implications for heat pumps. For greenhouse climate control, most owner-operators rely on venting and evaporative strategies rather than mechanical chillers, signaling minimal value from waste cooling for climate control purposes:

- O1 uses manual louvers and simple natural ventilation.
- O3, O4, and O6 use roof vents, side vents, shading, and plant transpiration.

[4] Field heat rejection is the practice of pre-cooling freshly harvested crops with cold water before adding them to cold storage facilities to preserve quality and shelf life, as well as to reduce the cooling load of the cold storage equipment.

- O5 provides a detailed example of a typical California setup at one site: relatively tight greenhouses with evaporative pads (wet walls) at one end and powered exhaust fans at the other, plus insect netting over openings. This system is effective for cooling, but it also adds moisture and can complicate humidity control.

Process cooling, packaging, and cold storage is where the real potential to use waste cooling lies for operators (O2, O4, O5, and O6). In particular, O2's applications stand out. Their geothermal heat pumps run three walk-in coolers and a field heat removal system, plunging hot produce into cold water to quickly remove field heat. Operating costs are very low, and this cooling is central to the farm's economics and product quality. For other farms we spoke with (O4, O5, and O6), year-round refrigeration loads included packaging lines and cold storage. From a heat pump integration perspective, these stories highlight two opportunities:

- **"Waste cooling" to offset existing refrigeration load.** Refrigeration loads (process cooling, packaging, and cold storage) can be offset by waste cooling from heat pumps. For estimates of the amount of refrigeration load that can be offset by heat pumps see Table 3 in the Energy Analysis section of this report.
- **Shared infrastructure.** The same heat pump or ground loop can serve both cooling (walk-ins, hydro-cooling) and heating (slabs, hydronic loops), improving asset utilization over the year.

Program staff and vendors noted that steady, year-round cooling loads may be an easier initial foothold for heat pumps than highly variable heating loads. At the same time, O5's experience with evaporative cooling underscores that current practice in many California houses is both water- and humidity-intensive, which may drive future interest in heat-pump-based cooling and dehumidification if water or disease pressures grow.

In short, space cooling is mostly passive/evaporative today, but the intersection of cooling, dehumidification, and heating via shared heat pump/TES systems looks like a significant but underdeveloped opportunity. There is clear technical and economic potential to link cooling and heating through shared heat pump and TES infrastructure, especially at sites with substantial refrigeration loads.

Crop Mix and Partitioning

All groups we spoke with agreed that crop mix and spatial partitioning heavily shape heating requirements, climate strategies, and where advanced systems make sense.

Program staff sketched a California crop mix landscape of floriculture, leafy greens, berries, microgreens, vegetable transplants, cannabis, and woody nursery stock, each with different value density and risk tolerance. That segmentation shows up clearly in the owner-operator cases:

- O2's propagation house supports both their own field crops and a transplant business for other farms, with four hydronic zones tuned to different crop groups. In this case, partitioning is primarily functional and thermal: the greenhouse is divided into multiple hydronic zones with different setpoints, but crops are broadly grouped by stage and use rather than by strict physical separation.

- O3 runs cannabis in multiple independently controlled zones: warm, tightly controlled propagation and vegetation; cooler, more relaxed flowering spaces. These zones are separated by physical partitions and have independent venting, heating, and climate control settings, allowing the grower to adjust temperature and humidity by crop phase and to limit the conditioned volume at any given time.
- O4's large UK glasshouses grow vine crops in big blocks, with cropping cycles and lighting strategies (lit vs. unlit blocks) tightly tied to heat schedules. Partitioning here occurs at the scale of whole glasshouses (e.g., separate houses for tomatoes, cucumbers, peppers), with internal layouts designed to be flexible among similar vine crops rather than heavily subdivided by curtains.
- O5 adds a CEA leafy greens model where the crop is relatively uniform (salads/leafy greens), but partitioning is driven by production modules, food safety, and logistics as much as agronomy. They think in terms of modular "lines" under a greenhouse, each with its own climate and lighting profile, but tightly integrated with harvesting, washing, and packing flows. That modularity influences how heating, cooling, and dehumidification are distributed: heat and air may be delivered under benches or modules, while envelopes and internal separations must support strict food-safety and cold-chain requirements.
- O1 and similar nursery-style operations grow ornamental and small vegetable starts for retail sales in large, relatively simple houses with no or minimal internal partitioning. Crops are moved dynamically within the space based on available area and sunlight rather than fixed zones or curtains, and heating is typically provided by simple unit heaters.

Manufacturers and vendors note that mid- to high-tech food and cannabis operations (like O2, O3, O5, O4) are where hydronics, energy curtains, physical partitions, and sophisticated control systems are most common. Energy curtains and internal separations are used to reduce the volume that must be heated or cooled, to create distinct climate zones for different crop phases, and to manage light and humidity. Lower-value or more risk-tolerant segments (e.g., O1 and O6) often stay with simple heaters, limited partitioning using energy curtains, and limited controls.

Interviews also helped narrow the question of whether expanded cooling capability could increase the diversity or value of crops grown in summer. Although growers and market actors acknowledged that tighter climate control in partitioned zones could, in principle, support higher-value summer production, this did not emerge as a major current market driver. Instead, respondents more often pointed to the value of cooling for refrigeration, post-harvest handling, cold storage, humidity management, and selective conditioning of sensitive zones. As a result, the near-term role of partitioning appears less about enabling broad shifts in crop mix and more about targeting climate control investments to the highest-value spaces.

For heat pumps and CHP, the implication is that not all square footage is equal. High-value, climate-sensitive zones (e.g., propagation, cannabis flower, CEA leafy greens modules, winter greens) are more likely to justify investment in heat pumps, CHP-driven hydronics, and TES. Bulky, less sensitive space may realistically stay on unit heaters or simpler systems for a long time. Partitioning—whether

by walls, curtains, or modular lines—becomes a practical way to target decarbonization where it delivers the most value, while leaving lower-value or less sensitive areas on simpler systems.

Baseline Attitudes Toward Heat Pumps

Attitudes towards heat pumps are highly context-dependent, ranging from enthusiastic to skeptical, and are heavily shaped by each operator's experience and constraints.

On the positive side:

- O2 and O4 are outspoken heat pump advocates, crediting heat pumps and TES with making their business models viable.
- O1 is strongly supportive in new designs where he can control temperatures, distribution, and integration, citing high COPs and good comfort.
- Some manufacturers and SMEs are similarly bullish in low-temperature, hydronic, or radiant contexts.

On the skeptical or constrained side:

- O3 is wary of heat pumps and broad electrification, citing Dutch experiences where subsidized heat pump systems fouled and underperformed, plus local grid and water-quality constraints that make heat pumps look risky and expensive.
- O5 is not "anti–heat pump" in principle but sees no obvious path to large-scale heat pump adoption at their sites under current interconnection limits, power prices, and lighting loads. From their vantage point, CHP better matches their risk profile and economic reality, even as they stay engaged with decarbonization narratives.
- O4 sees large heat pump networks as successful but stresses that they require strong policy support and careful system design.
- O6, a large California nursery operator relying on inexpensive gas-fired unit heaters, is hesitant to explore electrification of heating further. The combination of substantial first costs to convert to hydronic distribution, plus the additional cost of electrifying the heating system itself, makes heat pumps appear financially unattractive compared to maintaining low-cost unit heaters.

Program staff and policy experts confirm that most growers do not ask for a heat pump by name. Interest arises indirectly, such as when a grower is trying to solve for total cost, reliability, CO_2 footprint, or specific process needs (e.g., low-temperature root heating or efficient refrigeration). Rate design, demand charges, and fuel-substitution rules heavily color the perception of heat pump proposals.

In short, the baseline attitude across the dataset is: Heat pumps are attractive where systems are purpose-built and the enabling conditions (i.e., grid, rates, incentives) are favorable. They are viewed cautiously or bypassed where electrical supply capacity is constrained, loads are dominated by lighting, water quality is difficult, first cost barriers, or policy does not reward their broader benefits—leading some actors (like O3, O5, and O6) toward high efficiency gas and CHP instead.

First Cost Barriers to Electrification

Across owner-operators, vendors, and program staff, first cost appears as a central barrier to greenhouse heating electrification. Growers rarely frame decisions in terms of "heat pumps versus boilers" alone. They focus on the total capital stack: heat source, heat distribution upgrades, controls, and any required electrical service changes.

Owner-operators describe this in different ways. O6, a large California nursery operator, relies on inexpensive gas-fired unit heaters and keeps first costs low as a core business strategy. O6 hesitates to explore electrification because the capital cost to convert from unit heaters to hydronic distribution, plus the additional cost to electrify the heating system, looks far beyond their budget. Cheap unit heaters remain the only realistic option from their perspective.

O5, a leafy greens CEA operator, believes they can design either air or water distribution to work with an efficient heat source. However, O5 treats fuel economics, grid capacity, and total implementation cost as the decisive constraints. Large LED loads, cooling and dehumidification needs, and tight interconnection limits all feed into a single question: what does the cost stack look like under current rates and demand charges. That question pushes them toward gas CHP rather than large heat pump plants, even though they are climate-conscious and technically literate.

O3, a cannabis operator with Dutch-style hydronics, faces a different but related barrier. O3 has already invested in large boiler and pipe-rail systems and sits on a grid that cannot practically serve the multi-megawatt electric capacity needed for full electrification. In that context, the capital cost of new heat pump plants and potential electrical upgrades looks prohibitive, especially given their concerns about water quality in hydronic lines (scaling) and past underperforming heat pump projects in other markets.

O2 and O4 illustrate what it takes to overcome high first costs. O2, a Michigan geothermal grower, made a major upfront investment in geothermal heat pumps, PV, slab heating, and TES. That investment only made sense because incentives, favorable PV policies, and low operating costs combined to support their business model. O4, a UK investor in large glasshouse sites, financed multi-megawatt industrial heat pumps, district-style hydronics, CHP, and TES under a policy regime that explicitly rewarded renewable heat and heat networks. In both cases, strong policy support, long-term contracts, and clear revenue models offset very high capital costs. These examples highlight that high first costs do not disappear; they become manageable only when policy, tariffs, and financing align.

Program staff and policy experts confirm that most growers do not ask for heat pumps by name. They ask whether a project will fit within their capital budget, whether it will require major electrical upgrades, and whether incentives and rate tariffs will offset any added cost. Rate design, demand charges, and fuel-substitution rules shape whether a proposal looks affordable. In many cases, even when process temperatures, envelopes, and distribution systems are compatible with heat pumps, the capital cost of equipment, hydronic conversion, TES, and potential service upgrades make electrification hard to justify.

Taken together, these interviews show that first cost is not a secondary concern. It is a primary reason many growers stay with gas boilers and unit heaters or move toward CHP instead of or in

addition to heat pumps. Any realistic electrification strategy for greenhouse heating in California must address first-cost barriers directly through incentives, financing, staged upgrades, and design support, rather than assuming that technical feasibility or non-energy impacts alone will drive adoption.

Non-Energy Impacts (NEIs) of Greenhouse Heating Systems

In this report, NEI is used as an umbrella term that includes both non-energy benefits (positive impacts) and non-energy costs (negative impacts) associated with greenhouse heating systems. Non-energy impacts are the additional benefits or costs of energy efficiency and distributed energy resources beyond direct energy savings, affecting participants, utilities, and society. Non-energy benefits are the subset of NEIs that improve outcomes for growers, utilities, or society (e.g., higher yields, new revenue streams, reduced carbon emissions), while non-energy costs are NEIs that worsen outcomes (e.g., loss of "free" CO_2 from combustion systems when switching to heat pumps, or increased complexity and maintenance requirements).

For many growers, positive NEIs are not just "co-benefits" but the primary drivers of their heating system decisions. While energy savings are important, positive NEIs—such as improved crop quality, operational resilience, and new revenue streams—often define the business case for greenhouse heating systems. This section categorizes NEIs into three groups: (1) unique to heat pumps, (2) common to multiple systems, and (3) exclusive to non-heat pump systems, while contextualizing their value relative to energy costs. For a more detailed review of the project team's NEI analysis, please see Appendix B: NEI Valuation.

NEIS UNIQUE TO HEAT PUMPS

1. **Carbon Reduction and Sustainability Alignment**
    - Heat pumps enable growers to align with carbon reduction goals and sustainability mandates. For example, O4's UK operation relied on heat pumps to grow vine crops year-round, reducing food miles and improving local food security. This alignment with green investment strategies was critical to their business model.
    - O1 emphasized that heat pumps support progress toward carbon goals, a key driver for environmentally conscious growers.
2. **Water Savings and Humidity Control**
    - Heat pumps can reduce water use compared to evaporative cooling systems, which are common in California greenhouses. This reduction in water usage is particularly relevant as water scarcity and disease pressures grow, making heat-pump-based cooling and dehumidification an attractive alternative.
3. **New Revenue Streams and Extended Production**
    - O2's geothermal heat pump system allowed them to heat their greenhouses in winter, enabling February and March production and creating a transplant business for other

farms. These new revenue streams were only possible because heat pumps made winter heating affordable in their region.

NEIS COMMON TO HEAT PUMPS AND OTHER HEATING SYSTEMS

1. **Improved Crop Quality and Yield**
    - Warm root zones and bottom watering, as cited by O2, reduce disease pressure and improve crop quality. While these benefits are not exclusive to heat pumps, the ability to maintain precise low-temperature heating with heat pumps enhances their effectiveness.
2. **Labor Efficiency and Logistics**
    - Pipe-rail hydronic systems, common in both heat pump and boiler setups, reduce labor needs by doubling as transport tracks. O3 reported approximately 30 percent labor savings from these systems.
3. **Resilience and Risk Management:**
    - Systems with TES or hybrid configurations (e.g., heat pumps with backup boilers) provide growers with more options to manage risks, such as outages or fuel price volatility. O1 and O2 both highlighted the peace of mind that comes from having robust, flexible systems. Also, heat pumps integrate well with TES, enabling growers to store energy and ride through outages. O1 described a slab system that loses only about 0.5°F per hour under heat pump heating, providing a significant thermal buffer during equipment failures or grid disruptions.

NEIS EXCLUSIVE TO NON-HEAT-PUMP SYSTEMS

1. **CO_2 Enrichment from Combustion-Based Systems**
    - Boilers and CHP systems produce "free" CO_2 for plant enrichment, a significant NEI for growers like O3 who rely on CO_2 to boost yields. However, this benefit comes with risks, such as ethylene, carbon monoxide (CO), and NOx accumulation in sealed greenhouses, which can harm crops and require costly remediation. This is a non-energy benefit of combustion-based systems that is lost when switching to heat pumps and therefore appears as a non-energy cost in the electrification business case.
2. **High-Temperature Capabilities**
    - Boilers and CHP systems can more easily provide high-temperature water (e.g., 150°F to 190°F), which is critical for some applications that heat pumps may struggle to serve efficiently. In contexts where high-temperature service is essential, this capability is a non-energy benefit of combustion systems relative to current heat pump options.

CONTEXTUALIZING NEIS RELATIVE TO ENERGY COSTS

Even in high-cost energy markets like California, the financial benefit of positive NEIs to a grower can potentially outweigh the additional cost of switching from gas to electric heating and strengthen

while also strengthening these businesses overall. Conversely, negative NEIs—such as the loss of combustion-derived CO_2 enrichment or increased system complexity—can erode the business case for electrification if they are not addressed through design or complementary measures (e.g., separate CO_2 supply). This section explores some of these additional NEIs, with more detailed information on NEI calculations and cost savings estimates for individual customers available in Appendix B: NEI Valuation.

NEIs in greenhouse heating systems span yield, quality, disease control, labor efficiency, resilience, carbon reduction, water savings, and market positioning. For many operators, these factors define the business case for heating system choices. Heat pumps, gas boilers, and CHP systems each offer distinct NEIs, with trade-offs that must be carefully considered. Programs and policies should explicitly account for NEIs to better reflect the full value proposition of electrified greenhouse heating systems.

At the same time, the loss of CO_2 enrichment with heat pumps—despite the risk associated with operating boilers in well-sealed greenhouses of ethylene, CO, and NOx buildup (as noted by O3)—represents a negative NEI that must be addressed in the business case for electrification. Conversely, the water-intensive nature of evaporative cooling in California greenhouses may drive future interest in heat-pump-based cooling and dehumidification, especially as water costs and disease pressures increase.

Manufacturers and subject matter experts noted potential NEIs of heat pumps, such as replacing evaporative cooling or conventional condensers, water savings, less chemical refrigerant risk, and tighter control. However, those same market actors also concede that these positive NEIs are rarely quantified or center-stage in current programs.

Policy experts observed that most regulatory cost tests do not capture yield, labor, resilience, or rural economic development, despite operators describing these outcomes as core reasons for their choices.

To conclude, high-cost energy markets like California require more multifaceted messaging that demonstrates how positive NEIs can offset, and potentially exceed, their increased electricity costs from switching to an electrified heating greenhouse heating system, while also acknowledging and managing negative NEIs. The project team has crafted some of these tailored messages in the Communicating the Business Case of Electrified Greenhouse Heating by Messaging Non-Energy Impacts section.

Table 1: Non-energy impact valuations.

Non-Energy Impact (NEI)	Annual NEI ($)	Story Summary
New Revenue Stream: Transplant/Propagation Services	$100,000	Low-cost geothermal heat pump heating made winter heating viable, enabling O2 to become a transplant supplier for other farms. 50% of transplant production is now for other growers, generating $100,000/year in new revenue.
Carbon Emissions Reduction	$225,000	O4's HP greenhouse system reduced carbon emissions by ~75% compared to traditional gas methods. Avoided emissions: 4,500 tCO_2e/year. Social cost of carbon: $50/$tCO_2e$. Total societal benefit: $225,000/year.
The Fuel Price Volatility and Market Risk Reduction	$200,000	During the 2022 gas price crisis, O4's renewable heat system allowed them to offer competitively priced heat, outperforming gas-only competitors. Advantage in crisis year: $200,000. Probability of crisis: 10%.
Job Creation	$12,000,000	O4's HP greenhouse project created 360 permanent jobs and 120 seasonal positions. Permanent income: $10,800,000/year. Seasonal income: $1,200,000/year. Total labor income: $12,000,000/year.

Note: These NEI calculations are contextually specific and should not be generalized for other greenhouse operations. For additional notes, assumptions, and formulas, see Appendix B: NEI Valuation.

Onsite Self-Generation Policies and Their Impact on Electrification and Thermal Energy Storage

Policy and rate design around self-generation and energy storage shape the boundary conditions for electrification, CHP, and TES decisions. In California, respondents repeatedly mention:

- The shift from earlier net energy metering rules to NEM 3.0, which reduces the value of simple PV export and pushes customers toward PV plus storage plus load shifting (often via TES or flexible operations) if they want to make electrification pencil out.
- The complexity of accessing storage incentives and other programs, which can deter smaller growers.

- Fuel-substitution and Total Resource Cost (TRC) constraints that make heat pumps and fuel-switching measures harder to justify on paper, especially for propane-served facilities.

O2 benefitted from earlier, more favorable PV and incentive structures, reporting long stretches of near-zero bills. In contrast, many prospective heat pump users are now facing weaker export terms and steeper demand charges. O5's experience adds another dimension, illustrating that interconnection timing and feeder capacity are as important as tariff design. For a new leafy greens site with big LED and heating loads, uncertainty about when and how much electric capacity the utility can provide is a central planning constraint and a major reason they gravitate toward CHP.

In the UK, O4 shows the other side of the policy coin: Renewable heat incentives and heat-network policies created an attractive environment for multi-MW water-source heat pumps feeding greenhouses. There, heat pumps plus CHP plus TES are not niche experiments but core infrastructure.

Policy experts suggested that community choice aggregators and regional energy networks could be better vehicles for flexible, local solutions (e.g., microgrids, CHP-plus-HP hybrids, shared TES, or waste-heat networks), and that shifting from strict TRC toward the Program Administrator Cost Test (PAC) or societal-benefit metrics would better reflect the NEIs and cross-sector benefits described by all actor groups.

Across the interviews, the implicit message is: Where self-generation and storage policies are supportive, heat pumps and TES can thrive—as in O2's early PV case or O4's renewable heat incentive-backed networks. Where policies, rates, interconnection rules, and capacity constraints are misaligned, growers and investors tend to favor hybrid approaches (boilers plus CHP plus targeted heat pump/TES) or delay major transitions—exactly the pattern we see in O3 and O5's current strategies.

The TRC project team suggests directing future IDSM planning and funding toward specific sectors and measures where integrated financing best supports state electrification and GHG reduction targets. For instance, pairing onsite solar generation with greenhouse heat pump systems enhances project economics by lowering the spark spread—the ratio of electricity costs to natural gas costs. In California, cheap natural gas relative to electricity heavily discourages replacing gas equipment with electric heat pumps in CEH. For example, an AWHP spark spread below 2.5 is highly favorable, 2.5 to 3.5 is the break-even range, and anything above 3.5 is economically unfavorable. While commercial agricultural customers in California currently face a challenging spark spread close to or greater than 3.5, integrating onsite solar can slash this ratio below 2.5, making heat pump projects more economically viable.

Energy Analysis

The energy analysis aimed to evaluate the energy performance of various heat pump greenhouse heating strategies (full electrification, partial electrification, and full electrification with TES) for a target greenhouse typology and base case gas system. Specifically, the analysis examined:

- Full electrification with heat pumps
- Partial electrification via dual-fuel (heat pump + gas) systems
- Full electrification with integrated thermal energy storage (TES)

This analysis provides critical insights into heat pump sizing, TES sizing, energy use, peak electrical demand, and on-bill impacts of electrification strategies across all 16 California climate zones. With reference to promising use cases identified during stakeholder interviews, the analysis assessed the feasibility and scalability of full and partial electrification strategies, including the integration with thermal energy storage.

The project team intended this energy analysis as a planning and screening tool, not as a detailed design model for individual projects. This energy analysis should be used to identify which greenhouse typologies make the most sense to pursue electrification of heating in first and what other typologies need to do to prepare for electrification. We address these typologies in the Recommended Target Greenhouse Typologies for Heating Electrification section. This energy analysis is most appropriate for:

- Comparing relative performance and cost drivers of different heating strategies (gas vs. heat pump vs. dual-fuel vs. heat pump + TES).
- Identifying climate zones where electrification is likely to be more or less favorable.
- Informing program design, incentive levels, and technical assistance priorities.

The team did not intend it to:

- Provide final equipment sizing for specific sites.
- Replace detailed engineering design, site-specific load calculations, or manufacturer-specific performance modeling.
- Predict exact bills or demand charges for individual customers.

Given the use of generic typology, normalized performance curves, and scaling from limited customer data, we estimate that the results carry an uncertainty on the order of ±20 percent for annual energy use and demand metrics at the greenhouse level. The project team made several conservative modeling choices tending toward:

- Oversizing heat pumps and TES relative to typical design practice, to ensure that modeled systems can meet loads under design conditions.
- Conservative load assumptions, based on scaling from real gas usage and heating degree days, which may overstate loads for some sites with better envelopes or more aggressive operational strategies.
- Generic performance curves that do not assume best-in-class equipment, thereby avoiding overly optimistic COPs.

These conservative tendencies mean that, in many cases, the analysis is more likely to overestimate required capacity and energy use than to underestimate them. As a result, one should view the findings as a cautious baseline that can be refined downward with site-specific design.

Methods

To conduct the energy analysis of greenhouse heating strategies, the project team employed a multi-step approach that combines stakeholder insights, energy modeling tools, and scalability analysis. The project team designed the methodology to capture both technical feasibility and market applicability across diverse climate zones and from a scalability perspective, applies to greenhouses across California.

Use Case Development

The first step was to define representative use cases that reflect both stakeholder interest and plausible program pathways. Based on interviews with growers, manufacturers, and program staff, the team focused on three primary heating strategies:

- **Full electrification with heat pumps:** Gas-fired heating is fully replaced by heat pump systems sized to meet the entire heating load under design conditions.
- **Dual-fuel (hybrid) heating systems:** Heat pumps are paired with gas-fired equipment. The heat pump is deliberately sized below peak load, and gas equipment is retained to serve the remaining load during the coldest hours. This configuration is intended to balance gas savings with lower first costs and reduced electrical capacity requirements.
- **Full electrification with TES:** Heat pumps are combined with TES to shift electrical consumption away from peak periods while still meeting heating loads. TES is sized to allow the heat pump to turn off during the peak electric demand window defined in the PG&E Electric Schedule AG (5:00 p.m. to 8:00 p.m. daily).

The project team selected these use cases because they align with real-world constraints reported by growers (e.g., limited electrical capacity, high demand charges, need for reliability) and with program interests in both full and partial electrification.

Energy Modeling Framework

GREENHOUSE TYPOLOGY AND BASELINE GAS USAGE

The analysis focused on a representative greenhouse typology (Medium-Scale Rigid-Plastic Greenhouse) consistent with prior work in the California Electronic Technical Reference Manual measure package SWBE001-05: a 9,600-square-foot ridge-and-furrow greenhouse with single-layer polycarbonate covering and a single energy curtain. Baseline gas usage estimates (therms per square foot) for this typology were drawn from Virtual Grower 3 (VG3) results reported in SWBE001-05 and scaled to the typology used in this study. To anchor the analysis in observed behavior, the team also used daily gas usage data from six customer sites located in Climate Zone 3 (CZ03). Using actual customer data helped the team calibrate VG3 results, given VG3 did not produce hourly loads, only monthly averages. Without hourly data, the risk of undersized equipment would be high and the team would not have been able to calculate TES or dual fuel approaches. Current utility policy regarding customer confidentiality has imposed greater restrictions on sharing customer data of any sort, so the hourly data remains confidential. The team used these data to:

- Derive hourly heating load profiles for the baseline gas system.
- Correlate heating degree days (HDD) and load ratios to approximate peak demand and hourly part-load ratios.

The project team then applied these correlations to all sixteen climate zones to generate hourly heating load profiles for the typology in each zone.

USE OF USDA VIRTUAL GROWER 3 (VG3) AND SUPPLEMENTAL MODELS

The team used USDA Virtual Grower 3 (VG3) to simulate greenhouse operations and baseline energy use for the typology. VG3 outputs provided:

- Baseline heating energy use by climate zone.
- Sensitivity to envelope characteristics and curtain use.

Because VG3 does not natively model heat pump performance or TES, the team developed supplemental spreadsheet models to:

- Convert daily and monthly VG3 outputs into hourly load profiles using HDD-based scaling and customer data.
- Apply generic heat pump performance curves from Title 24 Alternative Calculation Method (ACM) to estimate COP and capacity as a function of outdoor air temperature and part-load ratio.
- Model TES charging and discharging behavior over the design day and off-design days.

This hybrid approach allowed the team to leverage VG3's greenhouse physics while layering in heat pump and TES behavior.

Heat Pump Sizing and Performance Modeling

FULL ELECTRIFICATION (BOILER-TO-HEAT-PUMP RETROFIT)

For the full electrification case, heat pumps were sized to meet the design heating load at the design outdoor air temperature (OAT) for each climate zone. Design OATs were based on the Title 24 JA2 Heating Winter Median of Extremes for 16 representative cities across the 16 climate zones. In the final analysis, heat pumps are effectively sized to meet the load at the design condition, with interpolation used only to align generic performance curves with zone-specific design temperatures. Interpolating the heating load and design OAT refers to the process of:

- Using the hourly load profile and design OAT to determine the required capacity at the design condition.
- Ensuring that the selected heat pump capacity curve intersects or exceeds that required capacity at the design OAT.

Heat pump performance was modeled using normalized performance curves from Title 24 ACM (Table 3). These curves were:

- Adjusted to reflect the selected equipment design conditions (e.g., supply temperature, outdoor design temperature).
- Used to estimate COP and available capacity at each hour, based on local outdoor air temperature and part-load ratio (Table 4).

This approach yields hourly estimates of electrical energy use and capacity utilization for the full electrification case in each climate zone.

DUAL-FUEL HEATING STRATEGIES

For the dual-fuel case, the heat pump is deliberately undersized relative to the peak load, and gas equipment is retained to serve the remaining load during the coldest hours. To determine an appropriate heat pump size, the team conducted a sensitivity analysis that applied the hourly load profiles across all sixteen climate zones to a range of sizing criteria. The analysis evaluated:

- The percentage of annual heating demand served by the heat pump at different sizing levels.
- The corresponding changes in equipment size, first cost, and gas savings.

From this analysis, the team selected a sizing criterion in which the heat pump is sized to meet approximately 90 percent of annual heating demand (on an energy basis), with gas equipment serving the remaining ~10 percent during the highest-load hours. This criterion:

- Reduces first costs and electrical capacity requirements compared to full-load sizing.
- Retains gas equipment for peak conditions, improving reliability and reducing the need for oversized heat pumps.
- Provides a clear, program-relevant benchmark for hybrid system design.

Heat pump performance in the dual-fuel case was modeled using the same normalized performance curves and hourly load profiles as in the full electrification case, with gas equipment filling the residual load when heat pump capacity is insufficient.

TES INTEGRATION

For the TES case, the objective was to design TES capacity such that the heat pump can turn off completely during the peak electric demand period defined in PG&E Electric Schedule AG (5:00 p.m. to 8:00 p.m. daily). The TES design followed National Laboratory of the Rockies design guidelines for heat pump TES systems and involved the following steps:

Design Day Selection:

- Modeled the total heating load of the greenhouse over the year and selected the day with the highest daily heating load as the design day for TES analysis.

Load Partitioning and TES Sizing:

- Determined the average heating load over the period when the heat pump operates (outside the 5:00 p.m. to 8:00 p.m. peak window).
- Calculated the TES tank load on the design day: the amount of heat that must be stored to cover the entire 5:00 p.m. to 8:00 p.m. peak period without running the heat pump.
- Converted this required heat into a volume of water (or equivalent storage medium) based on assumed temperature differential and storage efficiency, yielding the TES tank size needed to meet the design-day curtailment period.

This TES modeling provides estimates of heat supplied from heat pump via TES compared against daily heating requirements, as well as required storage volume.

Energy Outputs

For each use case (full electrification, dual-fuel, and full electrification with TES) and each climate zone, the analysis produced:

- Annual heating load
- Gas energy use
- Electrical energy use
- Peak electrical demand
- On-bill impacts

These outputs form the basis for comparing strategies and for assessing program-relevant metrics such as gas savings, electrification costs, and demand impacts.

Software Limitations

The project team also reviewed the capabilities and limitations of USDA VG3 and related tools to understand how well they support modeling of electrified greenhouse heating systems, including heat pumps and TES. VG3 was used primarily to:

- Represent baseline greenhouse physics and gas-heated operation for the selected typology.
- Provide a consistent starting point for scaling loads across climate zones.

Because VG3 does not explicitly model all the technologies and control strategies of interest (e.g., heat pumps, dual-fuel configurations, TES), the team supplemented VG3 with custom spreadsheet models and performance curves, as described in the preceding subsections. A more detailed discussion of VG3 functionality, gaps, and implications for program implementation is provided in the Results section, where we summarize how these limitations affect the interpretation of the analysis. We present the software limitations in

Appendix E: Software Limitations.

Results

Energy Analysis

HEATING LOADS ACROSS 16 CLIMATE ZONES

The team used a sample of actual greenhouse customer data from climate zone 3 as a base profile and scaled the hourly heating load proportionally based on the hourly temperature difference from a base of 65°F. Climate zones with higher heating degree days (HDD65) have higher annual heating loads. The weather data for each California Energy Commission (CEC) climate zone is based on the CZ2025 weather datasets, and each CEC climate zone uses weather data derived from a representative city.[5] The representative city for each climate zone, the corresponding annual HDD65, and the heating load are shown in Table 2.

[5] https://cedars.cpuc.ca.gov/deer-resources/tools/energy-plus/

Table 2: Heating degree days and annual heating load across 16 climate zones.

Climate Zone	City	HDD65	Annual Heating Load (MMBtu)
CZ01	Arcata AP	118352	2577
CZ02	Santa Rosa	93852	2044
CZ03	Oakland metro AP	73209	1594
CZ04	Paso Robles Muni AP	84424	1839
CZ05	Santa Maria Public AP	79507	1731
CZ06	Los Angeles IAP	35033	763
CZ07	San Diego Lindbergh Field	31102	677
CZ08	Fullerton Muni AP	36977	805
CZ09	Burbank Glendale Pasad AP	43307	943
CZ10	Riverside Muni	45219	985
CZ11	Red Bluff Muni AP	67305	1466
CZ12	Sacramento Executive AP	73645	1604
CZ13	Fresno Yosemite IAP	59913	1305
CZ14	Palmdale AP	74081	1613
CZ15	Palm Springs IAP	24110	525
CZ16	Blue Canyon AP	118183	2574

FULL ELECTRIFICATION HEAT PUMP IMPACT ACROSS 16 CLIMATE ZONES

The team identified the generic AWHP performance curves from Title 24 ACM, including the Heating Capacity Modifier Function of Temperature Curve (CAP_{fT}), the Heating Electric Input to Output Ratio Modifier Function of Temperature Curve (EIR_{fT}), and the Heating Electric Input to Output Ratio Modifier Function of Part Load Ratio Curve (EIR_{fPLR}). (Bucaneg 2025) For more details, see

Appendix C: Energy Analysis. As mentioned in methods of energy analysis, the team sized the heat pump using the design OAT based on Title 24 JA2 Heating Winter Median of Extremes for 16 representative cities across the 16 climate zones; additionally, the design OAT, design capacity of heat pump, annual heating consumption, peak heating power, and waste cooling generated by heat pump are shown in Table 3.

Table 3: Heat pump sizing and heating consumption across 16 climate zones.

Climate Zone	City*	Design OAT (°F)**	Heat Pump Design Capacity at Design OAT (kbtu/hr)	Annual Heating Consumption (MMBtu)	Peak Heating Power (kBtu/hr)	Waste Cooling Generated by Heat Pump (MMBtu)
CZ01	Arcata AP	28	806	851	429	1726
CZ02	Santa Rosa	24	893	691	506	1353
CZ03	Oakland metro AP	32	719	464	342	1130
CZ04	Paso Robles Muni AP	19	1002	642	530	1196
CZ05	Santa Maria Public AP	25	871	557	408	1174
CZ06	Los Angeles IAP	37	610	210	193	553
CZ07	San Diego Lindbergh Field	38	588	187	193	490
CZ08	Fullerton Muni AP	30	762	251	316	554
CZ09	Burbank Glendale Pasad AP	29	784	297	316	646
CZ10	Riverside Muni	27	828	314	344	671

Climate Zone	City*	Design OAT (°F)**	Heat Pump Design Capacity at Design OAT (kbtu/hr)	Annual Heating Consumption (MMBtu)	Peak Heating Power (kBtu/hr)	Waste Cooling Generated by Heat Pump (MMBtu)
CZ11	Red Bluff Muni AP	24	893	506	506	959
CZ12	Sacramento Executive AP	26	849	541	429	1063
CZ13	Fresno Yosemite IAP	24	893	438	384	867
CZ14	Palmdale AP	12	1154	626	613	988
CZ15	Palm Springs IAP	26	849	165	313	360
CZ16	Blue Canyon AP	13	1132	1068	618	1506

*Building Climate Zone (California Energy Commission).
** California Energy Commission. (2025). 2025 reference appendices for the 2025 building energy efficiency standards: Title 24, part 6, and associated administrative regulations in part 1 (CEC-400-2025-010-AP)

Potential for Offsetting Refrigeration Energy

As part of the process of moving thermal energy from the source to where it is required, heat pumps extract usable cooling energy as a waste product. In a greenhouse setting, this "waste cooling" can offset onsite refrigeration loads, such as walk-in coolers, packaging lines, and hydro-coolers (chilled water for field heat removal). Table 3 shows that a full-electrification heat pump generates substantial amounts of waste cooling in every climate zone. This underlines the technical potential that market actors described when they pointed to shared heating and refrigeration infrastructure as an opportunity. Heat pumps can produce enough waste cooling to make offsetting onsite refrigeration loads a meaningful opportunity at many sites, but the exact fraction of refrigeration energy served will depend on project specifics, which is a level of detail not covered here.

Thermal Energy Storage

The team first calculated the daily load for each climate zone as the design day load for the thermal storage analysis, and then used the design day load to evaluate the heat supplied by the heat pump and TES system. The team first used thermal storage analysis to calculate the daily load for each climate zone as the design-day load. Table 4 shows the total daily heating supply, broken down by the share of heat contributed by the heat pump, the share contributed by the TES system, and TES tank volume (which ranges between 6,157 gallons and 18,619 gallons in California).

Table 4: Thermal storage analysis across 16 climate zones.

Climate Zone	City	Total Daily Heating Supply (kBtu)	Heat Supplied Direct from Heat Pump (kBtu)	Heat Supplied from Heat Pump via TES (kBtu)	Volume (Gal H_2O)
CZ01	Arcata AP	14283	12184	2099	12584
CZ02	Santa Rosa	15079	13095	1984	11892
CZ03	Oakland metro AP	11682	9728	1954	11717
CZ04	Paso Robles Muni AP	14055	11442	2613	15666
CZ05	Santa Maria Public AP	11414	8308	3106	18619
CZ06	Los Angeles IAP	7936	6909	1027	6157
CZ07	San Diego Lindbergh Field	7418	5619	1799	10783
CZ08	Fullerton Muni AP	8782	7593	1189	7126
CZ09	Burbank Glendale Pasad AP	10270	8791	1479	8870
CZ10	Riverside Muni	10370	8219	2151	12893

Climate Zone	City	Total Daily Heating Supply (kBtu)	Heat Supplied Direct from Heat Pump (kBtu)	Heat Supplied from Heat Pump via TES (kBtu)	Volume (Gal H_2O)
CZ11	Red Bluff Muni AP	16045	14174	1871	11217
CZ12	Sacramento Executive AP	14968	13149	1819	10905
CZ13	Fresno Yosemite IAP	14418	12378	2040	12233
CZ14	Palmdale AP	16537	14577	1960	11751
CZ15	Palm Springs IAP	11107	9361	1746	10466
CZ16	Blue Canyon AP	20652	18265	2387	14311

Dual-Fuel

The team evaluated a dual-fuel strategy that balances gas energy savings and implementation cost by pairing a downsized heat pump with retained gas equipment. We ran a sensitivity analysis that applied the energy analysis results to several heat pump sizing criteria, tracking equipment size, cost, and the share of annual heating demand that the heat pump serves.

Table 5 below shows how required heat pump capacity changes as the share of annual heating demand served by the heat pump changes. Across all 16 California climate zones, the team saw an average reduction in required capacity of nearly 50 percent when the team reduced the share of annual heating demand served by the heat pump by only 10 percent.

Table 5 also shows that a heat pump sized for 54 percent of peak demand, based on the peak design heating load condition, met heating demands during 90 percent of annual hours on average across the 16 climate zones. This sizing approach produced a large reduction in equipment size and cost when compared to a heat pump sized for 100 percent of peak demand and to the gas boiler baseline.

Table 5: Dual-fuel equipment size and cost vs. baseline

HP Evaluation Criteria	Percent of Annual Heating Demand Met by HP					
	100%	90%	80%	70%	60%	50%
Capacity as Percent of Peak Demand	100%	54%	41%	31%	22%	14%
Associated HP Capacity, kBtu/hr	764	416	316	236	168	105
COP at Peak Heating Capacity	2.0	3.1	3.3	3.3	3.3	3.3
HP Size in Heating $Tons_{nominal}$	99	35	25	19	14	9

The dual-fuel option is further discussed in the following section.

Heat Pump Strategy: Cost Estimates

The objective of this section is to review the first costs of various heating system strategies for greenhouse applications, including modular and packaged air-to-water heat pumps (AWHPs)—with and without TES—as well as dual-fuel systems, and evaluate the implications. The system types, configurations, and specified energy output that were costed as part of this effort are described below.

1. **Baseline Boiler Systems**
    - Electric resistance boiler: 296 kilowatt (kW), 1010 thousand British thermal units per hour (kBtuh)
    - Gas-fired condensing boiler: 249 kW, 850 kBtuh
2. **Modular AWHP System**
    - Three modular AWHPs, each with a capacity of 90 kW (307 kBtuh) and a total combined capacity of 270 kW (921 kBtuh).
3. **Packaged AWHP System**
    - Single packaged AWHP with a capacity of 300 kW (1024 kBtuh).
4. **Dual-Fuel System**
    - System combining a 121 kW (405 kBtuh) AWHP with a 249 kW (850 kBtuh) gas-fired boiler to meet heating demands.

Data Collection Sources

To develop a broad understanding of heating system costs, the research team employed a multi-source approach to gather and analyze cost data for various system configurations, including dual-fuel options. This methodology ensures that the findings reflect real-world market conditions and provide a robust foundation for program design.

- **Vendor estimates**: We obtained budgetary pricing data from a California-based AWHP manufacturer's representative.
- **RSMeans online sata**: The team collected cost data for boilers and AWHPs from RSMeans Online for Salinas, California to provide a standardized reference.
- **Bid data**: We used recent project bid data supported by the research team to validate and supplement vendor and RSMeans estimates.

Cost Normalization and Comparison

- All cost data was converted to normalized metrics of $/kBtuh and $/kW to enable lateral comparisons across system types and configurations.
- For AWHP systems, the team also analyzed costs based on nominal tons of refrigeration capacity, a common budgetary pricing metric for commercial heat pump systems.
- Dual-fuel system costs were normalized similarly, with consideration for the cost of integrating gas and electric components.

The costs in Table 6 relate to the specified energy output for each technology type and option.

Table 6: Energy equipment first costs.

Equipment Type		Equipment Cost per energy unit ($/kBtuh)	Equipment Cost per energy unit ($/kW)
Baseline			
	Electric Boiler	$18	$63
	Gas Condensing Boiler	$31	$106
Air-to-Water Heat Pumps			
	Modular	$353	$1,209
	Packaged	$225	$770
Dual-Fuel System			
	Heat Pump sized to 90% of peak	$130	$445

The first-cost barrier associated with electrifying heating via a heat-pump-based option carries a significant incremental first cost when compared with a natural gas-fired boiler baseline condition.

For a set of modeled conditions, we translated the per unit energy capacity costs above into costs estimates for heat pump options—covering a heat-pump-only and several hybrid systems—to determine how different approaches to meeting energy needs could help manage costs of implementation and limit the need for additional utility service capacity.

Other Cost Factors from Energy Analysis

Heat pumps operate more efficiently as the ambient temperature increases. Sizing heat pumps for full electrification means that at their maximum output (the coldest day), the equipment will not operate as efficiently, which leads to a larger-than-expected unit to meet the peak heating load (see "COP at peak heating capacity" and "HP size in heating tons" in Table 7). This highlights three factors that can limit implementation costs:

1. Size heat pumps to meet the majority of the annual load rather than peak demand.
2. Minimize the impacts of heat pump performance derating in cold conditions (i.e., around 30°F OAT) by adopting the hybrid system approach, whereby the heat pumps operate minimally during the small number of very cold hours per year.

3. Upgrades to existing infrastructure, particularly electrical service, may be minimized or eliminated through careful heat pump sizing.

Table 7 below captures heat pump sizing and equipment costs for the full electrification and hybrid systems case, as well as the natural gas boiler baseline.

Table 7: Estimated heat pump sizing and equipment cost compared to a natural gas boiler base case.

HP Evaluation Criteria	Percent of Annual Heating Met by HP						Base Case
	100%	90%	80%	70%	60%	50%	0%
Percentage Peak Heat Demand Met by HP	100%	54%	41%	31%	22%	14%	0%
Associated HP Capacity, kBtu/hr	764	416	316	236	168	105	0
COP at Peak Heating Capacity	2.0	3.1	3.3	3.3	3.3	3.3	0
HP Size in Heating $Tons_{nominal}$	85	35	25	19	14	9	0
HP Cost at $2700/$Ton_{nominal}$	$229,500	$94,500	$67,500	$51,300	$37,800	$24,300	$0
Natural gas boilers at $29/KBtu-hr	$0	$10,900	$14,000	$16,500	$18,600	$20,600	$23,800
Total Heating System Equipment Costs	$229,500	$105,400	$81,500	$67,800	$56,400	$44,900	$23,800

Figure 11 below compares the impact of heat pump sizing on heat demand met via electrification.

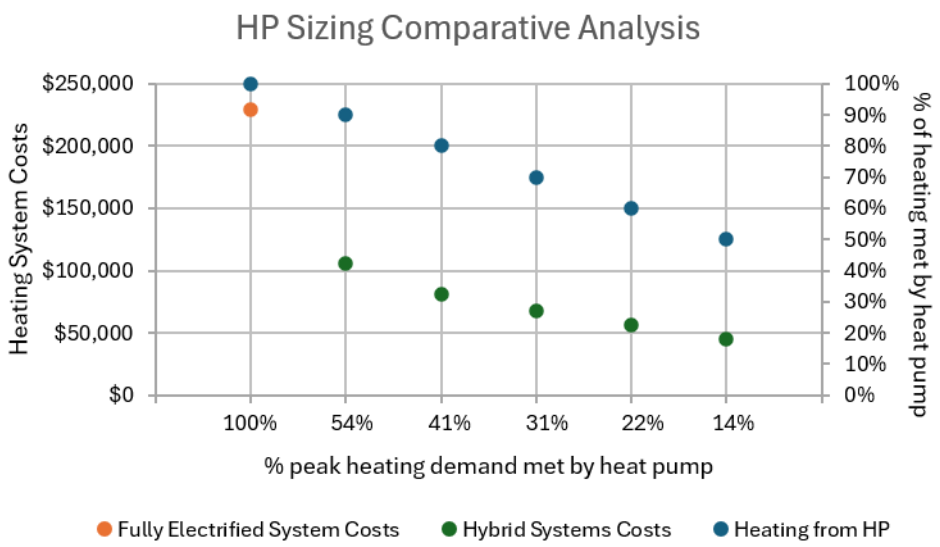

Figure 11: Impact of heat pump sizing on heat demand met via electrification

The cost estimates above represent equipment-only costs for boilers, heat pumps, and dual-fuel systems. The team did not include full installation labor and ancillary construction costs for these systems because those costs vary widely across California. Factors such as site layout, existing infrastructure, contractor availability, and local labor rates can change installed costs by tens of percent, and the project did not have consistent, statewide data for these elements.

For similar hydronic and heat pump systems, the team's experience suggests that installation labor and ancillary materials often add roughly 25 percent to 30 percent on top of equipment cost, with higher percentages for smaller or more complex projects. As a simple rule of thumb, readers can apply an additional 25 percent to the equipment costs reported in this section to approximate total installed costs for comparative planning. However, this rule of thumb does not replace site-specific estimates and should not be used for detailed budgeting.

Table 7 contains equipment-only cost estimates for heating systems for a full electrification scenario and five hybrid system scenarios. Based on similar projects, installation labor and ancillary materials often add roughly 25 percent to 30 percent on top of equipment cost, especially for smaller systems. Readers should treat the values in Table 9 as equipment baselines and apply a simple 25 percent adder for planning-level installed cost estimates, while recognizing that actual installation costs require site-specific analysis.[6] Hybrid systems offer a flexible approach to greenhouse heating whereby the site owner can select a heat pump capacity most suitable for their consumption and

[6] https://www.caetrm.com/measure/SWWH027/08/value-table/511606/

patterns of demand to keep first costs of electrification lower. Our analysis indicates that hybrid options with larger heat pumps are capable of meeting the majority of heating energy needs, at significantly reduced capacities—one hybrid configuration that meets 90 percent of annual heating has a heat pump rated at approximately 54 percent of peak load, which reduces the estimated equipment cost by over 50 percent.

Figure 11 shows the equipment cost of heating systems relative to the heating load met—the gap between the heat load data point and corresponding heating system equipment cost indicates that hybrid options are significantly more cost effective than the full electrification option in delivering the same service. In that context, partial electrification should be considered. However, as Table 7 shows, even the hybrid option with the smallest heat pumps analyzed is approximately double the cost of the natural gas boiler-only option.

TES Costs

Costs for TES depend on the size of the tank, which determines the quantity of steel required, the volume of concrete necessary to support the tank, the balance of equipment that interfaces the tank with the heat supply and load, and the labor to install and test it.

The team estimated the capacity requirements for TES for each climate zone based on the peak day conditions, and an assumed discharge period for the TES of the three hours for the peak day. We assumed a Delta T of 20°F across the tank in all cases.

Equipment cost estimates for thermal energy storage, based on storage of chilled water, came from a single vendor. Cost for the tank and plumbing were estimated at $4.50 per gallon installed, plus another $7.50 per gallon for the necessary concrete work. Labor required for installation is assumed to be 25 percent of the equipment cost.[7]

Table 8 include tank and concrete work, and therefore, sits between pure equipment cost and full installed cost. TES projects would still incur additional labor and integration costs beyond the tank and concrete. Because of these uncertainties, the team recommends that future work collect more detailed installed-cost data for boilers, heat pumps, dual-fuel systems, and TES across multiple regions and project sizes. That work would support more precise program design and cost-effectiveness testing .

Table 8: TES installed capital cost estimates.

California Climate Zone	TES Tank Capacity (gal)	TES Cost
Average – CZ01–CZ16	11,700	$175,000
Minimum – (CZ06)	6,160	$92,000
Maximum (CZ05)	18,620	$279,400

[7] SWWH027-07: Heat Pump Water Heater, Commercial, Fuel Substitution

Annual energy cost reductions available from TES operation depend on financial returns from participation in dynamic load flexibility or demand response program. For projects with large heating systems, these returns could potentially be significant. For cases assessed here, assuming five years as the maximum simple payback threshold a site owner would consider, the financial benefits from program participation would need to be greater than $18,000 per year to make the minimum size TES option for Climate Zone 6 (shown in Table 8) a palatable investment option. The capital cost barrier to implementation of TES itself would still need to be addressed.

Operating Costs

The current differential between natural gas costs and the price of electricity, or spark spread, is such that although heat pumps are more efficient per unit of energy delivered than natural gas boilers, they are more expensive to operate. Using the energy analysis from an average climate zone (CZ 3), we calculated an annual baseline gas charge of $27,757.32/year and for the full electrification heat pump case, calculated an electric is $58,382.20/year, based on average annual unit costs of $1.510/therm and $0.310/kWh. For the full electrification scenario, the energy and demand charges are $30,698.60 and $27,683.60, respectively. This is problematic because a primary recognized means for offsetting capital costs of energy efficiency equipment and practices is via energy cost savings. Current tariffs do not lead to operational energy cost savings.

Cost of Increased Utility Service

Adding a new electrical service to an existing commercial site necessarily requires an increase in the utility service capacity. A majority of our interviewees from California-based greenhouse businesses told us that their local IOU could take years to review a service upgrade application—and that IOU might also reject it. This reality means that greenhouse businesses cannot realistically plan for electrification of services, and given how resource constrained they are, the topic is pushed to the bottom of their priority list. Costs of an increased service will vary by location, due to existing service capacity, location on the electricity network, and remoteness of the location; consequently, we did not collect costs for this aspect of greenhouse electrification. The team also concluded that the likelihood of a service upgrade being approved and implemented is perceived to be so remote as to make it almost a moot point.

Recommended Target Greenhouse Typologies for Heating Electrification

This section defines a set of seven recommended greenhouse typologies and corresponding program archetypes for electrifying greenhouse heating systems in California. The project team derived these seven typologies from the technical and policy literature, coupled with insights from interviews (i.e., owner-operator, vendor, manufacturer, programs team, subject matter expert, policy expert) and in-house program implementation staff. The seven typologies summarized below in Table 9 are grouped into three categories: (1) near-term electrification targets where heat pumps and related measures can be deployed with relatively high confidence (typologies 1 through 3); (2) “prepare and

improve" segments where efficiency and readiness measures are warranted but full electrification is limited by structural barriers (typologies 4 and 5); and (3) long-term strategic buildouts that may shape the future of greenhouse heating but are not yet ready for broad deployment (typologies 6 and 7).

Table 9: Target typologies for greenhouse heating electrification.

Typology	Description	Key Challenges	Opportunities
1. High-Tech Food And Berry Greenhouses	Large, year-round operations with hydronic heating systems and efficient envelopes.	CO_2 enrichment tied to boilers; grid capacity constraints.	Hybrid systems with heat pumps for base loads and boilers/CHP for CO_2 and peak loads.
2. Medium-Scale Rigid-Plastic Greenhouses	Mid-sized operations with mixed hydronic and forced-air systems.	Variable CO_2 practices; moderate lighting loads.	Pilot heat pumps in low-temp zones; phased electrification with existing boilers for backup.
3. Propagation And Transplant Houses	Small, low-temp hydronic systems for young plants.	Smaller budgets; limited CO_2 enrichment needs.	Early success stories with heat pumps as primary heating; leverage thermal mass for efficiency.
4. Low-Tech Plastic-Film Houses	Simple structures with gas unit heaters and poor envelope performance.	High infiltration; high heating loads; low budgets.	Focus on envelope improvements, high-efficiency gas heaters, and basic controls to prepare for HPs.
5. High-Control Cannabis/CEA Facilities	Dense planting, heavy lighting, and strict environmental controls.	High lighting loads; grid constraints; complex heating/cooling/dehumidification needs.	Hybrid systems with heat pumps for cooling/dehumidification and CHP for heat/CO_2.
6. Heat Pump-Centric Campuses	New construction designed around heat pumps, TES, and low-temp hydronic systems.	High upfront costs; land and water availability; grid coordination.	Lighthouse projects to demonstrate feasibility and inform future standards.

Typology	Description	Key Challenges	Opportunities
7. Industrial Waste Heat Integration	Greenhouses co-located with industrial sites to use waste heat via district heating networks.	Regulatory and business model gaps; co-location requirements.	Low-carbon heat source for hard-to-electrify greenhouses; aligns with industrial decarbonization.

Two overarching themes appear across all typologies:

1. The interaction between heating systems, envelope performance, humidity control, and CO_2 enrichment.
2. The interaction between heating systems, lighting loads, and electric grid constraints, especially in high-power density CEA operations.

Reliance on boiler or CHP exhaust for CO_2 enrichment is a consideration when assessing electrification potential. Facilities that depend heavily on combustion-based CO_2 will face either ongoing gas use (in a hybrid scenario) or new CO_2 costs if they eliminate their boilers. Similarly, facilities with large lighting loads and limited electric capacity may be constrained from moving to heat-pump-dominated solutions, even if their heating distribution systems are technically compatible.

Many commercial greenhouses in California inject CO_2 to maintain concentrations in the 800 ppm to 1,000 ppm range, especially during lighted periods. In existing systems, that CO_2 is often obtained at very low marginal cost from combustion sources—typically, high-efficiency boilers or CHP plants where flue gas is cleaned and distributed into the greenhouse.

Electrified systems decouple heat supply from combustion, which has two important consequences:

- Where heat and CO_2 are currently co-produced from the same equipment, shifting most heating load to heat pumps reduces boiler or CHP run hours and therefore, reduces onsite CO_2 availability. CO_2 must then be supplied by a separate combustion asset operated primarily for CO_2, or by purchased CO_2, both of which increase operating costs.
    - However, switching to bottled CO_2 or other non-combustion sources also reduces the risk of ethylene, CO, and NOx buildup in crops—a significant quality and food safety risk that is costly to remediate. This trade-off may make electrification more attractive for growers prioritizing food safety and crop quality.
- Where CO_2 is not currently recovered from combustion (for example, unit-heater systems that simply vent exhaust to outdoors), electrification has less impact on CO_2 practices and may open the door to more precise climate control and lower humidity-driven heating loads.

The UK case study of large wastewater-fed heat pump greenhouses provides a concrete example of how these tensions can be resolved at scale. In that project, most heat—around 90 percent of

annual demand—is supplied by large water-source heat pumps tied to wastewater and reservoir heat sources. Gas CHP units are retained as peaking equipment and as a dedicated CO_2 source: their exhaust is cleaned, captured, and sold to the growers as CO_2, while their high-temperature loop covers short morning boosts and rare cold snaps. Even in this highly optimized hybrid system, CHP CO_2 is not sufficient to fully meet grower demand, and the timing of CO_2 delivery (no CO_2 at night) must be coordinated with crop needs.

High-density CEA operations producing leafy greens and similar crops add another wrinkle: They may have very large lighting loads, stringent food safety and uptime requirements, and tight interconnection limits. In such cases, even when hydronic distribution and temperature levels are ideal for heat pumps, grid capacity and tariff structures can make CHP or other combustion-based strategies the more practical near- to medium-term backbone, with heat pumps playing a more targeted role (e.g., cooling, dehumidification, or working in specific zones).

In short, typologies that currently rely heavily on combustion-based CO_2, or that are constrained by lighting-driven electric loads and limited interconnection capacity, are more likely to move first toward hybrid (dual-fuel) systems with heat pumps and gas boilers or CHP-centered hybrid systems rather than a full combustion phaseout. Typologies with little or no combustion-based CO_2 enrichment, moderate lighting loads, and manageable grid connections present more straightforward candidates for deeper electrification. These themes highlight the need for tailored approaches to greenhouse electrification, balancing technical feasibility, economic viability, and policy support. The typologies discussed in detail below in Appendix D reflect these considerations.

Appendix A: Interview Guides

Manufacturers and Vendors Interview Guide

1. Please tell us a little bit about your company, your role, and your experience with greenhouses, particularly those heating their crops. Probe: food crops?
2. What types of crops and greenhouse construction do you commonly see working with California greenhouse growers?

   Probe: high tech vs. low tech, crop specialization vs. multiple crops, and partitioning practices

   Probe: Which types are more likely to invest in efficiency/electrification, and why?
3. What types of existing heating, distribution, and ventilation systems do you typically see in CA greenhouses and what heating, distribution, and ventilation systems are growers in the California market most interested in upgrading to? When are these systems commonly replaced, on failure?

   Probe: Which process parameters (e.g., air temp vs. hot water set point) drive system design? Do greenhouse customers you work with typically distribute heating with forced air systems or hot water systems? How common is the use of root zone, bench zone, or floor zone heating?

   Probe: What greenhouse ventilation type do customer you serve typically have (Powered ventilation, Gravity ventilation, Condensing, Separated combustion)? Does your system work best with a certain type of ventilation strategy?
4. Is there interest in heat pumps among greenhouses you've worked with, and what are the biggest barriers to broader adoption in California?

   Probe: Do you actively market heat pumps to greenhouses? How do factors like greenhouse type, crop type, system age, or location affect these choices?
5. We are trying to build a profile of the best greenhouses to target for electrification of heating systems. In your opinion, which greenhouses are best candidates for electrified heating systems (such as heat pumps or electric boilers) and why? For which systems?

   Probe: What are greenhouse design considerations favor or discourage adoption of heat pumps? Air to water heat pumps? Adoption of electric boilers? Differences in CA regions?

6. What are the benefits and drawbacks of full electrification compared to dual-fuel equipment for greenhouse heating?

Probe: E.g. HP's, electric boilers with existing natural gas equipment

Probe: How does pairing electrification with onsite renewable energy create benefits or challenges, and where do you see overlaps between the two?

7. From your experience/market observations, what fuels are the most common for greenhouse heating, and how does fuel choice (natural gas, propane, delivered fuels) affect electrification potential?

   Probe: Have you seen greenhouses utilize waste process heat or other unconventional heat sources (e.g. onsite heat recovery or district heat from data centers)? What are commonly overlooked waste heat streams?

8. How do fuel and electricity prices, efficiency levels, and COP affect greenhouse decision making around heating?

9. How do greenhouses use cooling today? What benefits (if any) come from adding or expanding cooling capacity?

10. In your experience, how common is thermal energy storage in greenhouses?

    Probe: [If they have seen thermal energy storage] What capacities or types of greenhouses are best suited? [If not seen TES] would pairing with TES be beneficial for your greenhouse customers? What are barriers to implementing TES with your greenhouse heating solution?

11. Beyond energy use, what benefits of heat pumps do you highlight when selling to greenhouse customers? How have you seen heat pumps, as well as access to cooling, impact greenhouse operations? Electric boilers?

    Probe if needed: Changes in crop quality, ability to maintain temperature set points, differences in O&M needs, value of crops able to grow, longer grow season, increased crop yield, crop variation, etc.

12. How have you seen greenhouses integrate renewable energy (e.g., solar) with heating/cooling systems, and what barriers limit adoption?

13. Can you recommend greenhouse operators (in California or elsewhere) we could speak with about greenhouse heating practices, electrified heating systems, thermal energy storage or renewable integration? Greenhouse heat pump manufacturers?

Owners and Operators Interview Guide

Owners and Operators Interview Guide

1. Please tell us a little bit about your greenhouse growing facility and your role as it relates to the operation and design of the greenhouse heating systems.

2. Where is the greenhouse facility located? (City, State)

3. What crops do you grow and how are crops partitioned within greenhouses?

   Probe as needed for modeling: area by crop type?

4. In total, how many greenhouses do you have at your facility? What is the average area of your greenhouses?

   Probe as needed for modeling: length, width, side height, roof height, roof shape, number of span, kneewall heights. Is the size of heated greenhouses different from unheated greenhouses?

5. What materials are your greenhouses made of? (E.g. rigid plastic, glass, plastic film)

   Probe as needed for modeling: Roof, end wall 1&2, side wall 1&2, end kneewall 1&2, side kneewall 1&2

6. For the next few questions, we'll focus on your greenhouse's heating systems. What heating system(s) do you use in your greenhouse and can you provide us with any design drawings? Why was that system selected? (ex: unit heater, hot water boiler, steam boiler, high efficiency unit heater, heat pump (*air source heat pump or a water source heat pump)*, other?)

7. What is the capacity of that heating system(s)?

8. *(IF HEAT PUMP INSTALLED)* Do you think heat pumps are limited to similar greenhouses as where you installed, or could heat pumps be applicable to other greenhouses more broadly?

9. At a high level, tell me about your space heating schedule and setpoints. When do you use space heat throughout the day and how does this change between seasons? (E.g. Our target air temp is 70 degrees. Jan – March we use heating from 7:00am – 9:00am and 4:00-6:00pm)

10. Now in more detail, what are the setpoints of the system you installed? What was your target return and supply temp and delta T?
    Were you trying to hit 180* with the heat pump or a lower temp? If you wanted to, could you hit 180*? if so, tell us that manufacturer
    Probe: *What was the entering water temp to any fan coil? What is the delta t design for the piping?*

11. *(Should be obvious by this point, but confirm)* What heat delivery method(s) does your greenhouses use (e.g. forced air, hot water)?

12. What did the distribution system look like for the heat pump?
    Probe: Was there any more distribution? Fan coils? Convective pipes? How many pipes do your fan coils have and does it do cooling only or heating and cooling ? Was there any other terminal unit besides fan coils? Were you using the rejected cooling? If so, how did that look- can the HP use cooling or heating to the same hydronic system?

13. Does your greenhouses have any variations in heating zones? E.g. root zone (bench heating) or floor heating?

14. Do you have energy curtains installed?

    If yes: What material are the curtains and how is the material condition? How is the installation quality? What is the current air exchange rate and what is the current U value?

15. What ventilation type(s) do your greenhouses have?

    Probe: Powered ventilation, Gravity ventilation, Condensing, Separated combustion

16. What equipment do you use to maintain your target RH?

17. Tell me about your target relative humidity and the typical range. When do you use your dehumidification/ventilation equipment to maintain relative humidity and how does this change between seasons?
    Probes: How much of a challenge is maintaining your target RH? When is humidity the most difficult to control? How does your existing heating system impact/interact with RH?

18. Does your greenhouse use supplemental lighting?

    If yes: What type of lighting systems do your greenhouses use (HPS/LED)? how many lights per greenhouse of each type? What is the average wattage? What is your lighting schedule?

19. When do you use your supplemental lighting equipment and how does this change between seasons? (E.g. Dec – April we use lights from 4pm – 8pm)

20. What's the target PAR for each crop type in greenhouses that you heat?

21. How well is the greenhouse sealed? How many large gaps are there? How many small gaps are there? What other gap types do you have (outside air take in, gaps between greenhouse and vents, malfunctioning vent covers)?

22. Does your greenhouse have thermal energy storage?

    If yes: What's the capacity? What is your strategy for using the thermal energy storage? Is that enough capacity? Is the TES fully utilized?

23. Does your greenhouse operation use space cooling or refrigeration?

    If yes: How?

    If not: Could your greenhouse operation benefit from using space cooling or refrigeration?

24. Does your greenhouse utilize waste process heat or other heat sources?

    If not: Does your greenhouse currently exhaust any heat streams or have access to any? (Example: onsite heat recovery or district heat with a data center waste heat stream?)

25. What is your heater's age?

26. How often is your heater serviced? (E.g. annually)

27. What fuel(s) do you use to heat your greenhouse and why did you decide to pursue partial vs full electrification?

(For each fuel type mentioned) Can you estimate how much you typically pay per unit cost of that fuel?

28. In your greenhouses, how are rooms separated and insulated? Office, Retail Area, Shipping Area, Head House

29. Do you enrich your greenhouses with Co2? If so, Do you use heat for CO2 enrichment?

30. We're now going to discuss renewable energy. Do you currently use onsite renewable energy?

    If yes: How have these systems impacted your greenhouse operations?

    If no: Is this something you'd be interested in or have explored? (If yes): What barriers do you experience from installation

31. (If has electrified heating systems): Beyond energy use, what impacts has your HP (or electric boiler) had on your greenhouse(s)?

    Probes: Changes in crop quality, ability to maintain temperature set points, differences in O&M needs, value of crops able to grow, longer grow season, increased crop yield, crop variation, etc.

32. (If not already mentioned) Have you considered electrifying your greenhouse heating system, for example with heat pumps or an electric boiler? Why or why not?

    Probe if needed: Which system(s) have you looked into? What barriers to installation did you encounter?

33. Can you recommend any other greenhouse operators you know that currently use heat pumps or an electric boiler? In addition to greenhouses that have already electrified their heating systems, can you recommend any other California greenhouse operators for us to speak with about their existing heating systems? Beyond CA?

34. Can you recommend any heat pump manufactures serving greenhouses we should speak with?

Policy Interview Questions

1. Please tell us a little bit about yourself, your organization, and your experience with greenhouses, particularly those growing food crops.

2. Which current or upcoming policies have the greatest impact on California greenhouse growers looking to electrify?

3. *Probe For CEC title 24 interview (Kyle Booth): What are the current requirements for CEH heating systems (i.e., Section 141.1(c) and 120.6(h))? Do current requirements for CEH dehumidification impact heat pumps?*

   Probe for CARB: Existing CARB Ag programs appear to be focused primarily on

transportation, are there no current CARB mandates or programs that specifically target CEH electrification? Propane savings on the avoided gas infrastructure cost and associated TSB? What are the potential overlaps, barriers and benefits of electrification with demand response and onsite renewable energy?

4. Which greenhouses are affected the most by California's policies on self generation? E.g. Greenhouse size, crop types grown, shell materials, system capacity, CA region, etc.
5. Do these policies on self generation encourage or discourage heat pump implementation?
6. Can you describe how your work impacts the electrification of greenhouse heating and cooling systems? Probe as needed: including thermal storage, waste process heat, etc.
7. How do you design policy for greenhouse heating electrification and who are the key stakeholders? Probe for details as needed: What are the stakeholders' priorities?
8. From your perspective, what greenhouses are best candidates for electrification of heating systems? Best candidates for onsite self-generation systems? For thermal energy storage? Why? *Probe if needed: Crop types grown, shell materials, size, system capacity, CA region, etc.*
9. What policies you'd like to see in the future related to greenhouse electrification or self-generation at greenhouses? *Probe: Who at the CPUC would you talk to about this?*
10. What barriers make it difficult to implement these policies? E.g. using propane as a fuel source, cost of electricity etc.
11. Are there other renewable energy sources relevant for greenhouses that we haven't discussed?
12. Can you recommend any greenhouse operators you know for us to speak with that currently use self-generation, heat pumps, or an electric boiler? Any heat pump manufacturers currently targeting greenhouses?
13. In addition, greenhouses that have already electrified their heating systems, can you recommend any California greenhouse operators for us to speak with about their existing heating systems? Beyond California?

Programs and Subject Matter Expert Interview Guide

1. Please tell us a little bit about yourself and your experience with greenhouses, particularly those heating their greenhouses.
2. What types of crops and greenhouse construction have you seen working with California greenhouse growers?

   Probe: high tech vs. low tech, crop specialization vs. multiple crops, and

partitioning practices
Probe: Which types are more likely to invest in efficiency/electrification, and why?

3. What heating systems do you typically see in greenhouses, and what systems are growers most interested in upgrading to?
   Probe: How do factors like greenhouse type, crop type, system age, or location affect these choices?
   Probe: Which process parameters (e.g., air temp vs. hot water set point) drive system design?

4. We are trying to build a profile of the best greenhouses to target for electrification of heating systems. In your opinion, which greenhouses are best candidates for electrified heating systems (such as heat pumps or electric boilers) and why?
   Probe: What are greenhouse design considerations favor or discourage adoption of heat pumps? Adoption of electric boilers?

5. What are the benefits and drawbacks of full electrification compared to dual-fuel equipment for greenhouse heating?
   Probe: E.g. HP's, electric boilers with existing natural gas equipment
   Probe: How does pairing electrification with onsite renewable energy create benefits or challenges, and where do you see overlaps between the two?

6. From your experience/market observations, what fuels are the most common for greenhouse heating, and how does fuel choice (natural gas, propane, delivered fuels) affect electrification potential?
   Probe: How do utility program rules on propane/non-utility fuel switching impact electrification opportunities or energy efficiency portfolio programs? What is the impact on propane savings on the avoided gas infrastructure cost and associated TSB?
   Probe: Have you seen greenhouses utilize waste process heat or other unconventional heat sources (e.g. onsite heat recovery or district heat from data centers)? What are commonly overlooked waste heat streams?

7. How do fuel and electricity prices, efficiency levels, and COP affect greenhouse decision making around heating?

8. How do greenhouses use cooling today, and what benefits (if any) come from adding or expanding cooling capacity?

9. In your experience, how common is thermal energy storage in greenhouses?
   Probe: [If they have seen thermal energy storage] What capacities or types of greenhouses are best suited?

10. Is there interest in heat pumps among greenhouses you've worked with, and what are the biggest barriers to broader adoption in California?

11. How have you seen heat pumps, as well as access to cooling, impact greenhouse operations?

Probe if needed: Changes in crop quality, ability to maintain temperature set points, differences in O&M needs, value of crops able to grow, longer grow season, increased crop yield, crop variation, etc.

12. How do greenhouses integrate renewable energy (e.g., solar) with heating/cooling systems, and what barriers limit adoption?
13. Can you recommend greenhouse operators (in California or elsewhere) we could speak with about greenhouse heating practices, electrified heating systems, or renewable integration? Any heat pump manufacturers targeting greenhouses?

Appendix B: NEI Valuation and Messaging

NEI Valuation Table

Communicating the Business Case of Electrified Greenhouse Heating by Messaging Non-Energy Impacts

While the primary focus of this project is to assess the technical feasibility and energy performance of greenhouse heat pump systems, a full understanding of their value proposition requires the consideration of NEIs, both positive and negative. These impacts often influence grower decision making as much as—or more than—direct energy savings. The project team's approach to identifying and quantifying NEIs combined qualitative and quantitative methods as follows:

1. **Stakeholder interviews:** The project team asked growers, designers, and equipment vendors to describe observed NEIs (e.g., labor savings, improved crop outcomes, reduced risk) and to estimate the magnitude of these benefits.
2. **Economic translation:** For each NEI identified, the team explored pathways to monetization by linking observed outcomes to financial metrics. For example:

    - Improved yield → additional revenue per square foot or per crop cycle
    - Cooling capacity → revenue potential from growing higher-value crops in summer, estimated from crop price differentials
    - Process cooling synergies → avoided or deferred capital or operating costs for standalone cold storage or refrigeration systems
    - Reduced disease losses → avoided replacement costs and increased marketable product
    - Labor efficiency → fewer staff hours required for manual climate adjustments, valued at average labor rates
    - Worker comfort → reduced absenteeism or turnover, potentially lowering human resource costs (i.e., recruitment time)

By combining qualitative feedback with these economic translation methods, the project team estimated a range of dollar values for each NEI type. While not all impacts were directly quantifiable in every case, even illustrative estimates (e.g., dollars per square foot, per year of avoided disease loss) can help frame the broader business case for electrification. The NEI Valuation Table in Appendix B captures all NEIs documented through the market actor interviews, as well as our attempts to quantify them in dollars where possible.

Top NEIs to Support the Business Case for Greenhouse Heating Electrification

The project team used feedback from the market actor interviews to create a list of the top five recommendations for utility programs to highlight when marketing greenhouse heating electrification. Below is a list of heat pump NEIs that programs can highlight to improve the business case for electrifying greenhouse heating systems. More detailed information on NEI calculations is available in Appendix B: NEI Valuation; corresponds with the bolded NEIs in this section.

1. **"Heating electrification can make your greenhouse business viable and bigger."**

Opportunities for increasing viability and expanding business include:

- **Season extension** (i.e., winter production) using low-cost heat pump heating
- **New revenue streams** (e.g., more affordable heating made winter propagation viable for one operator, opening a whole new revenue stream as a transplant supplier)
- **Postharvest quality and shelf life**, supported by very low cooling bills
- **Competitive viability** of small- and mid-sized farms through reduced overhead costs

Program staff can market heating electrification because it:

- Directly speaks to revenue and survival, not just cost or carbon
- Gives a narrative: "Electrified hydronic greenhouse heating systems don't just save energy; they unlock new crops, new products, and new months of revenue."

2. **"You reduce loss risk and gain more levers to manage energy risk over time (but not magically cheaper heat)."**

   Potential opportunities for reducing project and crop loss risk while improving the management of energy risk include:

   - **Outage resilience via TES and slab mass**. Operators felt more at ease knowing they have backup options for energy outages or equipment issues.
   - **Backup boiler/hybrid system risk reduction**. Manufacturers emphasized the advantages of creating "hybrid stacks" by coupling multiple technologies to create blended solutions with reduced risk.
   - **Precision control, TES, and thermal strategies.** Allows for time-shifting and smoothing of thermal demand for use as a tool for managing risk, sizing, and utility bills.
   - **Solar and distributed energy resources integration.** One subject-matter expert noted that many growers are already adding solar on unused land, and that heat pump electrification gives them a bigger controllable electric load to soak up self-generation and participate in future distributed energy resources programs.

   Program staff can market heating electrification because:

   - Market actors worry about project failure, crop loss, and schedule risk, not just whether the average dollar per thousand British thermal units is a bit higher or lower.
   - It is compatible with high, volatile California electric rates. It also gives growers more structural levers, TES, hybrids, and distributed energy resources integration to manage risk over time.

   How to frame it:

   - "We are not going to pretend heat pumps make California energy cheap. What we are doing is helping you move to hybrid, storage-centered systems that reduce retrofit and crop-loss risk, as well as giving you more ways to manage future energy and carbon risk, even if today's electricity is expensive."

3. **"You get resilience and more ways to keep crops safe."**

   Owner-operators and manufacturers that the project team spoke with felt that TES and dual fuel approaches compliment electrification goals, as follows:

   - Thermal mass and thermal energy storage
   - Hybrid system design using both a heat pump and a boiler as risk management

   Reasons to market it:

   - Most growers are nervous about heat-pump-only technology for critical crops.
   - If the program explicitly supports hybrids and TES, you can credibly say electrification increases resilience, rather than threatens it.

   How to frame it:

   "Our electrification support is designed around hybrid, storage-rich systems so that you have more options when something goes wrong, not fewer."

4. **"Hydronic systems are a tighter climate-control engine; electrified hydronics add indoor air quality and environmental benefits."**

   Owner-operators interviewed by the project team recognized the benefits of hydronic distribution systems regardless of heating system type. They highlighted root-zone, pipe-rail, radiant, and TES-based systems as tools to manage disease and humidity and to streamline labor and logistics. These benefits arise from the hydronic platform itself and do not depend on whether a gas boiler or a heat pump supplies the heat.

   Electrification adds another layer of benefits on top of that platform. When heat pumps supply the hydronic system, growers can keep all the plant-health and labor advantages of hydronics and also gain indoor air quality and safety benefits from reduced onsite combustion, along with water and chemical savings on the condenser side. In that sense, electrified hydronic systems provide an extra environmental edge beyond what gas hydronics alone can offer.

   How to frame it:

   - Hydronic distribution equals primary grower value. Root-zone, pipe-rail, and radiant hydronics are where the big, intuitive NEIs live: better disease and humidity control, smoother plant environment, and meaningful labor savings versus cheap unit heaters.
   - Electrified hydronic distribution equals a cleaner version of the same platform. Once that hydronic distribution platform is in place, shifting more heat to heat pumps lets you keep all those plant and labor benefits while cutting combustion-side indoor air quality risks and condenser water/chemical use.
   - The program story is a staged, practical transition. This framing supports a credible "from direct-fired → hydronic → electrified hydronic" pathway instead of a jarring "rip out forced air/gas, add heat pump" narrative.

   Suggested pitch:

"Our goal is not just to swap your heat source. We help growers move from direct-fired/unit heaters to hydronic platforms, root-zone heat, pipe-rail, and thermal storage—these improve disease control, humidity management, and labor efficiency.

As customers are ready, we then support electrifying those same hydronic systems with heat pumps. That way, customers keep all the plant-health and labor benefits, while reducing combustion-related air-quality issues and condenser water/chemical use."

5. **"Heating electrification fits your carbon story and brand—and it is where policy is going."**

   For customers with sustainability, carbon, or other environmental, social, and governance goals, electrifying greenhouse heating systems address the triple bottom line:

   - Carbon reduction
   - Food security
   - Job security
   - Credible sustainability branding
   - Policy/incentive alignment

   Reasons to market it:

- For investor-backed CEA, institutional buyers, and some sophisticated growers, environmental, social, and governance/brand/policy alignment is not fluff; it drives access to capital and markets.
- For regulators and commissions, it impacts carbon, local food security, rural jobs, and innovation.

   How to phrase it:

   "These projects are a way to decarbonize, strengthen local food supply, and create and retain jobs, all while keeping you aligned with investor and policy expectations."

Appendix C: Energy Analysis

The two variables used in the performance curves are leaving water temperature (T_{lw}) and outdoor air temperature (T_{db}). The curve named CAP_{fT} modifies the rated capacity of the equipment based on operating temperatures. The curve named EIR_{fT} modifies the full-load energy input ratio (the inverse of COP) based on operating temperatures. The curve named EIR_{fPLR} adjusts the energy consumption based on the equipment's part load ratio (PLR), which is the actual load divided by the available capacity.

$$CAP_{fT} = a + b * T_{lw} + c * {T_{lw}}^2 + d * T_{db} + e * {T_{db}}^2 + f * T_{lw} * T_{db}$$

$$EIR_{fT} = a + b * T_{lw} + c * {T_{lw}}^2 + d * T_{db} + e * {T_{db}}^2 + f * T_{lw} * T_{db}$$

$$EIR_{fPLR} = a + b * PLR + c * (PLR)^2 + d * (PLR)^3$$

$$PLR = \frac{\text{Actual Load}}{\text{Design Capacity}}$$

$$P = P_{rated} * CAP_{fT} * EIR_{fT} * EIR_{fPLR}$$

The performance curve coefficients from a to f used by three performance curves (CAP_fT, EIR_fT, and EIR_fPLR) from Title 24 ACM are shown in Table 10.

Table 10: Heat pump generic performance curve from Title 24 ACM.

Curve Type	CAP_{fT}	EIR_{fT}	EIR_{fPLR}
a (Const)	0.79490	0.53073	2.01480
b (x1)	0.00389	0.00655	-4.30050
c ($x1^2$)	-0.00006	0.00026	6.12640
d (x2)	0.02781	-0.03621	-2.83280
e ($x2^2$)	0.00032	0.00127	-
f (x1*x2)	-0.00013	-0.00079	-

Then, the air-to-water heat pump from Manufacturer A was selected based on design capacity and design temperatures to normalize generic heat pump performance curves and support the heat pump analysis. The information from air-to-water heat pump technical specification is shown in Table 11. The outlet water temperature and outdoor air temperature were used to normalize the three performance curves. The normalized coefficients in the three performance curves are shown in Table 12.

Table 11: Selected air-to-water heat pump technical specifications from Manufacturer A.

Heat Pump Information	Unit	Air-to-Water Heat Pump from Manufacturer A
Capacity – Heating	kW	85.2
Unit Power Input – Heating	kW	27.4
COP	/	3.12
SCOP Low/Medium Temp	/	4/2.88
Water Temperature In	°C	40
Water Temperature Out	°C	45
Water Flow Rate	l/s	4.1
Water Pressure Drop	kPa	19.1
Air Temperature	°C	7

Table 12: Heat pump normalization performance curve given selected equipment design temperature.

Curve Type	CAP_{fT}	EIR_{fT}	EIR_{fPLR}
a (Const)	0.77709	0.58201	1.99901
b (x1)	0.00380	0.00718	-4.26679
c ($x1^2$)	-0.00006	0.00029	6.07838
d (x2)	0.02719	-0.03971	-2.81060
e ($x2^2$)	0.00031	0.00139	-
f (x1*x2)	-0.00013	-0.00087	-

The team calculated the amount of waste cooling produced by the heat pump that can be used to offset refrigeration loads based on the difference between the heating demand and the heat pump's electricity consumption, as well as the relationship can be quantified using the calculated heating COP.

Heating mode:

Q_heating = Q_cooling + W_hp

Q_heating – heating provided by heat pump

W_hp – heat pump electricity consumption

Q_cooling – the energy from cool side (outside)

COP_heating = Q_heating/W_hp

Q_cooling = Q_heating (1-1/COP_heating)

Appendix D: Target Greenhouse Typologies Detailed Recommendations

Near-Term Electrification Targets

1. High-Tech Food and Berry Greenhouses with Hydronic Heating (Hybrid Heat Pump and Boiler)

One of the most promising segments for near-term electrification is the set of high-tech food and berry greenhouses with glass or rigid plastic coverings and centralized hydronic heating systems. These facilities are typically located in the Central Coast, Sacramento, and Southern California regions; they produce tomatoes, cucumbers, lettuce, herbs, and (increasingly) berries under protection and are characterized by large footprints, sophisticated climate control systems, existing refrigeration loads, and year-round production. The literature identifies these structures as having relatively efficient envelopes and high heating demand, making them attractive candidates for electrification.

Heating in this segment is generally provided by centralized boiler plants serving hydronic pipe networks: overhead pipe rails, root-zone or under-bench loops, and (sometimes) hydronic unit heaters. Many sites use energy curtains and partitioning to limit conditioned volume and improve control of temperature and humidity. Setpoints for air temperature tend to fall within the 60°F to 80°F range, with humidity controlled through a combination of heating, ventilation, and, in some cases, mechanical dehumidification. These conditions are well within the capabilities of commercial air-to-water and water-source heat pumps. In addition, high tech food crop producers commonly have on-site refrigeration loads that can be offset by heat pump waste cooling.

A central complication is CO_2 enrichment. Many of these greenhouses use relatively clean boiler exhaust as a low-cost source of CO_2, injecting flue gas into the greenhouse to maintain concentrations around 800 ppm to 1,000 ppm during key growth stages. The technical literature highlights that this practice ties CO_2 supply to combustion-based heating systems; electrifying heat without a replacement CO_2 strategy can increase operating costs and disrupt crop performance. Interviews with vendors and manufacturers confirm that high-value vegetable, berry, cut flowers, and cannabis operations often regard exhaust-based CO_2 as integral to their production model.

In some high-tech food and leafy greens operations, electric capacity and lighting loads are an additional constraint. Where large LED arrays already consume most of the available service capacity, and interconnection upgrades are slow or uncertain, growers may favor gas CHP to meet both lighting and heating needs (potentially with CO_2 capture), even if hydronic systems and temperatures are technically compatible with heat pumps. In these cases, heat pumps may still play targeted roles, for example, serving specific low-temperature loops or providing shoulder-season heating, but are unlikely to carry the bulk of the load in the near term.

For this archetype, a full transition to all-electric heating is therefore not the most realistic near-term target. Instead, the most feasible approach is a hybrid configuration in which heat pumps carry a large share of the annual heating load while high-efficiency condensing boilers (or, in some cases, CHP units) remain in place for peak loads, redundancy, and CO_2 production. TES is a key enabling technology: Large hot-water tanks allow heat pumps to run at favorable times of day, reduce heat

pump capacity, minimize heat pump cost, reduce short cycling, and provide some buffer against grid disruptions.

From a targeting perspective, priority within this archetype falls into a hierarchy:

- **High priority:** Facilities that already rely on bottled or separate CO_2 generation, or that are actively exploring non-combustion CO_2 sources. In these greenhouses, electrifying a large share of the heating load does not immediately force a change in CO_2 practice.
- **Moderate priority:** Facilities that use boiler or CHP exhaust for CO_2 but are willing to retain a smaller combustion plant for CO_2 and extreme weather, while shifting most routine heating to heat pumps. For these sites, program design must explicitly account for the cost and operational implications of running combustion equipment primarily for CO_2.
- **Lower near-term priority:** Operations that are highly optimized around exhaust CO_2 and/or CHP, have limited appetite for operational change, face tight grid capacity, and lack access to alternative CO_2 sources. In these cases, hybridization may still make sense as an efficiency and resilience measure, but the electrified share of heating will likely remain modest in the near term.

The facilities in this typology are generally served by IOUs and are therefore eligible for custom fuel substitution incentives, unless they rely on non-utility fuels, such as propane, diesel, or fuel oil. Their large and relatively predictable heating loads also make them strong candidates for layered funding (e.g., state programs combined with federal tax incentives) and for detailed monitoring that can inform future deemed or hybrid savings methods.

2. Medium-Scale Rigid-Plastic Greenhouses with Mixed Hydronic and Forced-Air Systems

A second near-term archetype consists of medium-scale greenhouses, often between 10,000 and a few hundred thousand square feet, using rigid plastic or double-poly coverings and a mix of hydronic and forced-air heating systems. These operations may grow leafy greens, herbs, smaller tomato crops, ornamentals, and nursery products. Structurally, they are less capital intensive than large glasshouses but still represent “permanent” facilities with meaningful investments in infrastructure.

The technical literature highlights rigid plastic and well-maintained double-poly houses as promising electrification candidates because they have lower infiltration and better insulation. Interviews with vendors reinforce this characterization: Many of these growers already operate small boiler plants serving root-zone or bench loops, sometimes supplemented by gas unit heaters in peripheral zones. Some use a single energy curtain or partial partitioning to limit heat loss and manage microclimates within the same structure.

This segment is attractive because it combines hydronic compatibility with somewhat lower total loads than the largest glasshouses. Electrification strategies can focus on tying small to medium AWHPs into existing hot-water loops, particularly in low-temperature zones, such as propagation areas, benches, and root-zone systems. In many cases, hydronic distribution networks can be operated at lower supply temperatures than traditional high-mass Dutch systems, which improves heat pump efficiency and reduces the need for extensive piping modifications. The energy analysis for this typology used Climate Zone 3 conditions, with Salinas as the representative location, and the

propagation examples from interviews align most closely with Central Coast and similar mild coastal regions.

Unlike many of the very large food and berry facilities, these mid-scale operations are somewhat less likely to rely on boiler exhaust for CO_2. Some do not enrich at all; others rely on bottled gas. This reduces the risk that electrification will create an immediate CO_2 replacement problem. However, program designs still need to assess CO_2 practices site by site, because even within this segment there are examples of growers using combustion exhaust to keep costs down.

In some CEA leafy greens operations in this size range, modular production lines and stringent food-safety requirements drive internal layout and partitioning. For these sites, under-bench or under-module hydronics paired with centralized heat pumps can be technically attractive, but program designs must also consider the site's overall electrical capacity headroom and the possibility that CHP or other onsite generation may be viewed as a competing or complementary option.

For this archetype, a phased approach is appropriate. Programs can support "pilot zones" where heat pumps are installed on one house, one compartment, or one system (e.g., root-zone loops) while existing boilers or unit heaters remain for backup and peak conditions. Modest buffer tanks can serve both to stabilize heat pump operation and to showcase the benefits of TES without requiring the very large tanks seen in flagship projects. Over time, successful pilots can be scaled up across entire facilities or replicated at similar sites.

This segment is well-aligned with the literature's recommendation to prioritize greenhouses with modern structures, energy curtains, and controlled ventilation, particularly in the Central Coast, Sacramento, and southern regions. For many mid-scale growers, the key program design need is not a bespoke engineering analysis but streamlined tools: standard design packages, simplified savings methods, and practical guidance that reduce participation burden.

3. Propagation and Transplant Houses with Low-Temperature Hydronic Floors

A third near-term electrification target comprises smaller propagation and transplant houses with in-slab or bench-embedded hydronic systems. These spaces are commonly found in larger nurseries and vegetable operations, as well as standalone propagation businesses. They are typically smaller than main production houses, often a few thousand to tens of thousands of square feet, with dedicated climate control to support young plants.

Thermally, these structures are well suited to heat pumps. Root-zone systems are designed around relatively low water temperatures and rely on the thermal mass of the slab to maintain stable root temperatures. Interviews highlight examples where growers successfully use geothermal or AWHPs to charge the slab, effectively using the floor as a large storage reservoir. Because these houses prioritize root temperature rather than warm air at canopy height, they can tolerate lower air temperatures while maintaining crop quality.

The literature's process-parameter discussion reinforces this compatibility: target temperature ranges for many food crops (e.g., 60°F to 80°F air) and the focus on humidity and disease control align well with heat pumps that can provide both sensible heat and dehumidification. In propagation zones, CO_2 enrichment is often minimal or absent, further reducing complications. However, propagation and transplant houses of this type appear in many parts of California. Programs can

apply the same design logic in other climate zones, with adjustments to account for higher design loads in colder inland regions.

In this archetype, heat pumps can be treated as the primary heating technology, with only limited reliance on fossil backup if desired for resilience. Small to medium geothermal or air-to-water units, combined with the thermal mass of the slab and a modest hot-water storage tank, can provide high efficiency and very stable temperatures. Because overall loads are smaller, the capacity constraints and power upgrade challenges that loom large for full production houses are more manageable.

This segment offers an opportunity to create early, highly visible successes. Well-documented case studies of propagation houses heated primarily by heat pumps can help address skepticism among vendors and growers, provide real-world performance data, and serve as reference designs for future projects. As such, it is a logical focus for early "model projects" and for development of deemed or hybrid savings methods tailored to low-temperature hydronic applications.

"Prepare and Improve" Segments

4. Low-Tech Plastic-Film Houses with Gas Unit Heaters (Efficiency and Readiness Focus)

A large share of the California greenhouse market consists of low-cost plastic-film houses, often with single or double-poly coverings, simple structural frames, and inexpensive gas unit heaters for heating. These facilities can be very small (under 1,000 square feet), but there are also many medium-size plastic-film houses used for ornamentals, nursery stock, and seasonal vegetable production.

The technical literature and interviews converge on a clear picture: These structures have high infiltration, limited or no energy curtains, and rudimentary control systems. Forced hot-air unit heaters dominate because they are cheap, easy to size and install, and can be added incrementally as operations expand. However, the combination of poor envelope performance and inexpensive combustion equipment leads to very high heating loads per square foot and limited ability to maintain stable humidity and temperature.

From an electrification standpoint, these facilities are challenging. Their high losses push electric heating systems toward large capacities and high operating costs, especially under California electricity pricing. Many of these operations are served by propane or other delivered fuels rather than pipeline natural gas, complicating eligibility for IOU fuel substitution incentives. Interviews also indicate that rather than investing in infrastructure upgrades, some low-tech operators simply shut down winter production when fuel prices rise.

For these reasons, the most appropriate short- to medium-term strategy for this segment is a "prepare and improve" approach, focused on:

- Implementing low-cost envelope improvements such as double-poly inflation, repair of tears and gaps, improved door seals, and the introduction of energy curtains where feasible.
- Upgrading to high-efficiency gas unit heaters with separated combustion to reduce fuel use and improve plant health by limiting ethylene, CO, and NOx buildup.

- Adding simple controls that reduce unnecessary heating (e.g., basic setback and staging) and create a more stable climate that could eventually support partial electrification.

Low-tech plastic-film houses appear in every California climate zone, including coastal, inland valley, and desert regions. The analysis did not anchor this typology to a single climate zone because envelope performance dominates heating loads more than regional climate in these structures. Programs should treat this segment as statewide and should prioritize envelope and efficiency improvements first, regardless of climate zone, before considering electrification measures. Electrification measures may still be piloted in specific niches; for example, small packaged air-to-air heat pumps serving one hoop house producing high-value winter greens, but broad deployment is unlikely to be cost-effective in the near term. Where pilots are pursued, careful monitoring of heating costs, yield, and product quality will be critical to determining whether similar projects should be replicated.

This segment also raises equity and market-development questions. Many low-tech greenhouse operators may fall into disadvantaged or hard-to-reach categories. For these growers, efficiency and reliability improvements can be justified as transitional measures that reduce emissions and operating costs without imposing disruptive capital requirements or grid dependencies they cannot meet. Programs that support envelope and gas efficiency improvements in this segment can lay the groundwork for future electrification, even if immediate heat pump adoption is unrealistic.

5. High-Control Cannabis and Other Semi-Closed CEA Houses (Dehumidification and Hybrid Optimization)

Another "prepare and improve" archetype consists of cannabis and other high-control, semi-closed greenhouses and CEA facilities that combine dense planting, heavy lighting, and strict environmental parameters. These facilities often employ complex systems: multi-pipe hydronic networks, chillers, gas or electric dehumidifiers, energy curtains, and sophisticated building automation. Electricity consumption is already high and in many locations, grid capacity is constrained.

Process requirements for these facilities are demanding. Tight control of VPD, temperature, and humidity is central to crop quality and disease prevention. Lighting and equipment loads create internal heat gains, which in turn drive cooling and dehumidification needs even during cooler seasons. In this context, heating and cooling are intertwined: dehumidification often introduces heat that must be removed, while cooling and reheating cycles are used to maintain setpoints.

From a technical standpoint, heat pumps can play a valuable role in this environment—particularly for cooling and dehumidification—for serving low-temperature hydronic loops, and for providing reheat during dehumidification depending on the system type. Interviews include examples of greenhouses using hybrid gas-fired chillers and three-pipe systems that provide both heating and cooling, with favorable gas incentives for certain configurations. At the same time, high spark gaps between electricity and gas prices, limited available electric capacity, and the scale of peak loads all constrain the feasibility of fully electrified space heating.

In CEA leafy greens and cannabis facilities with similar control requirements, additional constraints arise from large LED lighting loads, stringent uptime and food-safety requirements, and uncertain timelines for electric service upgrades. In these settings, onsite CHP is often viewed as a more controllable and bankable option for meeting both electrical and thermal needs, with the potential

added benefit of CO_2 for enrichment. Heat pumps are still relevant, but they tend to be cast in targeted or complementary roles rather than as the primary heating source—often due to lack of available electrical capacity.

High-control cannabis and other semi-closed CEA facilities operate in many regions of California. Examples from interviews include coastal and inland locations in Climate Zone 3 and nearby zones, but similar facilities exist in hotter inland and desert zones as well. For this typology, facility type and internal loads drive design more than climate zone. Programs should therefore evaluate each site based on lighting density, control requirements, and grid capacity, and then adjust heating and cooling strategies to local climate conditions.

For this segment, the most realistic near-term strategy is to optimize hybrid systems rather than pursue complete replacement of combustion equipment. This includes:

- Integrating heat pumps or hybrid chillers in ways that maximize the recovery and reuse of waste heat from dehumidification and cooling processes.
- Improving distribution through root-zone and low-temperature hydronic systems, which can reduce the reliance on high-temperature air heating and standalone dehumidifiers.
- Deploying TES and advanced controls to smooth peak loads, sequence equipment intelligently, and reduce conflicts between humidity control and energy use.
- Where CHP is present or planned, explicitly designing hydronic and control systems to capture CHP waste heat and CO_2 as efficiently as possible, while using heat pumps where they add the most value (e.g., shoulder seasons, specific zones, or cooling-dominated processes).

These measures can significantly reduce gas consumption and improve environmental stability without requiring heat pumps to carry all heating loads. This strategy would also generate real-world data on how heat pumps perform in high-humidity, high-control greenhouse and CEA environments, which can inform future code and program development.

Given the strategic importance of cannabis and emerging CEA leafy greens operations to some regions—and their role as testbeds for controlled environment technologies—this archetype is important for learning and demonstration, even if near-term fuel substitution savings are modest. Over time, as equipment options, tariffs, grid capacity, and interconnection processes evolve, the lessons from hybrid optimization in this segment may support more ambitious electrification.

Long-Term Strategic Buildouts

6. Heat Pump-Centric Greenhouse Campuses with Integrated TES

Looking further ahead, a sixth archetype envisions new construction of greenhouse campuses or farm parks designed from the ground up around heat pumps and thermal storage. In this configuration, in-slab and root-zone hydronic systems, low-temperature distribution, and TES are not retrofits but core design features. Structures use glass or rigid plastic coverings, energy curtains, and carefully controlled ventilation to minimize non-process loads.

Some existing examples and interview references already point in this direction: facilities using geothermal loops or AWHPs to provide most or all of their heating, with large storage tanks or the slab itself acting as the primary buffer. These campuses aim to operate within the temperature and humidity bands identified in the technical literature as compatible with heat pump performance, while using storage and controls to avoid large peak demands.

In the California context, widespread adoption of this model will depend on land availability for geothermal fields, access to suitable water sources where water-source systems are used, and tariff structures that reward off-peak operation. It will also require high levels of coordination between designers, growers, vendors, and utilities to balance climate control requirements with grid impacts. In high-density CEA applications with large lighting loads, it will additionally require early coordination on interconnection capacity, so that heat pump plants and lighting can be planned together rather than compete for the same limited headroom.

Heat pump-centric campuses can, in principle, locate in any California climate zone. The most attractive opportunities will vary by region. Cooler coastal and valley zones reduce peak heating loads and improve heat pump performance, while inland and desert zones may offer stronger alignment with off-peak renewable generation and larger contiguous sites for new campuses. Programs should treat this typology as opportunity-driven rather than tied to a single climate zone and should prioritize locations where grid capacity, land availability, and local planning support coordinated campus-scale design.

From a program perspective, this archetype represents a strategic buildout rather than a near-term volume play. Early projects of this kind can function as “lighthouse” campuses where performance is carefully monitored, and results feed back into Title 24 development, CARB implementation plans, and future IOU portfolio planning. Over time, standardized design approaches developed for these campuses can lower transaction costs for subsequent projects.

7. Greenhouses Anchored to Industrial Waste Heat and Heat-As-A-Service Models

A final long-term archetype involves greenhouses anchored to industrial waste heat sources, such as food processing plants, data centers, wastewater treatment facilities, or industrial refrigeration systems. In this model, high-temperature water-source heat pumps are installed on the industrial host site to upgrade waste heat, which is then supplied via district hot-water networks to nearby greenhouses. The industrial host may effectively sell “heat as a service” to greenhouse or CEA operators.

European experience, referenced in interviews, demonstrates the technical feasibility of this model, particularly with ammonia heat pumps capable of delivering high water temperatures. Greenhouses and CEA facilities benefit from low-carbon, low-operating-cost heat without needing to install their own large electric heat pumps or expand electric capacity dramatically. Industrial hosts benefit by reducing their own waste heat and emissions, often as part of broader decarbonization strategies.

In California, the potential for such systems depends on co-location of suitable industrial sites and greenhouse or CEA clusters, land use patterns, and the regulatory framework for thermal networks. The host site and customer would also need to agree terms that could represent significant risks, in

a realm that is outside the scope of their core business. Implementing these systems also depends on the economics of high-temperature industrial heat pumps under local electricity and gas tariffs.

For greenhouse and CEA electrification planning, this archetype is significant because it offers a pathway to decarbonize heating for segments that are otherwise difficult to serve—such as large plastic-film operations, propane-reliant facilities, or CHP-oriented CEA sites—without forcing each facility to build its own electric capacity. This archetype also aligns with broader state and federal initiatives on industrial decarbonization and waste heat recovery.

In this target type, hydronic distribution provides the most practical and efficient heating approach. The district hot-water network delivers heat from the industrial host to the greenhouse as hot water, so the greenhouse side should use hydronic systems such as overhead pipe rails, root-zone or under-bench loops, and hydronic unit heaters. Hydronic distribution allows low-temperature operation, good integration with TES, and straightforward zoning within the greenhouse. Air-only unit heaters can still play a role for local boosts or frost protection, but the primary system should rely on hydronic loops that tap into the district hot-water supply.

Programmatically, early work in this archetype would focus on mapping candidate industrial greenhouse/CEA pairings, assessing technical potential, and developing pilot projects that braid industrial and agricultural funding streams. Over time, successful projects could inform new tariff structures, interconnection rules, and incentive mechanisms that recognize the shared benefits of industrial heat pump deployment and greenhouse/CEA heating decarbonization. Greenhouses anchored to industrial waste heat depend on the presence of suitable host facilities rather than on a specific climate zone. Potential pairings may occur in many regions, including coastal industrial corridors, inland food-processing hubs, and areas with large wastewater treatment plants or data centers. The opportunity will look different in each climate zone and with each host type. Programs should therefore identify candidate sites on a case-by-case basis and tailor system design to local climate, host process characteristics, and grid conditions.

Overall, these typologies suggest that greenhouse and CEA electrification in California should not be treated as a single, uniform transition. High-tech hydronic food and berry greenhouses, low-temperature propagation houses, and some hybrid cannabis/CEA facilities present immediate opportunities to deploy heat pumps and TES with careful attention to CO_2 practices, lighting loads, and grid constraints. In the near term, low-tech plastic-film houses, strongly CHP-oriented CEA sites, and highly CO_2-dependent operations are better served by efficiency, envelope upgrades, and hybrid strategies that improve readiness for future electrification. Long-term strategies involving heat-pump-centric campuses and industrial heat-as-a-service models offer promising but more complex avenues for decarbonizing the sector as policies, technologies, interconnection processes, and markets evolve.

Appendix E: Software Limitations

The team began the energy analysis using USDA Virtual Grower 3, a software tool designed to help greenhouse growers estimate heating costs and perform simple simulations to identify potential heat savings. Over time, Virtual Grower has added features that allow users to evaluate different greenhouse designs, predict crop growth, assist with scheduling, make real-time energy-use predictions, and assess the impact of supplemental lighting on plant growth and development. In this way, the software serves as a safety net, enabling users to experiment with "what-if" scenarios in a risk-free setting.[8]

However, its heating-load output is limited to monthly results. Although it can generate figures showing hourly heating-load results, it cannot export the hourly data, which limits its usefulness for heat pump and thermal storage analysis. Hourly heating-load data are important for evaluating heat pump part-load operation under changing outdoor environmental temperatures.

The heating system options are unit heater, hot water boiler, steam boiler, and high efficiency unit heaters and do not include heat pumps, so the tool cannot support energy modeling for greenhouse heating electrification with heat pumps. Therefore, an extended spreadsheet must be developed for heat pump analysis. The tool also does not support thermal storage modeling, and the generated file formats of greenhouse models can only be used within Virtual Grower 3. As a result, they cannot be integrated with the existing physics-based thermal storage model, and the thermal energy system analysis will require an additional spreadsheet.

[8] https://www.ars.usda.gov/midwest-area/wooster-oh/application-technology-research/horticulture/virtual-grower/virtual-grower-3-model/

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