Efficiency, Yield, and Resilience: Utility-Ready Impacts of Integrated HVAC+D in Controlled Environment Agriculture

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Abstract

Controlled environment agriculture (CEA) for cannabis cultivation reaches energy use intensities of 300–800 kBtu/ft²·yr, far exceeding the 50–200 kBtu/ft²·yr observed across commercial buildings based on national energy benchmarks (EIA CBECS), with HVAC and dehumidification loads accounting for approximately 56 percent of facility energy use (Mills 2012; Remillard and Collins 2017).

Conventional CEA facilities rely on non-integrated HVAC systems with standalone dehumidifiers, where direct expansion (DX) cooling and dehumidification operate independently. This creates a thermodynamic "tug-of-war" between sensible cooling and latent load removal, driving excess energy use, control instability, and environmental variability. Integrated heating, ventilation, air conditioning, and dehumidification (HVAC+D) systems resolve this by coordinating temperature and humidity within a unified control architecture. By managing sensible and latent loads together, these systems eliminate inefficiencies in non-integrated designs and maintain stable environmental conditions at the plant level.

This paper presents a year-long comparative field study of integrated HVAC+D and non-integrated systems across CEA facilities in Michigan, comprising 15 million data points across 21 parameters. Integrated systems achieved a 38 percent reduction in total energy use while maintaining stable conditions required for plant health.

The evaluation identifies a measurable yield response, with integrated systems demonstrating a threefold improvement in process efficiency and space utilization. Integrated systems improved electrical load characteristics, achieving a 1.5-fold increase in load factor and delivering a stable, grid-aligned demand profile. These results establish integrated HVAC+D as a system-level solution addressing energy efficiency, environmental control, and load predictability, supporting capacity-based utility program design aligned with overall system sizing.

Introduction

Indoor controlled environment agriculture (CEA) for cannabis cultivation reaches energy use intensities of 300–800 kBtu/ft²·yr, far exceeding the 50–200 kBtu/ft²·yr observed across commercial buildings based on national energy benchmarks (EIA CBECS). This range reflects published power density and modeled energy use for indoor cultivation, with heating, ventilation, air conditioning, and dehumidification loads accounting for approximately 56 percent of total facility energy consumption (Mills 2012; Remillard and Collins 2017).

This load dominance is structural, as environmental control in sealed grow environments is entirely mechanically driven, positioning environmental control system architecture as the primary determinant of both energy performance and cultivation stability, as reflected in the disaggregated end-use profile shown in Figure 1.

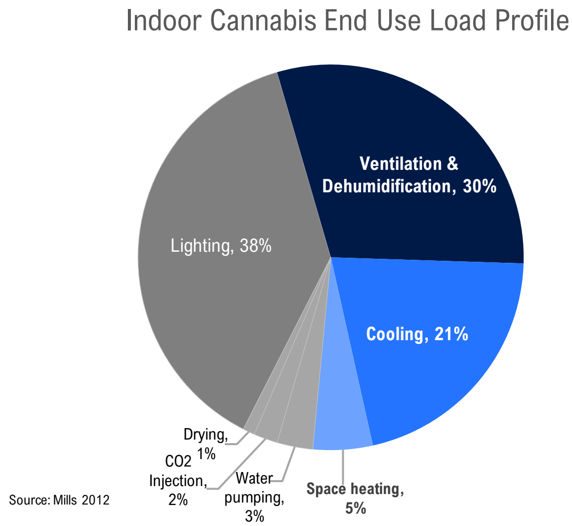

Figure 1: Disaggregated End Use Load Profile of Indoor cannabis cultivation facilities. *Source:* Mills 2012

Conventional CEA facilities rely on non-integrated HVAC systems with standalone dehumidifiers in which temperature and humidity are managed by separate equipment streams with no coordinated control logic. Under these conditions, cooling systems remove sensible heat while partially addressing latent load, even as standalone dehumidifiers reintroduce heat into the space during moisture removal. This interaction manifests as a persistent thermodynamic imbalance, driving continuous cycling, environmental overshoot, and unstable setpoints under 24/7 operational conditions, with a corresponding penalty in energy use and control precision (Mills 2012; RII 2023).

Integrated HVAC+D systems resolve this limitation by coordinating sensible and latent load management within a single control architecture. Through staged or variable capacity modulation, these systems maintain stable environmental conditions while eliminating the counteracting heat and moisture dynamics inherent to non-integrated configurations (Schimelpfenig et al. 2023). The result is a controlled environmental profile that is both thermodynamically stable and materially more efficient from an energy standpoint.

To quantify these differences under real operating conditions, this study evaluates integrated HVAC+D systems and non-integrated baseline configurations across multiple CEA facilities in Michigan using a year-long field measurement and verification framework (EVO 2022; ASHRAE 2023). By comparing thermally isolated flowering rooms operating in parallel under comparable conditions, the analysis provides a direct assessment of system-level performance, isolating the impact of HVAC+D architecture on both energy consumption and environmental outcomes.

Methodology

A rigorous evaluation framework is required when comparing HVAC+D performance in thermodynamically complex environments such as sealed flowering rooms. In these systems, environmental control must be treated as a coupled microclimate, where small deviations in latent load handling or heat rejection can propagate into measurable impacts on plant physiology and operational efficiency.

Accordingly, the study employs a controlled, parallel monitoring design, observing baseline and integrated rooms operating concurrently under active cultivation conditions. By pairing structured data governance with a comparison framework that minimizes weather and operational bias, the methodology isolates mechanical system effects for direct evaluation.

The evaluation of integrated HVAC+D system performance relied on a Measurement and Verification (M&V) framework aligned with the International Performance Measurement and Verification Protocol (IPMVP) and ASHRAE Guideline 14 (EVO 2022; ASHRAE 2023). The study was conducted across four facilities comprising ten thermally isolated flowering rooms, evenly distributed between baseline and integrated configurations. This configuration enabled a normalized, simultaneous assessment of 42 full grow cycles over a one-year period from June 2023 to May 2024, with flowering cycles ranging from approximately 8 to 10 weeks, capturing seasonal variation across Michigan operating conditions.

The data collection infrastructure captures approximately 15 million data points across 21 parameters. Revenue-grade logging devices were deployed across all primary HVAC components, including air handling units, condensers, and standalone dehumidifiers, recording power, current, voltage, and power factor at 15-minute intervals. The full set of monitored variables is summarized in Table 1.

Table 1: Monitored parameters organized by electrical, environmental, airside, and latent load measurement domains.

Category	Parameters
Electrical End Use	Amps (A); Real power (kW); Voltage (V); Power factor
Space Environment (Canopy Plane)	Space dry-bulb temperature (°F); Space wet-bulb temperature (°F); Space relative humidity (%); Space dew point (°F); CO_2 concentration (ppm); Vapor pressure deficit (kPa); Illuminance (lx)
Airstream (Duct Measurements)	Supply air temperature (°F); Supply air relative humidity (%); Return air temperature (°F); Return air relative humidity (%); Air flow rate (cfm)
Moisture / Latent Handling	Condensate flow rate (gpm)
Outdoor / Weather Context	Outdoor dry-bulb temperature (°F); Outdoor wet-bulb temperature (°F); Outdoor dew point (°F); Outdoor relative humidity (%)

Environmental monitoring was conducted using calibrated wireless psychrometric sensors deployed at the canopy level and within supply and return ducts. Dry-bulb temperature, relative humidity, dew point, and condensate flow were recorded at high temporal resolution to characterize environmental stability and latent load performance.

Beyond standard energy metrics, the monitoring stations tracked supplemental parameters including carbon dioxide levels (CO_2), vapor pressure deficit (VPD), and photosynthetic photon flux density to assess the holistic impact on the cultivation environment.

Data quality was maintained through continuous calibration and remote diagnostic verification protocols. This approach resulted in 99.89 percent data accuracy.

By monitoring both the baseline and integrated systems simultaneously under identical weather conditions, the study eliminated external climatic variables as a source of uncertainty. This allowed the analysis to focus exclusively on the technological differentiators and their impact on energy efficiency and process performance. This structure is essential in CEA, where internal loads dominate, and differences in mechanical architecture can be isolated cleanly.

Characterizing the Baseline vs. The Integrated Measure

CEA facilities operate under thermodynamic conditions that differ fundamentally from conventional commercial spaces, with dominant latent loads driven by plant evapotranspiration and continuous internal heat gains. In sealed cultivation environments, moisture absorbed through the root structure is released at the canopy through transpiration, introducing a sustained latent load that must be managed concurrently with sensible cooling. Effective environmental control therefore requires a system capable of simultaneous and coordinated handling of both latent moisture removal and thermal regulation.

Baseline: Non-Integrated HVAC with Standalone Dehumidification

The baseline non-integrated system utilizes separate equipment for temperature and humidity control and is commonly implemented in existing or repurposed facilities where conventional, off-the-shelf configurations are deployed.

The primary deficiency of the baseline system is the lack of coordinated control. For example, as an HVAC unit cools the space to meet a temperature setpoint, it may remove some moisture as a byproduct, yet the standalone dehumidifiers may simultaneously release sensible heat back into the room, triggering the cooling cycle to run longer than necessary. This lack of feedback loops leads to constant hysteresis, energy waste, and unstable environmental conditions (Mills 2012; RII 2023). Furthermore, standalone dehumidifiers are often poorly positioned, leaving "pockets" of moisture where mold and disease can proliferate. Under 24/7 operating conditions of a grow house, these off-the-shelf units are frequently overworked or oversized, regularly leading to mechanical failures, which significantly reduce equipment life from a 15-year standard to five to seven years.

Measure: Integrated HVAC+D Systems

The measure is an integrated HVAC+D system designed specifically for the high-latent loads of CEA. These self-contained, packaged units combine heating, cooling, and dehumidification into a single integrated system. By utilizing temperature and relative humidity sensors and programmable logic controllers (PLC), integrated systems monitor dry-bulb temperature and relative humidity to ensure only the necessary amount of conditioning is delivered.

One of the defining features of these integrated units is the use of hot gas reheat. This process captures hot refrigerant gas from the cooling cycle and uses it to reheat the air after dehumidification, enabling moisture removal without over-cooling the space, eliminating the need for external reheat sources and prevents the energy-intensive “tug-of-war” observed in non-integrated systems (Schimelpfenig et al. 2023). These systems also incorporate multistage or variable-speed compressors, providing precise capacity modulation to maintain tight environmental conditions.

Beyond energy efficiency, integrated systems offer other advantages, such as longer operational life, a smaller footprint, onboard diagnostics, and remote monitoring capabilities, etc. By automatically balancing the sensible and latent heat loads, the integrated HVAC+D systems provide the stable vapor pressure deficit required for optimal plant transpiration. This, effectively, de-risks the cultivation process while significantly reducing the facility's grid impact.

Comparative Facility Profiles

The validity of this comparative field study relies on normalization across ten thermally isolated flowering rooms, categorized into five baseline and five integrated measure cases. To ensure a defensible comparison, key cultivation and environmental parameters, including room size, canopy density, and target conditions, were aligned across facilities to maintain consistent internal load profiles. Facility and equipment characteristics are summarized in Table 2, with installed cooling capacity reported in tons and baseline energy use including both cooling and standalone dehumidification loads.

All facilities operated with LED lighting systems, eliminating lighting-driven variability and isolating HVAC+D system architecture as the primary differentiating factor.

Table 2: Facility characteristics and HVAC system configurations for baseline and integrated study cases.

Facility Case	Room Labels	Installed Cooling Capacity	Individual Equipment Count per Room
Integrated (Measure)	M1, M2	20 Tons	1 x 20-ton vertical self-contained unit
Integrated (Measure)	M3, M4, M5	90 Tons	2 x 45-ton horizontal packaged units
Non-Integrated (Baseline)	B1, B2, B3	5 Tons	1 x 5-ton split FCU + 2 x standalone dehumidifiers
Non-Integrated (Baseline)	B4, B5	25 Tons	5 x 5-ton split FCUs + 4 x standalone dehumidifiers

Non-Integrated Baseline Room Configurations

The baseline flowering rooms utilized non-integrated configurations, where temperature and moisture are controlled independently.

Non-Integrated rooms B1, B2, and B3 were identical, each spanning 827 square feet with 608 square feet of canopy area. Each room was conditioned by a single 5-ton unitary split fan coil unit and two standalone dehumidifiers.

Non-Integrated rooms B4 and B5 each spanned 754 square feet with 566 square feet of canopy area. Each room was equipped with five individual 5-ton unitary split systems, totaling 25 tons of capacity per room, along with four standalone dehumidifiers.

The elevated installed capacity in Rooms 4 and 5 was not configured for staged operation; rather, the full 25 tons of cooling was actively deployed to manage simultaneous sensible and latent load spikes driven by high-intensity cultivation practices. This over-provisioned configuration is representative of prevailing industry approaches, where multiple off-the-shelf systems are used to compensate for the environmental instability inherent in non-integrated designs. By including both lower-capacity and over-provisioned configurations, the study captures a representative range of system architectures and operating behaviors observed across the CEA market.

Integrated Measure Case Room Configurations

The integrated flowering rooms utilized HVAC+D systems with unified control of cooling and dehumidification.

Integrated Rooms M1 and M2, these rooms measured 1,371 square feet with a canopy area of 1,056 square feet. Each room was served by a single 20-ton water-cooled integrated unit.

Integrated Rooms M3, M4, and M5, these rooms represented the largest industrial scale in the study, each spanning 2,752 square feet with 2,147 square feet of canopy area. To meet the massive environmental demands, each room utilized two 45-ton packaged, ducted integrated units, resulting in an aggregate capacity of 90 tons per room.

These systems manage sensible and latent loads simultaneously, maintaining stable temperature, humidity, and vapor pressure deficit conditions.

By conducting simultaneous monitoring across the ten thermally isolated rooms normalized performance across 42 grow cycles, attributing observed energy and process efficiency improvements directly to system architecture.

To further contextualize these facility-level configurations, the underlying mechanical system architectures are described in the following section.

Mechanical System Topologies

Mechanical configurations across the ten monitored rooms are grouped into four system topologies, ranging from split-system arrangements to packaged integrated units.

Non-Integrated Baseline System Configurations

Baseline rooms represent non-integrated configurations, where cooling and dehumidification operate as independent systems.

Topology A (Rooms B1, B2, and B3) consists of 5-ton units utilizing a unitary split fan coil unit for temperature control paired with two standalone dehumidifiers. This configuration is typical of smaller-scale cultivation sites.

Topology B (Rooms B4 and B5) represents higher-capacity implementations, where each room is served by five independent 5-ton split fan coil units, resulting in an aggregate installed capacity of 25 tons, along with four standalone dehumidifiers. Despite higher installed capacity, systems operate on independent control loops, resulting in cycling and environmental instability consistent with field observations.

Integrated Measure Case System Configurations

Integrated rooms utilize HVAC+D systems where cooling, heating, and dehumidification are coordinated through a unified control architecture.

Topology C (Rooms M1 and M2) consists of 20-ton vertical, self-contained water-cooled integrated units. In contrast to the air-cooled split systems used in baseline configurations, heat rejection is managed through a fluid-cooled heat exchanger, enabling improved control of sensible heat removal under high internal loads.

Topology D (Rooms M3, M4, and M5) represents higher-capacity implementations, where each room is served by two 45-ton horizontal packaged integrated units, resulting in an aggregate capacity of 90 tons per room. These units are typically installed externally and ducted into the cultivation space, incorporating multi-stage compressor operation and hot gas reheat to maintain continuous latent load management and stable environmental control under variable evapotranspiration loads.

By contrasting these system topologies, the transition to integrated HVAC+D is characterized not merely as a change in equipment configuration, but as a shift from uncoordinated mechanical systems operating independently to a unified climate control architecture designed to simultaneously manage coupled sensible and latent loads.

Field-Verified Performance: Stability and Weather Independence

This study provides a comparative assessment of energy intensity and environmental control precision between baseline configurations and integrated systems. Over the year-long monitoring period, integrated HVAC+D systems achieved a 38 percent reduction in energy use relative to non-integrated baseline configurations. On a normalized basis, the baseline required 10,525 kWh per ton of installed cooling capacity, whereas the integrated systems required 6,488 kWh per ton. For the baseline configuration, this metric captures both cooling and standalone dehumidification loads, reflecting the energy penalty associated with uncoordinated latent load management. This observed reduction represents a direct efficiency gain associated with coordinated system control and the elimination of thermodynamic conflict inherent in non-integrated configurations.

Environmental Control and Stability

In addition to energy performance, verification data show improved environmental stability under integrated system operation. Figure 2 illustrates space temperature and relative humidity profiles for non-integrated HVAC configurations with standalone dehumidification, while Figure 3 presents corresponding profiles for integrated HVAC+D systems. The figures correspond to representative operating days selected from the monitoring period to illustrate typical system behavior under comparable conditions.

As shown in Figure 2, non-integrated configurations maintained daytime temperatures within the acceptable flowering range (75–80 °F) but exhibited large relative humidity excursions from approximately 45 percent to 75 percent. Nighttime temperatures remained elevated (74–77 °F), above the typical optimal range of 55–65 °F, with RH fluctuating between approximately 45 percent and 55 percent. This behavior reflects independent system cycling and a lack of coordinated control, resulting in broad environmental variation and limited separation between day and night operating conditions.

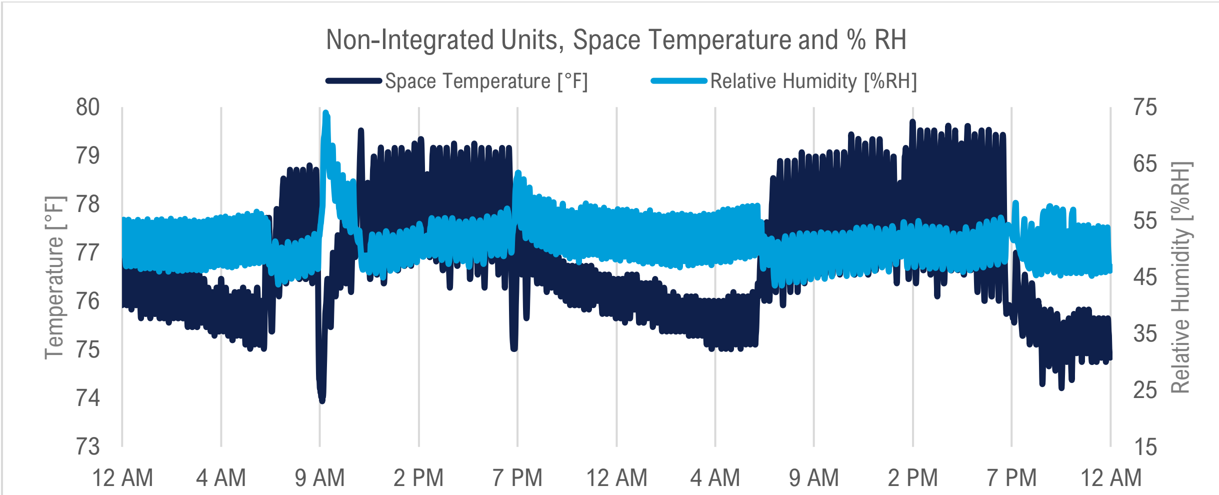

Figure 2. Space temperature and relative humidity profiles for non-Integrated HVAC systems with standalone dehumidification showing environmental variability under continuous operation.

In contrast, Figure 3 shows that integrated systems maintained tighter and more coordinated operating bands. Daytime temperatures remained near 70 °F with relative humidity held within a narrower range (approximately 63–65 percent), while nighttime temperatures reduced to approximately 55 °F, aligning with optimal targets. Although RH remained elevated during nighttime operation (approximately 71–75 percent), the system maintained a consistent and repeatable operating profile with clear temperature staging between day and night conditions.

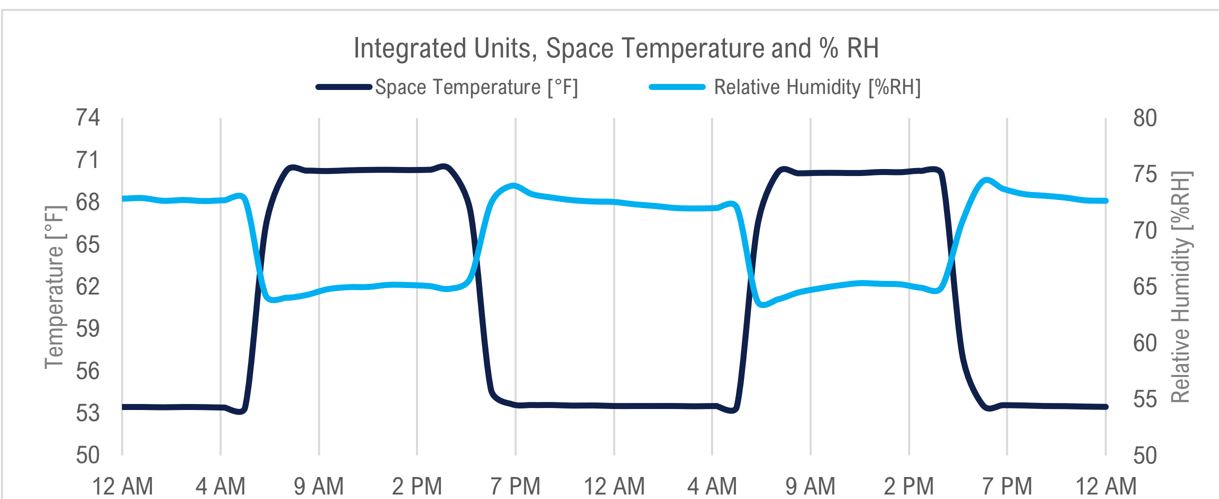

Figure 3. Space temperature and relative humidity profiles for Integrated HVAC+D systems showing environmental stability under continuous operation.

For indoor cultivation, environmental performance depends on maintaining temperature and humidity within stable, coordinated operating bands rather than allowing wide excursions. Relative to the non-integrated case, the integrated system demonstrates improved control stability and clear day–night temperature staging, while highlighting residual limitations in humidity control.

The Impact of Weather Independence

A key consideration in grid planning is the relationship between facility load and external weather conditions. In CEA environments, system demand is driven primarily by internal loads, including plant transpiration and sustained internal heat gains, rather than ambient conditions.

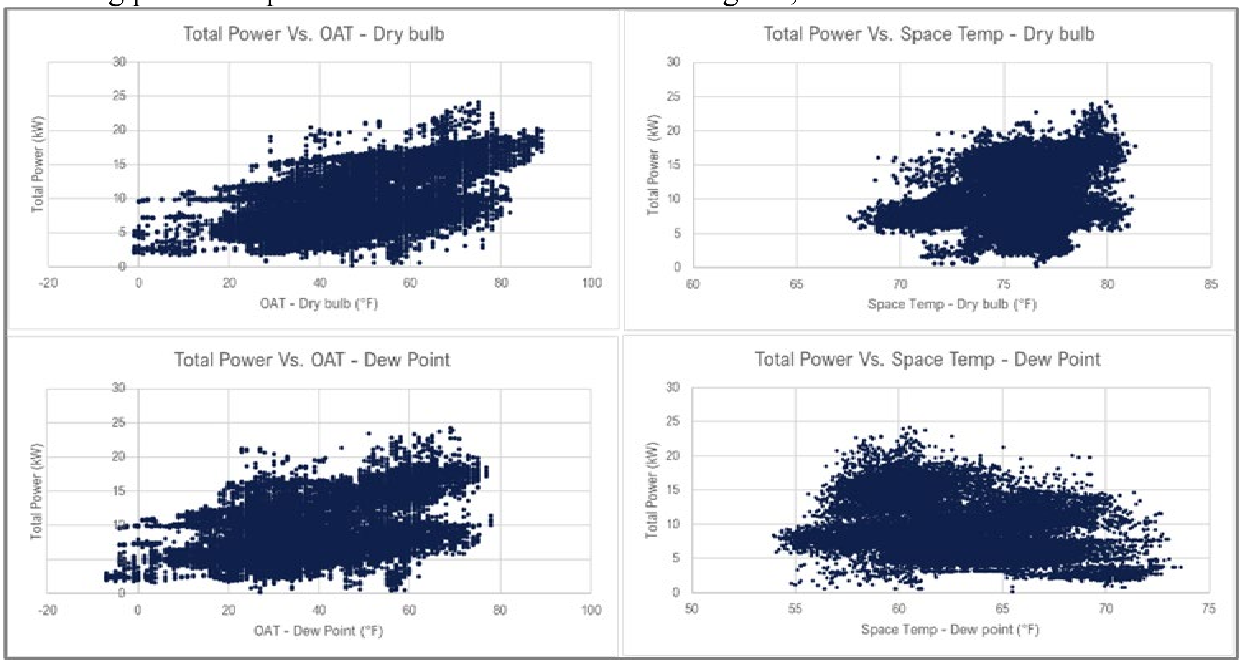

Figure 4. System power response relative to outdoor and space temperature and dew point conditions for non-integrated HVAC systems with standalone dehumidification, showing minimal sensitivity to ambient conditions.

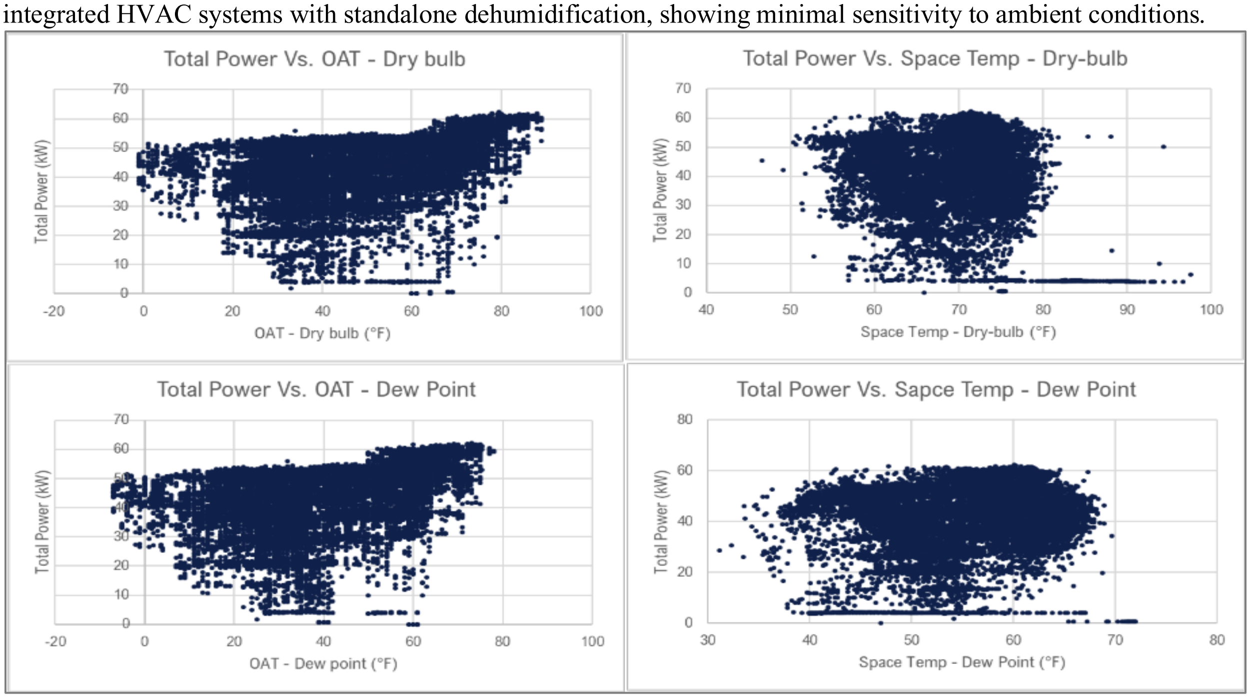

Figure 5. System power response relative to outdoor and space temperature and dew point conditions for integrated HVAC+D systems, showing minimal sensitivity to ambient conditions.

As shown in Figures 4 and 5, both integrated and non-integrated systems exhibit minimal sensitivity of power draw to variations in outdoor and internal environmental conditions. Across the monitored range of −1 °F to 89 °F, system power remains effectively invariant despite changes in outdoor air temperature, indoor temperature, and associated moisture conditions, indicating that internal load drivers dominate system response.

This behavior reflects the thermodynamic characteristics of sealed cultivation environments, where internal processes govern load behavior and limit exposure to external variability. As a result, CEA facilities exhibit stable and predictable demand profiles, supporting improved load factor performance, enhanced grid reliability, and more reliable demand forecasting.

The KPI Pivot: Driving Process Efficiency and Grid Resilience

Traditional demand-side management (DSM) programs focus on direct energy savings, but CEA requires a broader KPI framework to capture system-level performance. While energy cost is a major expense, overall facility performance is driven by yield, product quality, and process consistency.

This study shows that integrated HVAC+D systems introduce a compounded performance effect, where direct energy efficiency gains are coupled with measurable improvements in process stability and biological outcomes. Table 3 summarizes the KPI's, with baseline energy values inclusive of standalone dehumidification loads, demonstrating concurrent gains in energy, process efficiency, and load stability.

Table 3: Normalized performance comparison of baseline and integrated HVAC+D systems across energy, process, and load metrics.

Key Performance Indicator	Integrated (Measure)	Non-Integrated (Baseline)	Performance Delta
Process Efficiency	1.14 – 2.47 g/kWh	0.37 – 0.78 g/kWh	Threefold Improvement
Space Utilization	54 – 140 g/ft²	11 – 47 g/ft²	Threefold Improvement
Utility Load Factor	0.71 – 0.87	0.45 – 0.57	1.5-fold Improvement
Environmental Profile	"Flatline" Precision, see Fig 3	Significant "Hysteresis", see Fig 2	Stable VPD (1.0-1.5 kPa)
Energy Usage Intensity	6,488 kWh/ton	10,525 kWh/ton	38% reduction

Process Efficiency: Grams per kilowatt-Hour

Process efficiency, defined as grams of dry flower per unit energy consumed (g/kWh), is the primary metric for evaluating productive energy use in CEA systems. Field data indicate an approximately threefold improvement in this metric, with integrated systems achieving values ranging from 1.14 to 2.47 g/kWh compared to 0.37 to 0.78 g/kWh for non-integrated baseline configurations.

This improvement reflects stable environmental control supporting consistent transpiration and photosynthetic activity, combined with reduced total energy consumption.

Space Utilization and Canopy Productivity

Space utilization, expressed as grams of product per square foot of cultivation area (g/ft^2), reflects canopy-level productivity. The study indicates a similar threefold improvement in this metric, with integrated systems achieving values ranging from 54 to 140 g/ft^2 compared to 11 to 47 g/ft^2 in baseline configurations.

This increase is associated with improved environmental stability, particularly humidity and dew point control. Baseline configurations exhibited significant variability, including elevated dew point excursions, increasing the risk of mold formation and plant stress. In contrast, integrated systems maintained a consistently narrow dew point band.

Vapor Pressure Deficit (VPD) and Biological Optimization

Vapor pressure deficit (VPD) is the difference between the moisture content of the air and its saturation point and is a key indicator of the driving force for plant transpiration. Maintaining VPD within a range of approximately 1.0 to 1.5 kPa during the flowering stage is critical for supporting stable water transport and nutrient uptake.

Field data indicated that integrated systems maintained VPD within this target range for a greater proportion of operating time, supporting stable transpiration and reducing physiological stress. In contrast, baseline configurations exhibited wider variability, including both suboptimal and elevated VPD conditions associated with reduced water and nutrient transport efficiency and increased plant stress.

Load Factor Improvement

Load factor, defined as the ratio of average load to peak load, reflects demand stability. Integrated HVAC+D systems demonstrated an approximately 1.5-fold improvement in load factor, with values ranging from 0.71 to 0.87 compared to 0.45 to 0.57 for baseline configurations.

This improvement reflects reduced cycling and a more uniform system response. In contrast, non-integrated configurations exhibited greater variability in demand, driven by independent system operation and competing control loops.

Implications for DSM Program Design and Grid Integration

The regulatory landscape for CEA remains in early stages, with historical emphasis on lighting efficiency and limited treatment of HVAC+D performance. As system-level energy intensity becomes a focus, program frameworks are beginning to evolve toward approaches that reflect the coupled sensible and latent load dynamics inherent to indoor cultivation.

These findings indicate the need to redefine how efficiency is measured in CEA environments. Improvements in process efficiency, environmental stability, and energy use indicate that equipment-based metrics alone do not capture system performance.

The observed improvements support consideration of productivity-based efficiency frameworks, where program structures align with realized system outcomes rather than installed equipment alone.

However, implementation of productivity-based frameworks requires careful consideration of data verification challenges. Production metrics are often self-reported and commercially sensitive, limiting the extent to which utilities can independently validate performance at the facility level.

Grid Resilience and Flexible Load Characteristics

Integrated HVAC+D systems stabilize the electrical demand profile of CEA facilities by aligning system response with internally driven loads. In these environments, demand is governed by process conditions, including plant transpiration and sustained internal heat gains, with relatively limited sensitivity to short-term external variability.

Under integrated operation, coordinated control produces a consistent and repeatable demand pattern. This reduces intra-day variability and minimizes cycling behavior, resulting in a more uniform load profile relative to non-integrated configurations, where independent control loops introduce greater demand fluctuation.

These characteristics support improved predictability in facility-level demand. The ability to maintain stable demand while managing high energy intensity loads supports improved demand forecasting, enhances grid reliability, and provides a foundation for more advanced demand-side management strategies.

The Regulatory Horizon: Codes and Standards

The performance characteristics identified in this study have implications beyond individual facility operation, informing the development of building codes, energy standards, and utility program frameworks. The following sections situate these findings within the current regulatory landscape and highlight emerging trends in policy and standards development for controlled environment agriculture.

Evolution of National Standards

At the national level, building energy standards such as ASHRAE 90.1 provide the primary framework for CEA facilities, with provisions largely focused on horticultural lighting and photosynthetic photon efficacy (PPE) (ANSI/ASHRAE/IES 2022). While these standards establish important performance requirements for lighting systems, they do not address the mechanical and dehumidification demands of high-latent-load cultivation environments.

Upcoming code cycles, including ASHRAE 90.1 and the International Energy Conservation Code (IECC), are expected to expand toward humidity control and system-level performance considerations for indoor cultivation applications.

State-Level Code Developments

California is the clearest example of cultivation-specific mechanical and lighting requirements to date. The 2022 California Title 24, Part 6 code introduced a Controlled Environment Horticulture (CEH) pathway with mandatory dehumidification compliance options, including: (i) dehumidifiers that meet federal efficiency minimums under 10 CFR 430 (EPA 2019), or (ii) integrated HVAC with on-site heat recovery covering ≥ 75 % of annual reheat for dehumidification, or (iii) chilled-water systems with ≥ 75 % heat recovery, or (iv) desiccant systems for low-dew-point designs (CEC 2024). These provisions prioritize heat-recovery-based dehumidification, aligning with integrated HVAC+D system design. The 2025 Title 24 code retained these requirements and added monitoring provisions for aggregated horticultural lighting loads (Energy Code Ace 2025).

The 2028 code cycle, currently under development, reflects continued refinement of CEH provisions, including updates to space conditioning definitions, modeling approaches, and alignment between prescriptive and performance-based pathways (CEC 2024).

Other states generally apply energy codes derived from ASHRAE 90.1 or the IECC without cultivation-specific mechanical provisions. In Oregon, the state energy code is based on ASHRAE 90.1-2022 (2025 OEESC), while utility programs such as those administered by Energy Trust of Oregon provide targeted incentives for HVAC and dehumidification upgrades in cannabis and indoor cultivation facilities, demonstrating how utility programs address gaps where codes remain generic. (ETO 2024).

Massachusetts addresses energy performance for licensed cannabis facilities through the Cannabis Control Commission (CCC), which requires energy management documentation including HVAC and dehumidification provisions that are functionally binding for licensees.

Local Jurisdictions and Regional Adoption

At the municipal level, jurisdictions have often advanced more quickly than state or national frameworks in establishing CEA-specific requirements. Seattle introduced minimum lighting efficacy requirements as early as 2015, and Denver implemented targeted lighting and dehumidification efficiency requirements in 2019 (Kellogg 2019). In Michigan, statewide codes currently rely on ASHRAE 90.1-2019 and the 2021 IECC, with mechanical equipment governed primarily through broader federal efficiency standards (ANSI/ASHRAE/IES 2022; ICC 2024).

Trajectory Toward Performance-Based Standards

As regulatory frameworks continue to mature, there is a clear trend toward transitioning from equipment-specific requirements to system-level, performance-based standards. The findings from this study, particularly the lack of correlation between internal load and outdoor weather conditions, and observed improvements in process efficiency, provide an empirical basis for this transition.

These results support the continued evolution toward performance-based standards that recognize integrated HVAC+D system performance in high-latent-load cultivation environments.

Market Transformation: Program Design and Adoption

The transition of integrated HVAC+D systems to a standard utility offering requires a programmatic framework that balances technical rigor with market simplicity. While this comparative field study provides the data necessary to support high-impact incentives, the effectiveness of a market transformation strategy depends on clear and simple communication between utilities, contractors, and customers.

Financial Realities: CAPEX and OPEX Considerations

To understand the role of utility intervention, the capital expenditure (CAPEX) associated with integrated HVAC+D systems must be considered. The gross measure cost (GMC) for integrated systems exceeds that of conventional split systems with standalone dehumidification. Depending on system capacity and facility size, installed costs range from $30,000 to $190,000 per unit, corresponding to approximately $2,500 to $5,000 per ton, or $50 to $120 per square foot. The incremental measure cost (IMC) typically ranges from $7,500 for smaller systems (5 to 10 tons) to over $17,500 for larger installations (20 to 50 tons).

The higher initial CAPEX is offset by improvements in operational expenditure (OPEX) and system longevity. Integrated HVAC+D systems are designed for continuous 24/7 operation with an expected useful life of approximately 15 years, compared to 5 to 7 years for baseline configurations operating under sustained mechanical strain. Annual operation and maintenance costs for integrated systems are estimated to be between $1,500 and $3,000. Combined with the observed 38 percent reduction in energy consumption, this yields a simple payback on incremental cost of approximately two years in typical applications.

The Programmatic Pivot: Simplicity Over Complexity

Early program concepts explored tiered incentive structures designed to balance cost-effectiveness with support for larger cultivation facilities. While technically valid, stakeholder feedback indicated that tiered incentive caps introduced unnecessary complexity for growers and trade allies.

To reduce implementation friction and support broader adoption, program design shifted toward a simplified, capacity-based incentive structure of $600 per ton. This approach aligns with how HVAC systems are specified and procured in practice, enabling rapid and consistent assessment of economic viability. For a representative 35-ton flowering room, this structure provides approximately $21,000 in direct support, effectively offsetting incremental system cost.

This predictability improves program transparency, facilitates communication across stakeholders, and supports scalability across the CEA market.

Boundary Conditions and Opportunities for Future Calibration

The dataset underpinning this evaluation, encompassing over 15 million data points across 42 grow cycles, is defined by specific boundary conditions that establish the scope of analysis. These conditions provide context for interpreting results and applying them in regulatory and industry settings.

The first boundary condition is geographic and climatic. This evaluation was conducted within the Consumers Energy service territory in Michigan's lower peninsula. The results indicate minimal correlation between system power draw and outdoor weather conditions, reflecting internally driven load profiles and the thermal integrity of the evaluated facilities. In regions characterized by higher ambient humidity or in facilities with less controlled building envelopes, system behavior may vary due to increased infiltration and climate exposure, with integrated systems expected to improve load stability under these conditions.

The second boundary condition relates to crop type and growth stage. The analysis focused exclusively on the flowering stage of cultivation, which represents approximately 75 to 80 percent of total facility energy consumption. Because transpiration rates and environmental requirements vary significantly across plant species and growth phases, the observed improvements in process efficiency and space utilization are specific to the high latent load conditions associated with flowering canopies. Application to other crops requires additional calibration for differing physiological and environmental conditions.

The evaluation maintained consistent lighting conditions across all sites, with participating facilities operating LED systems isolating HVAC+D system performance as the primary variable. Alternative lighting configurations may shift sensible-to-latent load balance and system behavior.

Across all evaluated sites, observed performance reflects typical field variability in equipment configurations, with improvements attributable to system-level integration rather than uniform equipment performance.

Translation of this evaluation into broader program implementation recognizes variability inherent in commercial cultivation environments. The associated workpaper framework incorporates a calibration approach that allows for iterative refinement of savings values as additional projects are deployed. This methodology ensures that, as the program expands across a wider range of facilities, system sizes, and operational practices, updating performance assumptions to reflect real-world conditions.

Conclusions and Future Directions

This evaluation demonstrates that integrated HVAC+D systems deliver substantial performance gains in controlled environment agriculture, including a 38 percent reduction in energy use and a threefold improvement in process efficiency and space utilization. Improvements in load factor and weather-independent operation further indicate a stable and predictable demand profile, with implications for grid planning and facility performance consistency.

From a program implementation perspective, capacity-based incentive structures, such as a $600-per-ton framework informed by this study, provide a practical deployment pathway aligned with HVAC system specification and procurement.

These findings provide an empirical foundation for the continued evolution of codes, standards, and program design frameworks that incorporate system-level performance for integrated HVAC+D in high-latent-load environments. Future work should extend calibration to alternative lighting configurations and cultivar variations to refine system sizing methodologies and improve applicability across broader cultivation conditions.

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