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ADDITIONAL COMPLIANCE OPTION FOR GREENHOUSE ENVELOPE AND COVERINGS

June 23, 2026

California Energy Commission

Greenhouse industry concerns with the envelope requirements in the 2025 Energy Code prompted an investigation into alternative procedures that may be eligible for Energy Commission approval under 10-109(d) if it can be demonstrated that the proposed measure provides energy performance consistent with the intent of the current requirements.

This document provides technical analysis prepared in response to stakeholder requests received by the California Energy Commission regarding greenhouse envelope requirements. The analysis evaluates a potential compliance approach that may be considered by the Commission and identifies implementation considerations and example code language that may inform future code-cycle updates if the Commission determines broader adoption is appropriate.

Developed in collaboration with greenhouse stakeholders, the research findings contained within may help to build consensus around a practical compliance approach. The changes would introduce an additional compliance pathway without increasing the stringency of existing requirements or expanding their applicability. As such, this proposal does not require a cost-effectiveness analysis.

1. Opportunity Description and Justification

1.1 Description

One potential approach for addressing stakeholder concerns is to provide an additional compliance pathway for conditioned greenhouse envelopes. Under this approach, the existing requirement would remain unchanged while allowing compliance through a single-layer glass envelope paired with a qualifying internal greenhouse curtain system.

Under the current code, conditioned greenhouses are required to use nonopaque envelope assemblies consisting of two or more glazing layers separated by air or gas. This option would retain that requirement while adding an alternative compliance pathway allowing the use of a single-layer glass envelope when paired with a qualifying internal greenhouse curtain system.

The curtain system must meet defined material performance criteria, including a limit on air permeability, and must be equipped with automatic controls to ensure consistent operation. It also includes a functional acceptance test to verify that the curtain controls are configured for automatic operation and respond appropriately to control inputs. The Commission may also consider minimum manufacturer warranty requirements as one approach for supporting persistence of performance and helping ensure that curtain materials and associated operating components remain functional over some minimum duration. Stakeholders expressed concerns regarding mandatory warranty provisions; thus the Commission has several options to consider for supporting persistence, including warranties, acceptance requirements, maintenance provisions, or other mechanisms.

If the Commission elects to pursue future code updates, these requirements could be incorporated directly into Section 908.1.3, and Reference Nonresidential Appendix NA7, establishing a clear and enforceable alternative to the existing multi-layer glazing requirement.

If adopted as a compliance option or incorporated into a future code update, the provisions would apply to:

- Newly constructed conditioned greenhouses
- Existing greenhouses converted to conditioned greenhouses
- Additions to conditioned greenhouses.

A conditioned greenhouse is defined as a greenhouse with wood heating, mechanical heating exceeding 10 Btu/hr-ft², or mechanical cooling exceeding 5 Btu/hr-ft², and with a skylight ratio of 50 percent or greater.

Under this compliance option, projects would be able to comply with either:

- The existing requirement for two or more glazing layers separated by air or gas; or
- An envelope that has single-layer glass glazing paired with an internal greenhouse curtain system meeting the specified performance and control requirements.

If the Energy Commission were to incorporate this option, it would establish a second compliance pathway. Projects would not be required to perform energy modeling to demonstrate compliance. Instead, compliance would be achieved by meeting specified material and control requirements. This proposal uses air permeability and automatic controls as enforceable compliance criteria. The air permeability threshold is selected based on published permeability data, industry practice, available test methods, and enforceability. A separate comparative energy analysis is provided to evaluate whether a single-layer glass greenhouse with a qualifying automated thermal curtain can achieve heating performance consistent with the existing double-layer glazing requirement.

1.2 Benefits of Proposed Change

The proposed revision addresses a gap between current Energy Code requirements and established greenhouse design practices, particularly for conditioned greenhouses that rely on glass glazing systems. The intent of this proposal is to provide an alternative compliance pathway that maintains the energy-saving intent of the current code while providing additional options for conditioned greenhouse designs that combine single-layer glass glazing with an automated curtain system that decreases heat loss at night.

Under existing code, compliance is achieved using multi-layer glazing systems such as multi-wall polycarbonate or other plastic-based assemblies, which provide relatively high thermal resistance at low cost. While these systems meet the mandatory requirement, they may not be suitable for all greenhouse applications, particularly those that depend on high light transmission, durability, and long-term optical performance associated with glass glazing.

Higher-performance glass systems, such as double-layer glass, can meet both energy and operational objectives but are cost-prohibitive for some projects. As a result, the current mandatory multi-layer requirement may limit design flexibility or lead to the selection of glazing systems that do not align with project-specific operational needs.

Although alternative designs may be pursued through the Exceptional Methods process, that pathway is typically used for unique or highly customized projects and may involve additional documentation, modeling, and review. In practice, most projects rely on compliance with the mandatory provision, which limits the use of alternative envelope strategies even where technically viable.

This analysis and documentation respond directly to stakeholder requests by establishing a defined compliance pathway for greenhouses with single-layer glazing paired with thermal curtain systems. This analysis uses glass as the single-layer glazing in conjunction with movable curtains. Because single-layer glass is a common high-transmittance greenhouse covering and has relatively high thermal transmittance compared with many other single-layer greenhouse coverings, it provides a conservative basis for evaluating the proposed glass-and-curtain compliance pathway. The analysis supporting this proposal indicates that this alternative pathway can maintain the energy-saving intent of the current double-layer glazing requirement under the modeled assumptions.

Key benefits of providing a single-layer glass compliance pathway include:

- **Heating energy performance equivalency:** When paired with a curtain system that meets defined thermal performance and is automatically controlled, single-layer glass systems can reduce nighttime heat loss and achieve heating energy performance comparable to double-layer glazing systems under the modeled conditions used to support this proposal.
- **Improved design flexibility:** The proposal allows designers and operators to select envelope systems that better align with crop requirements, operational strategies, and facility design goals, without relying on the Exceptional Methods process.
- **Balanced performance and cost:** The proposed pathway introduces a middle-ground option between low-cost multi-layer plastic systems and higher-cost double-layer glass systems, improving feasibility for projects seeking the benefits of glass while maintaining energy performance expectations.
- **Predictable and enforceable compliance:** By defining a measurable material property and control requirements directly in the code, the proposal provides a clear and consistent compliance pathway for both designers and enforcement agencies.
- **High light transmission (ancillary benefit):** Single-layer glass typically provides higher light transmissivity than multi-layer plastic glazing systems, which can support plant growth and may reduce reliance on supplemental electric lighting under certain conditions. While reductions in lighting energy are not claimed as part of this proposal, this represents a potential secondary benefit.
- **Durability and long-term performance:** Glass glazing is generally more resistant to ultraviolet degradation and environmental wear compared to plastic materials, contributing to longer service life and more stable optical performance over time.

By introducing a compliance pathway that better aligns code requirements with real-world greenhouse design practices, this option would reduce practical and financial barriers to high-performance greenhouse construction while maintaining the energy-efficiency intent of the Energy Code. It would also establish a framework that can be refined in future code cycles as additional data, standardized test methods, and industry practices evolve.

1.3 Background Information

1.3.1 Nighttime Heat Loss in Greenhouses

Greenhouses experience their highest heating demand during nighttime periods, when solar gains are absent and outdoor temperatures are lower. In these conditions, heat is lost through the greenhouse envelope via radiative, conductive, and convective heat transfer. Reducing nighttime heat loss is therefore a primary strategy for improving greenhouse energy efficiency.

Radiative heat transfer is a significant component of nighttime losses. Interior surfaces, including plants and structural elements, emit longwave infrared radiation that can be transmitted through the greenhouse covering and lost to the sky. Single-layer glazing provides limited resistance to this radiative transfer, allowing a substantial portion of longwave radiation to escape. Double-layer glazing reduces these losses by introducing an additional barrier and, in some cases, reflective or low-emissivity surfaces.

Conductive and convective heat transfer also contribute to overall heat loss. Single-layer glazing has relatively high thermal transmittance, allowing heat to pass readily from the conditioned interior to the exterior environment. Multi-layer glazing systems reduce conductive heat transfer by incorporating air or gas layers that provide additional thermal resistance (Bartok, 2001).

Because these heat loss mechanisms are most pronounced during nighttime operation, strategies that reduce radiative and conductive losses during these periods can significantly lower heating energy demand. The proposed use of internal greenhouse curtain systems is intended to address these nighttime losses by introducing a temporary thermal barrier within the greenhouse envelope.

1.3.2 Daytime Heat Gains in Greenhouses

During daytime operation, greenhouse cooling loads are dominated by solar radiation and latent load from crop evapotranspiration, particularly in high-solar climates like California ￼￼. Incoming shortwave radiation is absorbed by plants and interior surfaces and converted to heat, while plant transpiration adds latent moisture that must be managed to maintain suitable growing conditions. Cooling approaches vary widely depending on climate zone and crop type, ranging from natural or mechanical ventilation in cooler regions to combined ventilation and evaporative cooling systems in warmer climates, with some intensive production systems relying on mechanical cooling. Shading curtains are commonly used to limit solar heat gains and can have a larger impact on cooling demand than glazing type. Differences in evapotranspiration rates across crop types further influence cooling requirements, contributing to a wide range of operating conditions across greenhouse facilities.

1.3.3 Overview of Greenhouse Curtain Systems

Greenhouse curtain systems are interior retractable assemblies installed below the roof structure. When deployed, they form a barrier between the growing space and the greenhouse glazing, reducing heat transfer and modifying the greenhouse microclimate. Curtains are typically operated automatically based on environmental conditions such as time of day, temperature, or solar radiation. See Figure 1 for an example of a gutter-to-gutter curtain installed below the greenhouse roof (attic) space, illustrating its position relative to the glazing and growing area.

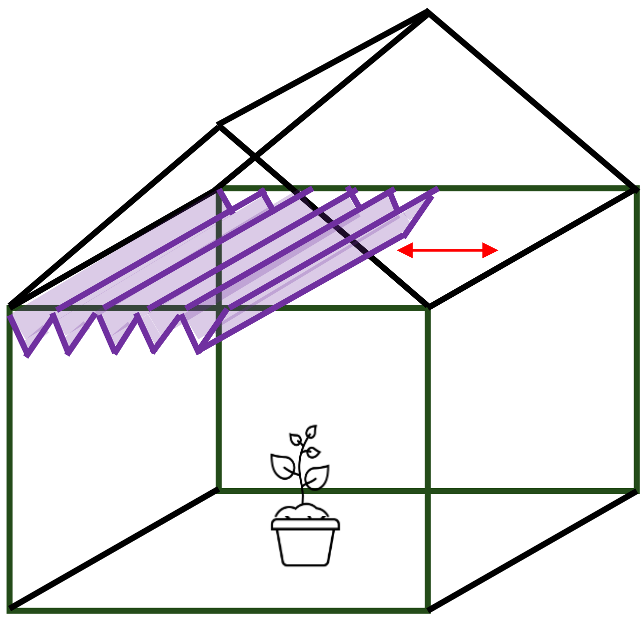

Figure 1. Illustration of a gutter-to-gutter curtain installed below the greenhouse roof (attic) space.

Curtain systems designed for energy retention function by reducing radiative, conductive, and convective heat transfer. When closed, the curtain creates an insulating air layer between the curtain and the glazing, reducing conductive and convective heat loss. In addition, curtain materials with low emissivity or reflective (e.g., aluminized) surfaces can reduce radiative heat loss by reflecting longwave infrared radiation back toward the growing space (Geelen, Voogt, & van Weel, 2018).

A wide range of curtain products is available; however, only certain types are intended for thermal performance. These include:

- **Energy Screens (Thermal Curtains):** Closed-weave or low-permeability materials designed specifically to reduce nighttime heat loss. These products are often characterized by manufacturer-reported energy performance metrics.
- **Dual Purpose (Shade & Energy) Screens:** Systems that provide solar shading during the day and thermal resistance when deployed at night.
- **Blackout / Light Abatement Curtains:** Primarily used for photoperiod control but often constructed with multilayer or low-permeability materials that also provide thermal insulation.

Curtains designed solely for daytime shading are not intended to provide significant thermal resistance and are not the focus of this proposal. Manufacturer-reported properties, such as air permeability and emissivity, provide a practical basis for identifying curtain systems capable of reducing nighttime heat loss.

1.3.4 Thermal Performance and Energy Impacts

Greenhouse curtain systems reduce nighttime heat loss by limiting radiative, conductive, and convective heat transfer between the greenhouse interior and exterior. As described in the California Electronic Technical Reference Manual (eTRM), thermal curtains reduce heat loss by:

1. Trapping an insulating air layer between the curtain and glazing
2. Reducing convective heat transfer
3. Reflecting longwave radiant heat back toward the growing space

Curtain materials play an important role in overall performance. Curtains with low-emissivity or reflective surfaces can significantly reduce radiative heat loss by reflecting longwave infrared radiation. Published studies indicate that such materials can reflect approximately 66-83 percent of outgoing longwave infrared radiation (Geelen, Voogt, & van Weel, 2018).

Air permeability is another key characteristic, as lower permeability reduces convective heat transfer. Lower permeability reduces air movement through the curtain, limiting convective heat transfer and improving overall thermal performance (Rabiu & Wook-Ho, 2022). Air circulation and pressure effects (e.g., from fans) can be addressed through the air permeability property, which governs airflow through the curtain material; low-permeability materials restrict this airflow and maintain thermal performance under typical operating conditions. When combined with the insulating air layer formed during deployment, these properties contribute to reduced heat transfer through the greenhouse envelope.

The energy impacts of curtain systems depend on climate, curtain type, and operating strategy. Industry sources and grower experience commonly report reductions in annual heating energy use on the order of 20 to 40 percent when thermal curtains are properly deployed (Bayles, 2021). While actual performance varies, these reported savings demonstrate the potential for curtain systems to significantly reduce heating demand during nighttime conditions.

For comparison, the thermal performance of glazing systems is commonly described using the U-value, which represents the rate of heat transfer through a material or assembly per unit area and per unit temperature difference between indoors and outdoors. Lower U-values indicate better insulating performance, meaning less heat is lost through the material.

Single-layer glazing systems, including single-pane glass, have relatively high U-values (typically on the order of 1.1–1.2 Btu/hr-ft²-°F), indicating that they allow heat to pass readily from the conditioned interior to the exterior environment. As a result, single-layer glass performs poorly as an insulating material and can contribute to significant heat loss during nighttime conditions when temperature differences between indoors and outdoors are greatest.

In contrast, double-layer glazing systems reduce heat transfer by incorporating an air or gas layer between glazing layers, which acts as insulation and lowers the overall U-value (typically to approximately 0.5–0.7 Btu/hr-ft²-°F) (Bartok, 2001).

The proposed compliance pathway addresses the higher heat loss associated with single-layer glass by incorporating an internal greenhouse curtain system that is deployed during nighttime periods. When closed, the curtain system reduces effective heat transfer through the envelope by limiting radiative, conductive, and convective losses and creating a thermally insulating layer of air between the glass and curtain, thereby improving overall thermal performance during the periods when heating demand is highest.

During daytime operation, greenhouse cooling requirements are driven primarily by solar radiation and crop evapotranspiration and vary widely by climate zone, crop type, and cooling strategy. Ventilation, evaporative cooling, mechanical cooling, and shading practices differ substantially across facilities, and shading systems can have a greater influence on cooling demand than glazing configuration. Many facilities already employ dual-purpose curtain systems that provide both shading and thermal benefits, which may yield additional energy savings. Given this variability, cooling impacts are not well suited to the development of a single mandatory requirement. In contrast, nighttime heat loss is directly influenced by envelope performance and provides a more consistent and technically supportable basis for evaluating greenhouse envelope measures across greenhouse types, crop types, and climate zones.

1.3.5 Industry Adoption and Market Availability

Greenhouse curtain systems are widely used in commercial greenhouse operations and are considered a mature and well-established technology. They are compatible with both new construction and retrofit applications and are commonly integrated with automated environmental control systems.

Industry guidance documents, including ANSI/ASAE EP406.4 (Heating, Ventilating, and Cooling Greenhouses) and publications from the National Greenhouse Manufacturers Association (NGMA), recognize the role of thermal screens and curtain systems in improving greenhouse energy performance (ASAE, 2003; NGMA, 1998; NGMA, 2010).

Curtain systems are used across a range of greenhouse types and climates, and products are available from multiple manufacturers with varying performance characteristics, including differences in emissivity, air permeability, and durability. This level of market availability supports the feasibility of incorporating curtain systems into a compliance pathway.

The widespread adoption of curtain systems, combined with their demonstrated role in reducing heating energy use, supports their inclusion as part of an alternative compliance approach for conditioned greenhouse envelopes.

2. Technical and Market Feasibility

2.1 Test Methods

Evaluating the thermal performance of greenhouse curtain systems presents unique challenges, as performance depends on both material properties and installation conditions. While several research institutions and manufacturers have developed methods to characterize curtain performance, there is currently no single standardized test method used across the greenhouse industry to directly measure the thermal performance of curtain-glazing assemblies.

Given this variability, this proposal focuses on material properties that are both measurable using established test methods and directly related to thermal performance, rather than relying on a single assembly-level metric such as U-factor. This approach supports consistency, comparability, and enforceability within a mandatory compliance framework.

The key performance properties relevant to greenhouse curtain systems include:

- **Radiative properties:** Radiative heat transfer through greenhouse curtain systems is influenced by multiple material properties, including emissivity, thermal infrared transmissivity, and reflectivity. Lower emissivity and lower transmissivity materials reflect a greater portion of outgoing infrared radiation back toward the greenhouse interior, reducing radiative heat loss, but neither alone can characterize radiative performance.

- **Air permeability:** Air permeability characterizes the rate of airflow through a material under a specified pressure differential. Lower permeability reduces convective heat transfer by limiting air movement through the curtain.
- **Assembly thermal performance U-factor:** The overall insulating performance of a curtain system depends on both material properties and installation conditions, including air space, airflow, and curtain placement. While U-factor is a useful indicator of system-level performance, it is typically not measured directly for curtain materials and is instead derived through modeling or full-system testing.

Established ASTM test methods are available to evaluate some relevant material properties of curtain systems:

- **Emissivity:** ASTM E408 or ASTM E434 can be used to characterize emissivity as an individual material property (ASTM, 2025; ASTM, 2020).
- **Air permeability:** ASTM D737 (ASTM, 2023)

Stakeholder engagement with curtain manufacturers indicates that, while standardized test methods are not currently widely used within the greenhouse industry, manufacturers are generally able to characterize material properties such as emissivity and air permeability using established laboratory procedures. In practice, performance data is often reported using manufacturer-specific methods or derived through project-specific modeling, which can limit comparability across products.

Although emissivity is relevant to radiative heat transfer, the available literature indicates that greenhouse curtain energy performance depends on the combined effect of emissivity and thermal infrared transmissivity, together with convective and moisture-related effects. The Wageningen University & Research (WUR) curtain study found that the highest energy savings are associated with curtains that combine low emissivity and low thermal infrared transmissivity, and specifically recommends reporting emissivity together with thermal infrared transmissivity and reflectivity rather than relying on emissivity alone as a basis for comparison (Hemming, Baeza, Mohammadkhani, & van Breugel, 2017). Because no standardized or practical method is currently available to establish enforceable requirements based on combined radiative properties, this proposal does not include a standalone emissivity requirement.

The use of established ASTM test methods for emissivity and air permeability provides a pathway toward consistent, third-party verifiable performance metrics that can be applied uniformly across products. While this represents a shift from current industry practice, it aligns with approaches used in related building technologies, such as window attachments evaluated under the Attachments Energy Rating Council (AERC) framework (AERC, 2026).

Air permeability is included as a key performance metric because it directly influences convective heat transfer through the curtain material. Lower air permeability reduces airflow through the curtain layer, limiting convective heat loss and improving the effectiveness of the insulating air space formed when the curtain is deployed.

Air permeability of curtain materials can be measured using established textile test methods, including ASTM D737 (Standard Test Method for Air Permeability of Textile Fabrics) or ISO 9237 (ASTM, 2023; ISO, 2023). These methods measure airflow per unit area under a defined pressure differential and are widely used for porous textile materials. They are appropriate for greenhouse curtain fabrics, which are typically woven or knitted materials.

Assembly-level air leakage test methods, such as ASTM E283, are not used for this purpose, as they are designed to evaluate air leakage of complete assemblies rather than intrinsic material properties (ASTM, 2026).

Establishing standardized test methods in code also supports improved transparency and comparability for code officials, designers, and project teams, reducing reliance on non-uniform manufacturer data.

Because assembly-level thermal performance depends on both material properties and installation conditions, and because no standardized and widely adopted method currently exists to determine the U-factor of greenhouse curtain-glazing systems in a manner suitable for code compliance, this proposal does not rely on a U-factor requirement for either the curtain material or the curtain-glazing assembly.

Instead, the proposal uses a simplified compliance approach based on:

- A measurable material property related to convective performance (air permeability); and
- Required automated control strategies to ensure consistent deployment.

This approach balances technical rigor with practical enforceability, while allowing flexibility in system design and installation. As standardized methods for evaluating whole-system performance continue to evolve, future code cycles may consider incorporating additional metrics or test procedures.

At the Utility-Sponsored Stakeholder Meeting held on March 5, 2026[1], all four participants representing greenhouse manufacturers reported using a combination of international standards and internal test procedures to evaluate greenhouse curtains. Follow-up discussions with the two largest manufacturers confirmed the use of two methods commonly employed across the industry to measure thermal curtain properties:

1. A method developed by the Netherlands Organisation for Applied Scientific Research (TNO) and Wageningen UR for measuring thermal curtain properties and their impact on greenhouse U-values (Baart de la Faille, 2009)
2. A research-based evaluation method documented by Wageningen University and Research to characterize the energy-saving performance of greenhouse curtain materials (Hemming, Baeza, Mohammadkhani, & van Breugel, 2017)

In follow-up discussions, a North American general manager noted that a key challenge is the lack of standardized testing approaches, resulting in variability in how greenhouse curtain energy savings are calculated.

Compliance with the air permeability requirement is demonstrated through manufacturer documentation based on standardized test methods.

2.2 Installation Considerations

Installation practices can influence the thermal performance of greenhouse curtain systems. In particular, air leakage at curtain edges, seams, penetrations, and transitions can reduce overall effectiveness by allowing heat to bypass the curtain layer (Goldammer, 2025). The magnitude of these effects depends on greenhouse geometry, structural constraints, and system configuration.

In practice, greenhouse curtain systems are designed and installed using a variety of approaches to manage air movement and improve thermal performance. These may include overlapping curtain panels, track-mounted systems, flexible edge seals, and other installation-specific solutions. The effectiveness of these strategies varies based on greenhouse design, curtain type, and operational requirements.

Stakeholder feedback indicates that installation practices are highly variable across projects and are often tailored to specific greenhouse configurations, crop types, and

[1] Notes from the March 5, 2026 Utility-Sponsored Stakeholder meeting are available here: https://title24stakeholders.com/wp-content/uploads/2026/03/3.5.2026-T24-Stakeholder-Meeting-Notes.pdf

operational strategies. As a result, mandatory requirements for features such as edge sealing or gap tolerances would be difficult to standardize, verify, and enforce within a code compliance framework.

Given this variability, installation details are more appropriately addressed through manufacturer design guidance and project-specific engineering rather than mandatory code requirements. This approach reflects current industry practice and avoids introducing requirements that may not be consistently applicable across greenhouse designs. For compliance purposes, curtain systems must be installed as continuous, retractable assemblies that provide broad coverage of the conditioned growing area when fully deployed, rather than partial or localized curtain segments.

By limiting mandatory requirements to characteristics that can be consistently measured and verified, the proposed approach supports enforceability while maintaining flexibility for a range of greenhouse configurations.

Responses to a stakeholder poll at the Utility-Sponsored Stakeholder Meeting on March 5, 2026 indicate that gap sealing is commonly considered in greenhouse curtain design, with only 7 percent of respondents reporting that it is not considered.

2.3 Controls

Automated controls are essential to achieving consistent and energy-efficient operation of greenhouse curtain systems. Because the thermal performance of curtains depends on their deployment during periods of heat loss, particularly nighttime conditions, reliance on manual operation would not provide reliable or consistent energy savings.

Industry practice indicates that greenhouse curtain systems are commonly integrated with automated environmental control systems that respond to time of day or environmental conditions such as temperature and solar radiation. These control strategies are used to ensure that curtains are deployed when thermal performance benefits are highest and retracted when solar gains are desirable.

Acceptable control strategies may include:

- Time-based controls (e.g., scheduled or astronomical clock-based operation)
- Sensor-based controls (e.g., temperature, light level, or solar radiation)
- Integrated control systems that incorporate multiple environmental inputs

These approaches are widely used in commercial greenhouse operations and are compatible with existing greenhouse control platforms.

To support consistent performance, curtain systems should operate in automatic mode, defined as operation based on predefined schedules or sensor inputs consistent with typical greenhouse operation, rather than crop- or climate-specific optimization. Automated operation should occur during all routine operating periods and is not expected to occur during maintenance activities, emergency events, or intentional manual intervention. While manual override capability may be necessary for operational flexibility, systems should be configured to return to automatic operation after a defined period to maintain intended performance.

In some applications, curtain operation may be adjusted to manage humidity or other environmental conditions, including partial deployment or temporary ventilation strategies. These functions are typically implemented through automated control systems using environmental sensors and do not require manual intervention.

Requiring automated controls ensures that curtain systems provide consistent and repeatable thermal performance, rather than relying on occupant behavior, which is critical for establishing a reliable compliance pathway. These requirements, together with the acceptance test, are intended to ensure that curtain systems operate automatically under normal conditions and do not rely on manual intervention to achieve energy savings.

2.4 Costs

This section provides high-level cost information to support an understanding of market feasibility and relative cost differences between greenhouse envelope options. Consistent with the scope of this proposal, this is not a cost-effectiveness analysis, but rather a summary of available data on typical installed costs and maintenance considerations. Because this recommended update provides an additional compliance option and does not increase the stringency of the code, a full cost-effectiveness analysis is not included.

Greenhouse curtain systems are widely used in commercial applications and are generally considered a moderate-cost measure for reducing heating energy use. Available data from utility programs and industry sources (eTRM, 2026).

Curtain systems include both the curtain material and associated mechanical components, such as drive motors, cables, tracks, and control systems. These systems require periodic maintenance and eventual replacement, with replacement frequency dependent on material type, environmental conditions, and operating practices. While reported lifetimes vary, stakeholders indicate that curtain materials and mechanical components are typically replaced on a multi-year cycle consistent with standard greenhouse maintenance practices. Available literature and field observations suggest greenhouse curtain fabrics may remain in service for up to approximately 10 years, while manufacturer warranties are typically limited to around 5 years (Ludvig Svensson, n.d.; Ludvig Svensson, 2026; Ridder, 2026; Gulf Agriculture News Desk, n.d.).

Poll data from the Utility-Sponsored Stakeholder Meeting on March 5, 2026 show that greenhouse curtain fabric replacement intervals in California span a range, with 1 of 11 respondents reporting five years or fewer, 5 of 11 reporting 5–10 years, and 5 of 11 reporting 15–20 years. For curtain hardware motors, respondents reported prompt replacement after failure, with 55% indicating replacement within a month, 27% within a year, and 18% immediate replacement.

For comparison, rigid glazing systems such as glass generally have higher installed costs. Industry sources indicate that single-layer glass systems may cost on the order of $3 per square foot, while double-layer glass systems may cost approximately $6 per square foot or more, depending on system specifications and installation complexity (RII, 2023). These values are intended as order-of-magnitude estimates and may vary based on project-specific factors.

These cost differences highlight the economic tradeoffs associated with current compliance options. Multi-layer plastic glazing systems can provide a relatively low-cost pathway to meet code requirements, with polycarbonate siding ranging from approximately $1.50 per square foot for double-wall panels to as much as $8 per square foot for higher-performance, multi-wall configurations (RII, 2023). In contrast, double-layer glass systems offer improved performance but at substantially higher cost. The proposed compliance pathway—single-layer glass combined with a high-performance curtain system—provides an intermediate option that can reduce overall system cost relative to double-layer glass while maintaining thermal performance consistent with the intent of the code.

Stakeholder feedback indicates that the incremental cost of adding a curtain system to a single-layer glass greenhouse is generally lower than the cost premium associated with upgrading from single-layer to double-layer glass.

By introducing an additional compliance pathway that leverages a moderate-cost, widely available technology, this proposal improves the feasibility of compliance for projects seeking to use glass glazing systems without requiring higher-cost envelope assemblies.

Stakeholder discussions and analysis of this proposal highlighted the importance of persistence of performance over time. One potential approach the Commission could consider is the use of minimum warranty requirements for curtain materials, controls, and associated operating components. Such requirements could provide a mechanism for supporting persistence of the compliance pathway and helping ensure that key system components remain functional over time. However, stakeholders expressed concerns regarding mandatory warranty requirements, noting that warranty durations may not align with actual service life, replacement practices, or current industry offerings. The Commission may wish to consider whether persistence objectives are better addressed through warranty provisions, acceptance requirements, maintenance documentation, other compliance mechanisms, or a combination thereof. If warranty requirements are ultimately included, their purpose would be to support persistence of the compliance pathway over time and provide assurance that key components continue to operate as designed under normal conditions. Similar persistence considerations are reflected in other areas of Title 24 where long-term performance depends on the continued operation of installed systems. If the Commission elects to include warranty requirements as part of a future compliance pathway, stakeholders indicated that warranty duration, covered components, and alignment with typical replacement cycles would require further consideration.

Survey results from the Utility-Sponsored Stakeholder Meeting on March 5, 2026 show differing warranty expectations for longer-lasting thermal curtains and automated controls. Most respondents reported longer warranties for controls, with 55% indicating 10 years or longer for controls and 5 years for curtains. An additional 27% reported 5-year warranties for both components, while 18% reported longer warranties for curtains than controls.

2.5 Market Availability and Feasibility

Greenhouse curtain systems are widely available and are commonly used in commercial greenhouse operations, including applications that require temperature control and energy management. These systems are offered by multiple manufacturers and are available in configurations suitable for a range of greenhouse types, sizes, and operational needs.

Curtain products with varying performance characteristics are commercially available, including differences in emissivity, air permeability, durability, and integration with control systems. Many of these products are designed specifically for energy retention and are compatible with automated environmental control platforms commonly used in modern greenhouse facilities.

Stakeholder engagement conducted as part of this proposal confirmed that curtain systems are a mature and well-established technology. Manufacturers and industry experts indicated that products capable of meeting defined performance criteria, such as low air permeability and compatibility with automated controls, are currently available or can be readily provided. In addition, stakeholders indicated that integrating curtain systems with automated controls is standard practice in commercial greenhouse design.

These systems are applicable to both new construction and retrofit installations, including existing greenhouses that are converted to conditioned operation. This flexibility supports the use of curtain systems across the range of project types covered by this proposal.

Multiple manufacturers serving the North American greenhouse market currently offer curtain systems with performance characteristics consistent with those described in this proposal.

While standardized methods for evaluating curtain system performance are still evolving, the underlying technologies, materials, and control systems are well established and widely deployed. The combination of demonstrated market availability, established use in commercial practice, and compatibility with automated controls supports the technical and market feasibility of using greenhouse curtain systems as part of a compliance pathway.

3. Selection of Curtain Performance Metrics

The proposed air permeability requirement is intended to identify greenhouse curtain materials capable of reducing nighttime heat loss to a degree that supports heating energy performance comparable to that of the baseline double-layer glazing configuration under the modeled conditions.

This section explains the rationale for selecting air permeability and automatic controls as the enforceable compliance criteria for the proposed pathway. The air permeability threshold is not derived directly from the energy model; rather, it is based on published permeability data, industry practice, available test methods, and the need for a practical and enforceable code requirement. The comparative energy analysis in Section 4 evaluates whether the proposed pathway can provide heating energy performance consistent with the existing double-layer glazing requirement under the modeled assumptions.

The modeling results demonstrate that a single-layer glazing system with an internal curtain can reduce nighttime heat loss sufficiently to achieve heating energy performance comparable to that of a double-layer glazing system under the modeled conditions. This target level of performance reflects the combined effects of reduced longwave radiative heat loss, decreased convective heat transfer, and the formation of an insulating air layer when the curtain is deployed.

Because whole-system thermal performance of curtain-glazing assemblies is not currently standardized for code compliance, the proposal does not directly regulate assembly U-factor. Instead, it uses a measurable material property, air permeability, as a practical screening metric for convective performance, together with control requirements intended to ensure operation consistent with the energy-saving function of the proposed compliance pathway.

The analysis does not assume that any single material property fully determines total system performance. Rather, these properties are used as practical, measurable indicators of material characteristics that are most directly related to nighttime heat retention and can be consistently verified within a mandatory compliance framework.

The air permeability requirement, together with the automatic control requirement, is intended to identify greenhouse curtain systems that are consistent with those shown in the analysis to reduce nighttime heat loss and support heating energy performance comparable to the baseline double-layer glazing configuration.

3.1 Why Assembly-Level U-factor Is Not Proposed

Because whole-system thermal performance of curtain-glazing assemblies is not currently standardized for code compliance, the proposal does not directly regulate assembly U-factor. Instead, it uses a measurable material property (air permeability) as a practical screening metric for convective performance, together with control requirements to ensure operation consistent with the compliance pathway.

While U-factor is a useful indicator of overall thermal performance, it is not currently a practical metric for code compliance in this application for several reasons:

- No standardized and widely adopted test method exists for determining the U-factor of greenhouse curtain systems or curtain-glazing assemblies under representative conditions.
- Curtain system performance depends strongly on installation configuration, including air gaps, sealing, and placement relative to the glazing.
- Curtain operation is dynamic and dependent on controls, meaning that a single steady-state U-factor does not fully represent real-world performance.

Because of these limitations, U-factor is used conceptually in the analysis but is not used as a code requirement. Instead, this proposal uses a simplified compliance approach based on identifying curtain systems that are consistent with those shown to provide energy savings in the analysis.

Stakeholder engagement and follow-up discussions with manufacturers indicate that energy performance of greenhouse curtain systems is often evaluated using model-based methods that estimate heat transfer and energy savings based on multiple input parameters. Examples include methods developed by the Netherlands Organisation for Applied Scientific Research (TNO) and Wageningen University & Research, which use combinations of measured material properties, assumed installation conditions, and modeled heat transfer relationships to estimate effective U-values or energy savings (Hemming, Baeza, Mohammadkhani, & van Breugel, 2017; Baart de la Faille, 2009).

While these methods provide useful insight into relative performance and are widely used within the greenhouse industry, they are not currently suitable for code compliance. These approaches rely on multiple inputs, including air permeability, radiative properties, installation configuration, and operational assumptions, that are not consistently measured using standardized test methods. In addition, different modeling approaches may produce different results depending on assumptions and boundary conditions, leading to variability in reported performance.

Because of this lack of standardized, repeatable, and verifiable testing and calculation procedures, energy performance metrics derived from these methods, such as assembly-level U-factor or percent energy savings, cannot be reliably used as enforceable code requirements. For these reasons, this proposal does not adopt a model-based or energy-savings-based compliance metric, and instead uses a simplified mandatory approach based on measurable material properties and control requirements.

3.2 Radiative Performance: Emissivity and Transmissivity

Radiative heat transfer is a significant component of nighttime heat loss in greenhouses. Curtain systems can reduce radiative losses by reflecting longwave infrared radiation back toward the greenhouse interior.

However, radiative performance depends on the combined effects of emissivity, thermal infrared transmissivity, and reflectivity. Available research shows that curtains with both low emissivity and low transmissivity provide the highest energy savings and recommends evaluating these properties together rather than individually (Hemming, Baeza, Mohammadkhani, & van Breugel, 2017).

Because no standardized and practical method is currently available to define enforceable requirements based on combined radiative properties, this proposal does not include a standalone emissivity requirement. Radiative performance is instead addressed indirectly through the modeled comparative analysis and the requirement that qualifying curtains be of types commonly used for thermal energy savings.

Radiative performance is addressed implicitly through the analysis but is not directly regulated through requirements in this proposal. As standardized methods for combined radiative performance metrics become available, future code cycles may evaluate whether explicit radiative performance requirements can be incorporated.

Thermal curtain materials commonly incorporate reflective or metallized layers, such as aluminized films, coatings, or composite constructions, which contribute to reduced radiative heat loss. These characteristics are typical of commercially available “energy screens” designed for thermal performance. While developing this recommendation, the Statewide CASE Team considered whether requirements based on material construction, such as requiring aluminized or reflective layers, could be used to identify qualifying products. However, these approaches were not included because they would prescribe specific material designs rather than performance-related characteristics, could exclude alternative or emerging technologies, and would be difficult to standardize and enforce within a code compliance framework.

As a result, the suggested compliance option does not include construction-based requirements for radiative performance and instead relies on a combination of material screening through air permeability and control requirements to ensure overall system performance.

3.3 Convective Performance: Air Permeability

Air permeability is used as a screening metric to distinguish thermal (energy-saving) curtain materials from non-thermal shading or ventilation-oriented materials. Air permeability is included to address convective heat transfer through the curtain material. Heat transfer through greenhouse curtains occurs through a combination of conduction, radiation, and convection, with convective heat transfer strongly influenced by airflow through the curtain layer.

Airflow through greenhouse curtain materials can be described using porous media flow theory (Darcy's Law), in which the permeability of the material governs the magnitude of airflow and associated convective heat transfer (Kalazic, Badrov, Schwarz, & Brnada, 2023). Lower permeability reduces air exchange between the greenhouse interior and the space above the curtain, suppressing convective heat loss and enabling the curtain to function as an effective thermal barrier (Lopez, Molina-Aiz, Valera, & Pena, 2016; Teitel, Haim, & Tanny, 2009).

Materials with lower air permeability restrict airflow between the greenhouse interior and the space above the curtain, reducing convective heat loss and enabling the curtain to function as an effective thermal barrier. In contrast, materials with higher air permeability allow increased airflow through the curtain, reducing or eliminating its effective thermal resistance.

Published research and greenhouse climate studies indicate that thermal (energy-saving) curtain materials are characterized by low intrinsic permeability, while open-structure shading materials exhibit significantly higher permeability and provide minimal resistance to airflow. Measurements of greenhouse screens and curtains reported by Miguel et al. (1997) show permeability values for thermal curtains on the order of 10^{-11} m^2, with observed values ranging approximately from 2×10^{-11} to 9×10^{-11} m^2 (Miguel, van de Braak, & Bot, Analysis of the airflow characteristics of greenhouse screening materials, 1997). These results indicate that materials intended to provide thermal resistance exhibit low permeability relative to more open or ventilation-oriented curtain materials. Lower permeability is associated with reduced airflow and improved temperature retention in greenhouse environments (Lopez, Molina-Aiz, Valera, & Pena, 2016).

The selected air permeability threshold is intended to distinguish between curtain materials that function as thermal barriers and those that primarily serve shading or light-diffusion functions. At lower permeability levels, convective airflow is sufficiently restricted to allow the formation of an effective insulating layer. At higher permeability levels, airflow increases significantly, reducing thermal effectiveness.

The permeability threshold of $1\times10^{-11} m^2$ can be related to standard textile air permeability measurements (ASTM D737 / ISO 9237) using Darcy's law. Assuming typical greenhouse curtain thicknesses on the order of 0.3–1.0 mm and standard air viscosity (~1.8×10^{-5} Pa·s), this intrinsic permeability corresponds to an airflow rate on the order of 5–50 $L/m^2\cdot s$ at 100–125 Pa, with 50 $L/m^2\cdot s$ representing a conservative upper bound for qualifying thermal curtains.

ASTM D737 and ISO 9237 are repeatable methods for measuring airflow through porous textile materials and are appropriate for greenhouse curtain fabrics, which are typically woven or knitted materials. These methods quantify material-level airflow resistance under controlled pressure differentials and therefore provide a practical basis for an enforceable proxy requirement.

Based on the analysis and available data, this proposal establishes a maximum air permeability threshold of 50 $L/m^2\cdot s$, as measured in accordance with ASTM D737 or ISO 9237 at a pressure differential of 125 Pa. The selected value represents an upper bound within the range of air permeability values reported for thermal greenhouse curtains in the literature and is intended to capture commercially available products designed for energy retention.

This value is intended to identify curtain materials that provide meaningful resistance to airflow and are capable of functioning as thermal barriers under typical greenhouse operating conditions. The recommended threshold corresponds approximately to intrinsic permeability values observed in thermal greenhouse screens and curtains and is consistent with the range of performance associated with reduced convective heat loss in published studies.

For multi-layer curtain assemblies, each material layer should be evaluated individually in accordance with ASTM D737 or ISO 9237 test procedures. If any of the curtains in the assembly comply with the air permeability threshold, that layer can be used for compliance. If none of the individual curtains comply, the overall air permeability can be determined analytically. The airflow resistance is the inverse of the air permeability. The combined airflow resistance of the assembly can be determined by summing the airflow resistances of the individual layers in series. This approach is consistent with porous media flow theory based on Darcy's Law and with standard transport principles in which resistances through layered systems are additive (Bear, 1972; Incropera, DeWitt, Bergman, & Lavine, 2007; ASHRAE, 2021). Evaluating layers individually and combining them analytically will provide a transparent and repeatable method for estimating multi-layer performance, while avoiding the limitations of stacked specimen testing, which may not represent installed conditions due to compression of layers and the absence of inter-layer air gaps, and which is not consistent with the specified test procedures. Because airflow resistance through layered porous materials is additive, multiple curtain layers can collectively provide thermal performance similar to that of a single low-permeability thermal curtain. The proposed compliance calculation is intended to recognize this physical behavior while maintaining a measurable and enforceable compliance criterion.

In practical terms, the selected threshold distinguishes between:

- Thermal (energy-saving) curtains, which are designed to reduce heat loss and typically exhibit low air permeability; and
- Non-thermal shading or diffusion curtains, which are designed for light control and ventilation and typically exhibit higher air permeability and limited thermal benefit.

By selecting a threshold within the range associated with low-permeability materials, the proposal ensures that qualifying products provide meaningful resistance to convective heat transfer while maintaining a practical and enforceable requirement based on measurable material properties. Air permeability is used as a screening criterion to identify thermal curtain materials, rather than as a direct predictor of energy performance.

3.4 Threshold Selection and Application

The recommended air permeability threshold is intended to identify curtain materials that are consistent with thermal (energy-saving) curtains used in practice and represented in the analysis.

The selected air permeability is not derived directly from the modeling analysis, but is instead based on:

- Published data on the physical characteristics of thermal greenhouse curtains
- Industry practice distinguishing thermal screens and curtains from shading or ventilation screens and curtains
- The need for a practical, measurable, and enforceable criterion for code compliance

The selected threshold is intended to ensure that installed curtain systems are of a type that provides meaningful resistance to airflow and is consistent with the thermal curtain systems evaluated in the analysis.

Stakeholder engagement also indicated that manufacturers and industry organizations are actively working to develop standardized methods for characterizing the thermal performance of greenhouse curtain systems, including approaches to determine assembly-level U-factor. While these methods are not yet sufficiently standardized for use in mandatory code, they may provide a basis for future refinement of performance requirements.

The approach used in this proposal is intended to provide a practical and enforceable framework based on currently measurable material properties, while remaining compatible with future incorporation of standardized assembly-level performance metrics as they become available.

The threshold is intended to identify curtain materials that, when combined with automated controls, are likely to provide meaningful reductions in nighttime heat loss consistent with the modeled energy performance. Compliance with this measure is achieved by meeting the specified air permeability and control requirements. No project-specific modeling or performance calculation is required.

4. Energy Performance Evaluation of the Proposed Compliance Pathway

4.1 Overview

The Statewide CASE Team evaluated whether a single-layer glass greenhouse paired with a qualifying automated thermal curtain system could provide heating energy performance consistent with the current double-layer glazing requirement. The modeling analysis is not used to derive the air permeability threshold; rather, it is used to evaluate the expected energy performance of the proposed compliance pathway under consistent assumptions.

The evaluation used a spreadsheet-based model to compare the thermal performance of three greenhouse envelope strategies:

1. Single-layer glazing
2. Double-layer glazing
3. Single-layer glazing and an internal greenhouse curtain system

The purpose of this analysis is to compare the relative impact of these configurations on greenhouse heating demand under consistent operating assumptions. The analysis focuses on heat transfer through the greenhouse envelope and resulting heating energy requirements, rather than full building system performance or equipment sizing.

The evaluation is structured as an hourly energy-balance model using a common greenhouse prototype and weather data from CEC 2028 Weather Files. This approach allows for a consistent comparison of envelope performance across configurations, with particular emphasis on nighttime conditions when heat loss is greatest.

In addition to evaluating discrete envelope configurations, the model is used to evaluate how variations in curtain system performance, such as effective thermal resistance and radiative properties, affect overall heating demand. The objective of this analysis is to evaluate whether a single-layer glazing system paired with a thermal curtain can achieve heating energy use comparable to that of a double-layer glazing system under consistent operating assumptions.

4.2 Assumptions

The analysis is based on a prototypical greenhouse configuration and a consistent set of operating assumptions applied across all scenarios. These assumptions are intended to isolate the impact of envelope characteristics on heating energy use. Cooling impacts are not evaluated because nighttime heating savings provides the most appropriate representation of energy impacts from a thermal curtain requirement, and cooling impacts vary significantly by climate zone, crop type, and shading strategy.

The analysis draws on inputs from prior greenhouse energy modeling efforts used in earlier code development cycles, including models developed using eQuest. The eQuest-based modeling framework evaluated only nighttime heating energy impacts associated with greenhouse curtain deployment and did not assess daytime heat gains or cooling energy impacts. Where appropriate, selected parameters—such as greenhouse geometry, operating conditions, and baseline material properties—were adapted from these prior models to maintain consistency with established assumptions. These inputs were reviewed and updated as needed to better reflect current greenhouse design practices and the objectives of this analysis.

The USDA Virtual Grower 3 (VG3) tool was also evaluated as a modeling tool. Evaluation of the VG3 inputs indicated that thermal curtain performance is represented using only qualitative inputs describing curtain material quality and installation quality. The model does not allow users to specify curtain permeability, thermal resistance, emissivity, infrared reflectivity, deployment schedules, or control strategies. In addition, VG3 is intended as a simplified decision-support tool and does not perform a detailed greenhouse heat balance, incorporate ASHRAE-based heat transfer calculations, or account for thermal mass effects. As a result, while VG3 provides useful directional guidance regarding greenhouse energy conservation measures, it was not considered suitable as a validation benchmark for the detailed physics-based energy modeling conducted in this study.

Several updates were made to the original eQuest-based assumptions to better align the analysis with the intended representation of nighttime curtain operation. Airflow was revised from a 100 percent outside air system with autosized fans to a constant 1.1 air changes per hour. This change reflects SME input indicating that nighttime airflow rates vary significantly depending on greenhouse conditions (e.g., crop type, growth stage, location), with airflow primarily used for latent load removal from plant evapotranspiration (dehumidification) and typically ranging from 0.5 to 2.5 air changes per hour; the selected 1.1 air changes per hour represents a mid-range value that includes both infiltration and intentional ventilation, and 100 percent outside air is therefore not representative of typical nighttime operation. The selected value results in identical fan sizing and energy use for both baseline and curtain cases. The HVAC representation was also updated to reflect nighttime conditions in which the volume below the deployed curtain is conditioned while the volume above the curtain is not, rather than conditioning the space above the curtain. Under this approach, nighttime heating energy demand is determined using an overall greenhouse energy balance, with heat supplied directly to the occupied volume below the curtain rather than assuming a unit ventilator solely heats incoming outdoor air. Heat transfer and air exchange between the conditioned space below the curtain and the unconditioned space above are captured using an overall U-value, which is intended to reflect both conductive heat transfer and air permeability across the curtain layer.

In addition, envelope properties were revised to represent single-layer glass for the single-layer and curtain cases and double-layer glass for the double-layer case.

These assumptions provide a consistent basis for evaluating how changes in curtain system performance characteristics influence overall greenhouse heating demand.

4.2.1 Greenhouse Geometry and Configuration

The model uses a gable-style greenhouse geometry consistent with prior code development analyses. While the geometry does not represent all greenhouse designs currently in use, it provides a consistent basis for comparing envelope performance across scenarios. Greenhouse geometry assumptions are outlined in Table 1.

Table 1. Greenhouse geometry and materials

Variable	Value	Unit	Source or Notes
Form	Gable design	N/A	eQuest Model
Orientation	End walls East-West	N/A	eQuest Model, maximizes solar load
Length	256	ft	eQuest Model
Width	32	ft	eQuest Model
Wall height	16	ft	eQuest Model
Peak height	24	ft	eQuest Model
Roof angle	31.3	degrees	eQuest Model

This geometry is used consistently across all scenarios to isolate the impact of envelope configuration on thermal performance.

4.2.2 Operating Conditions and Controls

The analysis assumes typical greenhouse operating conditions, including daytime and nighttime temperature setpoints, ventilation rates, and curtain operation schedules, as outlined in Table 2.

Table 2. Setpoints, schedule, and controls

Variable	Value	Unit	Source or Notes
Daytime start	6	Hour of day	Engineering judgment, SMEs on Statewide CASE Team. Common practice for heating system operation.
Daytime end	18	Hour of day	Engineering judgment, SMEs on Statewide CASE Team. Common practice for heating system operation.
Daytime setpoint	75	Deg F	eQuest Model
Nighttime setpoint	72	Deg F	eQuest Model
Curtain controls	Time clock	N/A	Most conservative (lowest energy savings)
Furnace lockout; outdoor air temperature	75	Deg F	Matches daytime setpoint of greenhouse
Ventilation: nighttime air change rate	1.1	Air changes per hour	Common practice per CASE Team SMEs.

Curtain operation is modeled to reflect the most conservative automated control strategies, with deployment based on sunrise and sunset conditions. This assumption is consistent with standard industry practice and the control requirements described in this proposal.

4.2.3 Envelope Material Properties

The thermal and optical properties of glazing materials are based on representative values from literature and prior modeling efforts, as shown in Table 3. These values are consistent with typical clear glass properties reported in the Lawrence Berkeley National Laboratory (LBNL) software for International Glazing Database (WINDOW/IGDB) (Lawrence Berkeley National Laboratory, 2026) and ASHRAE Handbook—Fundamentals (ASHRAE, 2021) and are intended to represent commonly used baseline glazing performance rather than specific product ratings.

Table 3. Envelope material properties

Material property	Value	Unit
Single pane conductance	1.13	Btu/hr-ft^2-ºF
Single pane solar/visible transmissivity	0.85	Ratio
Single pane longwave emissivity	0.88	Ratio
Double pane conductance	0.7	Btu/hr-ft^2-ºF
Double pane solar/visible transmissivity	0.7	Ratio
Double pane longwave emissivity	0.88	Ratio

These values are intended to represent typical performance characteristics for single-layer and double-layer glazing systems and are applied consistently across scenarios.

4.2.4 Thermal Curtain Modeling Assumptions

The modeled thermal curtain case is intended to represent a commercially available energy-saving curtain system consistent with the proposed compliance pathway. The modeled curtain uses an air permeability of 50 L/m²·s at 125 Pa, which corresponds to the proposed maximum air permeability threshold. The model also uses representative thermal and radiative properties for an energy-saving curtain system, including an effective U-value of 1.4 Btu/hr-ft²-°F and an emissivity of 0.59.

These modeling inputs were selected to represent the combined nighttime heat-retention function of a qualifying curtain system, including reduced convective heat transfer, reduced radiative heat loss, and the insulating effect of the air layer formed between the deployed curtain and the greenhouse glazing. The proposed compliance pathway uses air permeability and automatic controls as enforceable requirements because standardized code-compliance methods are not currently available for rating whole-system curtain-glazing U-factor or combined radiative performance.

4.2.5 Additional Modeling Assumptions

- Heating is provided by a greenhouse furnace with an assumed thermal efficiency of 82 percent
- Heating operation is subject to a constant outdoor air temperature lockout condition of 75°F
- Ventilation and infiltration are represented using a fixed air change rate

- Soil and plant heat transfer are modeled as thermal mass, increasing the effective heat capacity in the temperature calculation and reducing hourly temperature swings

These assumptions provide a consistent basis for evaluating how changes in curtain system performance characteristics influence overall greenhouse heating demand.

4.3 Methodology

The analysis is implemented as an hourly energy-balance model that estimates greenhouse heating energy use based on heat gains and losses through the building envelope.

For each hour of the year, the model calculates:

- Solar heat gain through the greenhouse envelope
- Conductive heat transfer through glazing and structural elements
- Long-wave radiative heat exchange with the sky
- Sensible heat loss due to ventilation and infiltration

Outdoor air temperature and solar radiation are derived from 2028 CEC Weather Files, and solar radiation is adjusted to account for greenhouse roof geometry.

For the single-layer and double-layer glazing cases, the greenhouse is modeled as a single thermal zone. Hourly heat gains and losses are used to determine whether heating is required to maintain the specified setpoint.

For the single-layer glazing with curtain system case, the model incorporates a simplified representation of the thermal barrier created by the curtain when deployed. Curtain operation is represented as fully closed during nighttime periods, consistent with typical thermal-curtain use for heat retention. During curtain operation, heat transfer between the greenhouse interior and exterior is reduced through a combination of decreased radiative exchange, reduced convection, and the formation of an insulating air layer. When the curtain is not deployed, the model reverts to whole-greenhouse behavior consistent with the other scenarios.

Hourly heating loads are calculated based on the net energy balance and aggregated to estimate annual heating energy use for each configuration. Heating energy is reported in therms using an assumed furnace efficiency.

This methodology is intended to support a comparative evaluation of envelope performance under consistent assumptions, rather than to replicate all aspects of greenhouse operation. By applying the same modeling framework across all scenarios, the analysis isolates the relative impact of glazing and curtain configurations on heating demand.

In addition to evaluating discrete envelope configurations, the model is used parametrically to assess how variations in curtain system performance—such as effective thermal resistance and radiative properties—impact heating energy use. This parametric approach supports the conclusion that a single-layer glazing system paired with a properly selected and operated thermal curtain can achieve heating energy performance comparable to a double-layer glazing system. Consistent with the scope of this evaluation, the parametric analysis is limited to nighttime heating impacts and does not assess daytime cooling performance, which is driven by solar gains, evapotranspiration, and operational strategies that vary widely by climate zone.

When the curtain is deployed, the model represents the curtain as a thermal barrier separating the lower conditioned greenhouse volume from the upper roof zone. The model characterizes the combined thermal effect of the curtain using effective thermal conductance, curtain surface emissivity, and airflow assumptions. The model does not separately resolve every radiative subcomponent, such as thermal-infrared transmission through the curtain material; however, it captures the dominant heat-transfer mechanisms needed to compare the three envelope configurations under consistent nighttime heating assumptions.

4.4 Energy Consumption per Prototypical Greenhouse

Table 4 summarizes annual heating fuel consumption for the prototypical greenhouse across all 16 California climate zones. Results are shown for three envelope configurations: single-layer glazing, double-layer glazing, and single-layer glazing paired with an internal thermal curtain system. The modeled curtain case reflects a thermal curtain system consistent with the proposed air-permeability limit and automatic-control requirements, using representative effective U-value and emissivity assumptions for commercially available energy-saving curtain products. These representative thermal and radiative inputs are used for comparative modeling only and are not proposed as compliance requirements.

The analysis is based on an hourly engineering heat-balance model that evaluates the dominant nighttime heating mechanisms relevant to greenhouse envelope performance, including conductive envelope losses, long-wave radiative exchange, solar gains, and ventilation/infiltration losses. Cooling impacts are not included because the proposed curtain pathway is intended primarily to address nighttime heat loss, and cooling performance varies substantially by climate zone, crop type, shading strategy, and greenhouse operating practice.

Table 4. Climate sensitivity of annual heating energy use for the prototypical greenhouse with single-layer glazing, double-layer glazing, and single-layer glazing paired with a thermal curtain having emissivity of 0.59 and an effective U-value of 1.4 Btu/hr-ft²-°F.

Climate Zone	Single-Layer Annual Heating Fuel Consumption (Therms)	Double-Layer Annual Heating Fuel Consumption (Therms)	Single-Layer + Curtain Annual Heating Fuel Consumption (Therms)	Percent Reduction in Heating Fuel Consumption of Single-Layer + Curtain Relative to Double-Layer Glazing
1	40,007	28,467	20,751	27%
2	34,122	24,318	18,114	26%
3	26,467	18,515	13,022	30%
4	30,372	21,654	16,334	25%
5	26,615	17,884	11,917	33%
6	15,347	10,449	6,475	38%
7	12,879	8,745	5,294	39%
8	15,324	10,585	6,924	35%
9	17,559	12,272	8,336	32%
10	17,707	12,286	8,369	32%
11	30,210	22,482	17,449	22%
12	29,053	21,161	16,145	24%
13	23,518	17,337	12,895	26%
14	28,904	21,062	16,104	24%
15	11,421	8,255	5,437	34%
16	49,948	37,231	30,759	17%

Across all climate zones, the single-layer glazing case results in the highest annual heating fuel consumption, while the double-layer glazing case reduces heating demand through improved envelope thermal resistance. The single-layer glazing with thermal curtain case results in the lowest modeled annual heating fuel consumption in every climate zone evaluated. Compared with the single-layer glazing case, the thermal curtain case reduces annual heating fuel consumption by approximately 38 to 59 percent, or approximately 48 percent on an aggregate basis across the 16 climate zones. Compared with the double-layer glazing case, the thermal curtain case reduces annual heating fuel consumption by approximately 17 to 39 percent, or approximately 27 percent on an aggregate basis across the 16 climate zones.

These results demonstrate that a single-layer glass greenhouse paired with a qualifying automated thermal curtain system can reduce nighttime heat loss sufficiently to achieve heating energy performance comparable to, and in the modeled cases lower than, the current double-layer glazing requirement. While the model does not represent every project-specific greenhouse energy mechanism or operating strategy, it applies the same engineering heat-balance framework to each envelope configuration and captures the primary heat-transfer pathways that drive nighttime heating demand. The modeled results indicate that, under the selected representative curtain assumptions and automated nighttime operation, the proposed optional compliance pathway can maintain the energy-saving intent of the existing double-layer glazing requirement under typical nighttime heating conditions.

5. Stakeholder Engagement to Inform Proposal

Stakeholder engagement for this measure was initiated in response to consistent industry feedback that the existing mandatory requirement for multi-layer glazing does not adequately accommodate greenhouse designs that utilize glass glazing systems. Stakeholders indicated that the current code structure limits practical compliance options for certain applications, particularly where high light transmission and durability are important design considerations.

To evaluate these concerns and inform development of an alternative compliance pathway, the Statewide CASE Team conducted targeted outreach with a range of stakeholders, including greenhouse manufacturers, curtain system manufacturers, testing and certification organizations, consultants, and subject matter experts. Engagement activities included a utility-sponsored stakeholder meeting, review of stakeholder meeting poll responses and Q&A, follow-up correspondence, and a series of technical interviews and discussions.

A utility-sponsored meeting was held on March 5, 2026, to present the proposed concept and solicit feedback on key technical and implementation considerations. Topics discussed included greenhouse heat loss mechanisms, curtain system performance characteristics, testing approaches, installation practices, control strategies, and potential compliance pathways.

Stakeholder feedback consistently identified greenhouse curtain systems (energy screens) as a widely used and effective strategy for reducing nighttime heat loss in commercial greenhouse operations. Participants indicated that these systems are commonly integrated with automated environmental controls and are considered a standard component of energy management in conditioned greenhouses.

At the same time, stakeholders highlighted several challenges relevant to code development. These included the lack of standardized methods for measuring whole-system thermal performance of curtain assemblies, variability in installation practices across greenhouse designs, and uncertainty in manufacturer-reported performance metrics. Stakeholders emphasized that performance is influenced by both material properties and operational factors, and that mandatory requirements based on installation details would be difficult to implement and enforce.

Follow-up interviews and discussions provided additional insight into curtain system performance and testing practices. Stakeholders indicated that material properties such as emissivity, transmissivity, and air permeability are more consistently characterized than assembly-level metrics; these were discussed as possible bases for code requirements. Based on subsequent review, the proposal was narrowed to use air permeability as the enforceable material requirement, while radiative performance is discussed qualitatively and reserved for possible future refinement. Manufacturers also indicated that standardized test methods, including ASTM procedures, could be applied to these material properties, even though such methods are not yet widely used within the greenhouse industry.

Stakeholders further noted that installation practices, particularly with respect to curtain edge sealing and system configuration, vary significantly depending on greenhouse geometry, crop requirements, and operational strategies. As a result, stakeholders generally advised against mandatory requirements for installation details and instead supported an approach based on measurable material properties combined with automated control strategies.

Based on this feedback, the proposal was refined to:

- Establish a compliance pathway using a measurable material property (air permeability)
- Avoid reliance on assembly-level U-factor as a compliance metric
- Exclude mandatory installation requirements that would be difficult to standardize and enforce
- Require automated controls to ensure consistent curtain operation and energy performance

Stakeholders also indicated that emissivity alone is not sufficient to characterize radiative performance, and that performance depends on the combined behavior of emissivity and infrared transmissivity, supporting the decision not to include a standalone emissivity requirement.

Overall, stakeholder engagement indicates that the recommended approach aligns with current industry practices, is technically feasible, and addresses identified gaps in the existing code by providing a more flexible and implementable compliance pathway.

The Statewide CASE Team hosted one stakeholder meeting for Greenhouse Envelope Alternative via webinar, as described in Table 5. The table includes dates and links to event pages on Title24Stakeholders.com.

Table 5. Utility-Sponsored Stakeholder Meeting.

Meeting Name and Link to Materials	Meeting Date	Summary of Items Discussed
Utility-Sponsored Stakeholder Meeting https://title24stakeholders.com/wp-content/uploads/2026/03/2028-T24-Stakeholder-Round-2_-CEH-Greenhouse-Envelope-and-Glazing.pdf https://title24stakeholders.com/wp-content/uploads/2026/03/3.5.2026-T24-Stakeholder-Meeting-Notes.pdf	Thursday March 5, 2026	• Recommended alternative compliance path • Greenhouse heat loss (radiative, convective, and conductive) • Curtain properties and testing procedures • Installation and sealing practices • Controls requirements • Energy and cost savings methodology • Compliance verification

The Statewide CASE Team conducted direct outreach through email, videoconference, and phone conversations with a range of stakeholders representing manufacturers, research institutions, and technical experts. These discussions informed the development of the recommended greenhouse envelope alternative and provided valuable insights into test methods, control strategies, and implementation considerations.

Table 6 lists key organizations and individuals engaged during the proposal development process.

Table 6. Engaged Stakeholders

Organization / Individual	Market Role	Key Takeaways
Greenhouse Curtain Manufacturer 1 **Representatives from US Sales and Greenhouse Climate Consultants, North America Management, Research and Development**	Curtain manufacturer	Curtain performance is derived from small-scale greenhouse tests and back-calculation rather than standardized methods, raising concerns about consistency and enforceability, particularly for offshore manufacturers. Manufacturers are open to testing with standard test procedures, as long as they are material properties and not greenhouse assemblies.
Greenhouse Curtain Manufacturer 2 **Representatives from North America Sales, International Sales and Business Development, Product Specialist, Regional Sales Manager**	Curtain manufacturer	U-values are calculated for the entire greenhouse system using third-party testing and detailed models that account for structure, materials, air gaps, location, and climate, resulting in comprehensive but costly analyses. Advanced tools (e.g., Wageningen Radiation Monitor) are used to assess light and energy tradeoffs.
Greenhouse Modeling Team **Technical and Program Development Representative**	Greenhouse modeling	The Virtual Grower software tool is intended for directional insight and screening of energy-saving measures, not accurate or predictive results. Noted the greenhouse sector lacks validated models, data, and testing to support robust energy decisions.
Cannabis Grower Organization **Co-Founder and Executive Director**	Grower organization	Referred CASE Team to other connections.
Organization for Window Attachment Performance/ **Representatives from Consulting Team, Operations Capacity and Administration, Technical Issues**	Independent standards and rating organization	There is currently no greenhouse curtain rating system in place, though one could potentially be developed as a new framework.

6. Potential Code Language Updates

6.1 Guide to Markup Language

The Statewide CASE Team recommends including this measure as part of the 2028 updates to the Energy Code. The recommended updates to the standards and Reference Appendices are provided below. Recommended changes are marked with dark blue underlining (new language) and ~~strikethroughs~~ (deletions).

6.1.1 Administrative Code (Title 24, Part 1)

There are no proposed changes to Title 24, Part 1.

6.1.2 Energy Code (Title 24, Part 6)

SECTION 100.1 – DEFINITIONS AND RULES OF CONSTRUCTION

INTERNAL GREENHOUSE CURTAIN SYSTEM is a retractable assembly installed within a greenhouse envelope above the plant canopy, consisting of one or more curtain layers that operate as a single system, and when deployed, span the primary roof glazing area and reduce conductive, convective, and radiative heat transfer through the roof or upper glazing.

AIR PERMEABILITY is the airflow rate through a material per unit area under a specified pressure differential.

SECTION 120.6(h) - Mandatory requirements for Controlled Environment Horticulture (CEH) spaces.

1. Indoor growing, dehumidification. Dehumidification equipment shall be one of the following: …

2. Indoor growing, electrical power distribution systems. Electrical power distribution systems serving CEH spaces shall be designed so that a measurement device is capable of monitoring the electrical energy usage of aggregate horticultural lighting load. …

3. Conditioned greenhouses, building envelope. Conditioned greenhouses shall meet the following requirements:

A. Opaque wall and opaque roof assembly shall meet the requirements of Section 120.7; and

B. Nonopaque envelopes shall meet one of the following requirements:

i. The nonopaque envelope shall have two or more glazing~~s~~ layers separated by either air or gas fill~~.~~; or

ii. The nonopaque envelope shall have one glass glazing layer and at least one internal greenhouse curtain system meeting all of the following requirements:

a. The internal greenhouse curtain system material shall have an air permeability not exceeding 50 L/m²·s when determined in accordance with ASTM D737 or ISO 9237 at a pressure differential of 125 Pa. Compliance shall be demonstrated using either:

   i. A single internal greenhouse curtain system meeting the air permeability requirement of this subsection; or

   ii. Two or more internal greenhouse curtain systems that each comply with subsections b through f, or two or more curtain layers within a single internal greenhouse curtain system that complies with subsections b through f, may be evaluated as a combined assembly provided that the equivalent air permeability of the combined curtain layers does not exceed 50 L/m²·s. Equivalent air permeability, Peq, shall be calculated as follows:

   $1/P_{eq} = 1/P_1 + 1/P_2 + \ldots + 1/P_n$

   where:

   P_{eq} = equivalent air permeability (L/m²·s)

   P_i = air permeability of curtain layer i, determined in accordance with ASTM D737 or ISO 9237 at a pressure differential of 125 Pa.

b. The internal greenhouse curtain system shall be designed and installed to cover the primary overhead glazing area and shall be capable of deploying to cover the primary overhead glazing area serving the conditioned growing space.

c. The internal greenhouse curtain system shall be motorized and automatically controlled to deploy during nighttime periods or other periods identified by the automatic control strategy when solar gains are unavailable. Acceptable control strategies include time-based, astronomical, sensor-based, or integrated control systems that respond to indoor and/or outdoor environmental conditions

d. The controller shall be configured such that, following a manual override, the system automatically returns to automatic operation after a programmed time period.

e. Any scheduling device shall have program backup capabilities that prevent the loss of the device's schedule for at least 7 days and the device's date and time for at least 72 hours if power is interrupted.

f. Before an occupancy permit is granted for a greenhouse using the single-layer glass and internal curtain system compliance pathway, the equipment and systems shall be certified as meeting the Acceptance Requirement for Code Compliance, as specified by the Reference Nonresidential Appendix NA7.X. A Certificate of Acceptance shall be submitted to the enforcement agency that certifies that the equipment and systems meet the acceptance requirements specified in NA7.X.

6.1.3 Reference Appendices

Appendix NA7.X — Greenhouse Curtain System Controls Functional Testing

NA7.X.1 Purpose

This test verifies that internal greenhouse curtain systems installed as part of the compliance pathway in Section 120.6(h)(3) are capable of automatic operation and respond appropriately to control inputs.

This test applies to all internal greenhouse curtain systems used to comply with Section 120.6(h)(3)B(ii).

NA7.X.2 Functional Testing

Step 1: Verify System Configuration

a. Confirm that the curtain system is configured for automatic operation.
b. Confirm that the control system is programmed with an active schedule or sensor-based control logic.

Step 2: Functional Test of Automatic Deployment

Using one of the following methods, initiate a control condition that triggers curtain deployment:

a. Adjust the system time to a scheduled deployment period; or
b. Adjust a control setpoint (e.g., temperature, light level, or solar radiation) to simulate conditions that require curtain deployment.

Acceptance Criteria

a. The curtain system shall automatically initiate deployment without manual intervention.
b. The curtain shall visibly begin movement toward the closed position within 2 minutes of the control signal.

Step 3: Functional Test of Automatic Retraction

Using one of the following methods, initiate a control condition that triggers curtain retraction:

a. Adjust the system time to a scheduled retraction period; or

b. Adjust a control setpoint to simulate conditions that require curtain retraction.

Acceptance Criteria

a. The curtain system shall automatically initiate retraction without manual intervention.

b. The curtain shall visibly begin movement toward the open position within 2 minutes of the control signal.

Step 4: Manual Override Reset Test (if applicable)

a. Activate the manual override control to interrupt automatic operation.

b. After the override period expires or is cleared, verify system behavior.

Acceptance Criteria

a. The system shall return to automatic control mode within the programmed reset period.

b. The system shall resume normal automatic operation without requiring manual reactivation.

NA7.X.3 Documentation

The following shall be documented:

a. Type of control strategy (time-based, sensor-based, or integrated)

b. Description of method used to simulate deployment and retraction conditions

c. Verification that the system responded automatically

d. Verification of manual override reset (if applicable)

7. Potential Code Language Updates - Restructured

7.1 Guide to Markup Language

The Statewide CASE Team recommends including this measure as part of the 2028 updates to the Energy Code. New to the 2028 energy code is the convention of *italicizing defined terms* when the terms are being used in their defined context. In-line comments that are not part of the proposed code language but are used to help describe the purpose of what is proposed are included *with greyed highlight and italics.*

Markups are provided to the restructured 2025 Energy Code that the CEC developed in response to feedback that aligning the structure of Title 24, Part 6 with other parts of the California Building Standards Code (Title 24) would improve readability, usability, and navigation. New section numbers are shown as bold followed square brackets that document the section in the 2025 Title 24, Part 6 section numbers prior to the restructuring. For example, "**Section 601.1** [Section 130.0(a)] **General"** contains the content that is in the current Section 130.0(a).

The proposed changes to the standards and Reference Appendices are provided below. Changes to the 2025 documents should be marked with dark blue underlining (new language) and ~~strikethroughs~~ (deletions).

7.1.1 Administrative Code (Title 24, Part 1)

There are no proposed changes to Title 24, Part 1.

7.1.2 Energy Code (Title 24, Part 6)

SECTION 201
DEFINITIONS

INTERNAL GREENHOUSE CURTAIN SYSTEM is a retractable assembly installed within a greenhouse envelope above the plant canopy, consisting of one or more curtain layers that operate as a single system, and when deployed, span the primary roof glazing area and reduce conductive, convective, and radiative heat transfer through the roof or upper glazing.

AIR PERMEABILITY is the airflow rate through a material per unit area under a specified pressure differential.

908.1 *[Section 120.6(h)1]* **Mandatory requirements (Newly Constructed, Additions, Alterations).**

908.1.1 *[Section 120.6(h)1]* **Indoor growing, dehumidification.**

Dehumidification *equipment* shall be one of the following: …

908.1.2 *[Section 120.6(h)2]* **Indoor growing, electrical power distribution systems.**

Electrical power distribution systems serving CEH spaces …

908.1.3 *[Section 120.6(h)3]* **Conditioned greenhouses, building envelope.**

Conditioned greenhouses shall meet the following requirements:

1. Opaque wall and opaque *roof* assembly shall meet the requirements of Section 301.2 *[Section 120.7]*; and
2. Nonopaque *envelopes* shall meet one of the following requirements:
   2.1. The nonopaque envelope shall have two or more glazings layers separated by either air or gas fill.; or
   2.2. The nonopaque *envelope* shall have one glass glazing layer and at least one *internal greenhouse curtain system* meeting all of the following requirements:
      2.2.1. The *internal greenhouse curtain system* material shall have an *air permeability* not exceeding 50 L/m²·s when determined in accordance with ASTM D737 or ISO 9237 at a pressure differential of 125 Pa. Compliance shall be demonstrated using either:
      2.2.1.1 A single internal greenhouse curtain system meeting the air permeability requirement of this subsection; or
      2.2.1.2 Two or more internal greenhouse curtain systems that each comply with subsections 2.2.2 through 2.2.6, or two or more curtain layers within a single internal greenhouse curtain system that complies with subsections 2.2.2 through 2.2.6, may be evaluated as a combined assembly provided that the equivalent air permeability of the combined curtain layers does not exceed 50 L/m²·s. Equivalent air permeability, P_{eq}, shall be calculated as follows:

      $1/P_{eq} = 1/P_1 + 1/P_2 + \ldots + 1/P_n$

      where:

      P_{eq} = equivalent air permeability (L/m²·s)

      P_i = air permeability of curtain layer i, determined in accordance with ASTM D737 or ISO 9237 at a pressure differential of 125 Pa.
      2.2.2. The *internal greenhouse curtain system* shall be designed and installed to cover the primary overhead glazing area and shall be capable of deploying to cover the primary overhead glazing area serving the conditioned growing space.
      2.2.3. The *internal greenhouse curtain system* shall be motorized and automatically controlled to deploy during nighttime periods or other periods identified by the automatic control strategy when solar gains

are unavailable. Acceptable control strategies include time-based, astronomical, sensor-based, or integrated control systems that respond to indoor and/or outdoor environmental conditions.

2.2.4. The controller shall be configured such that, following a manual override, the system automatically returns to automatic operation after a programmed time period.

2.2.5. Any scheduling device shall have program backup capabilities that prevent the loss of the device's schedule for at least 7 days and the device's date and time for at least 72 hours if power is interrupted.

2.2.6. Before an occupancy permit is granted for a greenhouse using the single-layer glass and internal curtain system compliance pathway, the equipment and systems shall be certified as meeting the Acceptance Requirement for Code Compliance, as specified by the Reference Nonresidential Appendix NA7.X. A Certificate of Acceptance shall be submitted to the enforcement agency that certifies that the equipment and systems meet the acceptance requirements specified in NA7.X.

908.1.4 *[Section 120.6(h)4]* **Conditioned greenhouses, space-conditioning systems.**

Space-conditioning systems used for plant production ...

908.1.5 *[Section 120.6(h)5]* **Horticultural lighting.**

In a *building* with CEH spaces or a greenhouse ...

…

908.4 *[Section 141.1, 141.1(c)]* **Additions and alterations to existing buildings.** *Covered processes* in *additions* or *alterations* to existing *buildings* that will be *nonresidential*, *hotel/motel*, or *multifamily* occupancies shall comply with the applicable requirements of Section 400.5.1 *[Section 110.2(a)]* and Section 913 *[Section 120.3]*.

908.4.1 *[Section 141.1(c)1]* **Indoor Growing, Space-Conditioning Systems and Dehumidification.**

All newly installed heating, ventilation, air conditioning systems or dehumidification systems in *buildings* with *indoor growing* shall meet the applicable requirements of Section 908.1.1 *[Section 120.6(h)1]* and Section 908.1.2 *[Section 120.6(h)2]*.

908.4.2 *[Section 141.1(c)2]* **Greenhouses, Building Envelope and Space-Conditioning Systems.**

A greenhouse being converted to a *conditioned greenhouse* or *additions* to a *conditioned greenhouse* shall meet the requirements of Section 908.1.3 *[Section 120.6(h)3]* and Section 908.1.4 *[Section 120.6(h)4]*.

8. About the authors

The California Statewide Codes and Standards Enhancement (CASE) initiative presents recommendations and information to support the California Energy Commission's (CEC's) efforts to update California's Energy Code (Title 24, Part 6), including revisions to simplify and clarify existing code requirements.

Three California Investor-Owned Utilities (IOUs) — Pacific Gas & Electric Company, San Diego Gas & Electric, and Southern California Edison sponsored this effort as a group.

If you have questions about the analysis, please contact info@title24stakeholders.com.

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Appendix A. Energy Model Details

This analysis estimates annual greenhouse heating energy use for three envelope configurations: single-pane glazing, double-pane glazing, and single-pane glazing with a heat curtain. The model is structured as an hourly energy-balance analysis using a common greenhouse geometry and a selected climate dataset. Its purpose is to compare the relative thermal performance of the three envelope strategies under consistent assumptions, rather than to size heating equipment or reproduce every aspect of greenhouse operation.

For each hour of the year, the model reads outdoor dry-bulb temperature and solar radiation from the 2028 CEC Weather File dataset and converts the horizontal solar input to roof-normal radiation using the greenhouse roof angle. User-defined inputs, including daytime and nighttime setpoints, operating schedules, greenhouse dimensions, envelope properties, and air-change rate, are then applied to calculate the principal heat-gain and heat-loss terms. These include transmitted solar gain, long-wave radiation exchange with the sky, conductive heat transfer through the roof and wall assemblies, and ventilation-related sensible heat transfer.

For the single-pane and double-pane cases without thermal curtains, the greenhouse is represented as a single thermal zone. An hourly net energy balance is calculated from the sum of solar gains and heat losses, and the greenhouse air temperature is rolled forward from the prior hour using the greenhouse air volume, air density, and specific heat. When the hourly balance is negative and the greenhouse would otherwise fall below the active setpoint, the model records the heating energy required to maintain the setpoint, subject to the specified outdoor-air lockout condition.

For the single-layer glazing with thermal curtain case, the model uses a simplified two-zone approach to represent thermal separation between the lower greenhouse volume and the upper roof zone. When the curtain is active, heat transfer across the curtain, roof conduction to outdoor air, and roof radiation to the sky are used to update the upper-zone temperature, while the lower zone is evaluated separately for solar gain, envelope losses, ventilation losses, and heating requirement. When the curtain is inactive, the model reverts to a whole-house balance consistent with the single-zone formulation.

The thermal curtain parameters used in the analysis are based on representative values derived from manufacturer data for commercially available thermal (energy-saving) curtain systems. For the purposes of this modeling effort, the curtain assembly is characterized using an effective U-value of 1.4 Btu/hr-ft^2-°F and an emissivity of 0.59. These values are intended to reflect typical performance characteristics of thermal curtains designed for energy retention, rather than best-available or minimum-performance products. Because curtain performance depends on a combination of material properties, including air permeability, emissivity, and thermal-infrared transmissivity, as well as installation and operation, these parameters are used solely to support comparative analysis of envelope strategies and are not proposed as mandatory requirements in this measure.

The current model represents the deployed curtain as a thermal barrier between the lower greenhouse volume and the upper roof zone. Curtain emissivity is represented for the curtain surface; however, the model does not explicitly simulate thermal-infrared transmission from the lower greenhouse zone through the curtain to the roof or sky. As a result, the modeled curtain case may understate radiative heat loss relative to actual field performance. The curtain-case results should therefore be interpreted as comparative estimates under the selected assumptions rather than precise predictions of field performance.

Hourly heating results are aggregated to annual therms for each case, and a conversion is applied to express furnace fuel input using an assumed thermal efficiency. The resulting outputs are used to compare annual heating demand, major heat-transfer components, and relative savings across the three envelope strategies. The methodology is therefore intended to support comparative evaluation of glazing and curtain options under the selected climate scenario.

The night sky temperature is calculated from the hourly outdoor air temperature using a clear-sky correlation rather than being treated as a fixed offset below ambient conditions. The model first converts outdoor air temperature to an absolute temperature basis and then calculates an effective sky emissivity using $\varepsilon_{sky} = 9.36\times10^{-6}\cdot T_{air,K}^{2}$. It then estimates night sky temperature using $T_{sky,K} = 0.0552\cdot T_{air,K}^{1.5}$ and converts that result back to degrees Fahrenheit for reporting and use in the radiation calculations. This calculated sky temperature is applied in the long-wave radiation term, where the difference between greenhouse temperature and sky temperature governs radiative heat loss from the envelope. As a result, nighttime radiation losses vary dynamically with hourly weather conditions rather than relying on a single fixed sky-temperature assumption.

Table 7. Key equations in model.

Term	Representative Equation	How It Is Applied in the Model
Roof-plane solar conversion	I_roof = I_horizontal / cos(theta_roof)	The model converts horizontal solar radiation from the weather file to radiation normal to the greenhouse roof using the roof angle derived from greenhouse geometry. This creates the incident solar term used in the solar-gain calculations.
Transmitted solar gain	Q_solar = I_roof x 0.317 x tau x A	Solar heat gain is calculated as roof-normal solar intensity multiplied by the transmissivity of the envelope material and the applicable roof / wall area.
Conductive heat transfer	Q_cond = U x A x (T_out - T_zone)	Conductive heat transfer through the roof and non-roof envelope is computed from the material conductance, surface area, and temperature difference between the greenhouse zone and outdoor air. The double-pane case uses a lower U-value than the single-pane case, which reduces this loss term.
Long-wave radiation exchange	Q_rad = -epsilon x sigma x [(T_zone,K)^4 - T_sky^4] x conversion x A_exposed	Radiation loss is calculated using envelope emissivity, the Stefan-Boltzmann relationship, and the difference between zone temperature and modeled sky temperature. In the curtain case, upper- and lower-zone radiation terms are calculated separately.
Ventilation sensible heat transfer	Q_vent = (ACH x V / 60) x 1.08 x (T_out - T_zone)	Ventilation / infiltration is estimated from greenhouse volume, the air-change-rate input, and the temperature difference between outdoor air and the greenhouse zone. When the curtain is active, the lower-zone ventilation term uses the lower greenhouse volume.

Term	Representative Equation	How It Is Applied in the Model
Zone temperature roll-forward	T_t = max(T_set, T_t-1 + Q_net,t-1 / (V x C_model))	The model updates zone temperature hour by hour using the prior-hour net balance and a simplified storage term. In the current workbook implementation, C_model is represented by the heat-capacity constant used in the roll-forward denominator.
Heating requirement	Q_heat = negative portion of Q_net, subject to lockout and setpoint checks	If the net hourly balance is negative, and outdoor air temperature is below the furnace lockout threshold, the negative balance is recorded as heating energy output needed to maintain the active setpoint.
Fuel-use reporting	Fuel therms = -SUMIFS(Q_heat) / 100,000 / 0.82	Hourly heating output is summed to annual therms in Model Analysis, and converted to estimated furnace fuel input using 100,000 Btu per therm and an assumed 0.82 furnace efficiency.