



# Commercial Building Duct Sealing Energy Savings and Cost Analysis

## Final Report

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## Executive Summary

This report builds on the Commercial Building Duct Sealing Market Characterization study, which identified significant energy efficiency opportunities from duct sealing technologies in small commercial buildings (J. Breda et al., 2024). Through comprehensive market analysis and field research, the prior study highlighted critical factors impacting duct configurations and leakage characteristics. This subsequent study focuses on quantifying energy savings potential through detailed energy modeling and cost-effectiveness analysis to guide targeted incentive programs.

The project team conducted EnergyPlus simulations across 16 California climate zones using standardized small commercial prototypes: small office, fast food restaurant, retail store, and restaurant dining. The simulations considered two distinct leakage modeling methods—leakage-to-inside and leakage-to-outside—to capture realistic operational and energy-impact scenarios reflective of typical small commercial buildings. Energy modeling results show meaningful energy savings, with heating, ventilation, and air conditioning system savings of up to 30 percent, depending on the leakage scenario, system type, and climate zone. In general, leakage-to-outside scenarios yielded greater savings, especially in climate zones with more extreme temperatures and in buildings with continuous fan systems, emphasizing the potential benefit of advanced sealing methods.

Cost analysis further substantiates the practicality of duct sealing measures. Manual sealing approaches, primarily mastic and tape, typically cost between \$0.5 and \$1.5 per square foot of building, delivering moderate leakage reduction of about 40 to 50 percent. Aerosol-based sealing, though higher in initial investment at \$1 per square foot, significantly reduces leakage by 70 to 90 percent and substantially decreases labor costs, particularly in buildings where ducts are difficult to access.

Because California's energy prices are more than double the US commercial average, duct sealing represents an unusually attractive efficiency investment in the state. Coupling utility-funded leakage diagnostics with tiered, performance-based rebates that buy aerosol projects down to a less than or equal to five-year payback can unlock verifiable savings while supporting the state's climate goals.

This comprehensive evaluation of cost versus savings and payback periods highlights duct sealing as a strong candidate for incentive programs. The substantial energy savings, combined with relatively short payback periods, demonstrate duct sealing's effectiveness in achieving rapid energy and cost reductions. Therefore, targeted diagnostic programs and performance-based incentives tailored for sealing projects present a highly attractive investment opportunity for California's small commercial sector, supporting statewide energy efficiency and decarbonization goals.

## Abbreviations and Acronyms

| Acronym | Meaning                                         |
|---------|-------------------------------------------------|
| CAV     | Constant air volume                             |
| CMC     | California Mechanical Code                      |
| CPUC    | California Public Utilities Commission          |
| DEER    | Database for Energy Efficient Resources         |
| DOE     | United States Department of Energy              |
| DXGF    | Direct expansion cooling with gas furnace       |
| DXHP    | Direct expansion heat pump                      |
| DXOH    | Direct expansion cooling with no heating        |
| EIA     | United States Energy Information Administration |
| HVAC    | Heating, ventilation, and air conditioning      |
| IOU     | Investor-owned utility                          |
| NCGF    | No cooling with gas furnace heating             |
| OA      | Outdoor air                                     |
| OfS     | Small office building                           |
| PNNL    | Pacific Northwest National Laboratory           |
| RFF     | Fast food restaurant                            |
| RSD     | Dine-in restaurant                              |
| RtS     | Retail store                                    |
| SDG&E   | San Diego Gas & Electric                        |

SDLM

Simplified Duct Leakage Method

VAV

Variable air volume

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## Introduction

Duct systems play a central role in delivering heating, ventilation, and air-conditioning (HVAC) services to commercial buildings. When properly designed and maintained, these systems ensure occupant comfort, maintain indoor air quality, and promote energy efficiency. However, duct leakage can significantly undermine these benefits. Prior research suggests that leakage rates in certain commercial buildings can exceed 30 percent of total HVAC airflow, resulting in substantial energy losses and elevated utility costs. Beyond energy penalties, duct leakage can compromise indoor air quality, reduce occupant comfort, and increase wear on HVAC equipment.

In recognition of these impacts, the Commercial Building Duct Sealing Market Characterization study ET24SWE0041 (J. Breda et al., 2024) examined a broad range of factors influencing the adoption and efficacy of duct sealing measures. Through literature reviews, expert interviews, code and standards analysis, and market assessments, the first study identified promising sealing technologies, cost considerations, and market drivers that could enable greater uptake of duct sealing initiatives. One key finding was that small commercial buildings with constant-air-volume (CAV) systems and long operation hours frequently exhibit high leakage rates relative to their HVAC system size, creating an outsized potential for cost-effective energy savings if sealing measures are applied.

The project team builds on these insights in the present study, Commercial Building Duct Sealing Energy Savings and Cost Analysis, aiming to quantify the energy and cost impacts of duct sealing interventions in small commercial buildings with HVAC systems serving 5,000 square feet or less. The first study identified small commercial buildings—such as retail spaces, offices, and restaurants—as having significant potential for energy savings due to their often overlooked and leaky duct systems. This in-depth technical examination will involve detailed energy modeling, cost analysis, and feasibility evaluation to inform the development of a commercial duct sealing measure package for San Diego Gas & Electric (SDG&E) and other California investor-owned utilities (IOUs). By leveraging refined assumptions, incorporating recent literature, and employing advanced modeling tools, this study will provide robust estimates of potential energy savings. Ultimately, the goal of the study is to support utility program strategies that encourage practical and cost-effective duct sealing solutions for smaller commercial properties, aligning with California’s broader goals of reducing energy consumption and greenhouse gas emissions.

## Objectives

This second study’s objective was to build upon the findings from the first study by quantifying energy and cost impacts of duct sealing in small commercial buildings. The research focused on developing energy models, assessing cost-effectiveness, and evaluating the feasibility of duct sealing measures under real-world conditions. The results serve as a practical resource to inform and support the development of a commercial duct sealing measure package.

## Background

The duct sealing technology market offers a diverse range of solutions that aim to improve energy efficiency in HVAC systems across both residential and commercial buildings. Traditional products, such as mastic sealants and aluminum foil tape, have long been favored for their ease of application and reliability in sealing leaks of varying sizes. Mastic sealants, commonly applied with a brush or caulk gun, are known for their durability and flexibility, making them suitable for tackling both minor and more substantial duct leaks. Aluminum foil tape, on the other hand, is often used for sealing joints in accessible areas of duct systems, providing a quick fix with a lower labor cost. Butyl tape and mechanical fastening methods add to the landscape of options, though these are more common in commercial or industrial environments where higher-temperature resistance, robust material properties, or specialized labor may be required.

In recent years, more advanced duct sealing methods have emerged in response to market needs for greater effectiveness and ease of use. One notable innovation is an aerosol-based sealant that can reach leaks in inaccessible parts of a building's duct network, such as those hidden behind walls, ceilings, or floor cavities. Field data have shown that this method can seal between 70 and 90 percent of duct leaks, surpassing the 40 to 50 percent sealing range achievable through many manual approaches. Despite these impressive results, the widespread adoption of aerosol sealants has been tempered by the higher cost of the technology and the specialized equipment required. This challenge signals a broader issue in the commercial duct sealing market: many building owners—especially those overseeing small commercial properties—remain either unaware of the available solutions or hesitant to commit the necessary resources due to perceived complexity and expense.

To address these barriers, the California Public Utilities Commission (CPUC) has issued directives aimed at broadening energy efficiency measures offered by utilities, particularly those that achieve gas savings without directly burning natural gas, such as envelope improvements, insulation, and duct sealing. As a direct result of the CPUC's decision,<sup>1</sup> SDG&E is exploring new ways to integrate duct sealing into their program portfolio. Through these expanded offerings, building owners can be guided toward cost-effective improvements that reduce both energy use and carbon emissions.

Within this evolving regulatory and market context, the first study established a foundation by outlining the technologies, costs, potential savings, and market drivers relevant to duct sealing measures in commercial settings. That study found that smaller commercial buildings—those with HVAC systems serving roughly 5,000 square feet or less—often face high duct leakage levels relative to their overall HVAC system size, making them strong candidates for targeted sealing interventions. These findings provide the basis for the current effort, the Commercial Building Duct Sealing Energy Savings and Cost Analysis, which focuses on the energy modeling and economic evaluation of duct sealing options for small commercial buildings. By focusing on quantifiable metrics of energy savings, along with other factors such as durability and ease of implementation, this second study

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<sup>1</sup> Decision Addressing Codes and Standards Subprograms and Budgets and Staff Proposal on Reducing Ratepayer-Funded Incentives for Gas Energy Efficiency Measures

will further illuminate the value proposition of duct sealing and guide the development of a commercial duct sealing measure package for SDG&E.

## **Current Duct Sealing Requirements in California for Commercial Buildings**

California regulates HVAC duct sealing primarily through two key documents: the California Mechanical Code (CMC) and the California Energy Code (Title 24, Part 6). Although both codes govern duct systems, Title 24, Part 6 is focused on energy efficiency and therefore adds specific performance-based duct leakage criteria to complement the construction-focused language of the CMC.

Under the CMC 2022, Section 603.9 requires duct systems to be made substantially airtight by means of tapes, mastics, gasketing, or other approved sealing methods. This is a continuation of language present in older CMC versions; however, unlike earlier editions, the 2022 CMC expands on this by mandating, under Section 603.10, that a minimum of 10 percent of the duct system must be tested for leakage. The tested portion must demonstrate compliance with Leakage Class 6, setting a verifiable performance threshold for sealing quality. The 2019 CMC introduced this testing requirement for the first time in nonresidential duct systems—prior versions relied on qualitative language about airtight construction but lacked a formal testing mandate.

At the same time, Title 24, Part 6 imposes additional duct sealing requirements to meet energy efficiency goals. The requirements are found primarily in Section 120.4, which was reorganized and expanded in the 2022 code cycle. This section changes duct sealing from a largely prescriptive condition to a mandatory requirement for certain systems. Specifically, if a new duct system meets several criteria—such as serving less than 5,000 square feet of conditioned floor area, operating as a single-zone CAV system, and having more than 25 percent of the duct surface area located in unconditioned space—it must be sealed to a maximum leakage rate of 6 percent of the nominal air handler airflow and verified via testing. If a system does not meet these criteria, it must follow the CMC testing requirements in Section 603.10 or another applicable testing approach.

In addition to new construction, Title 24, Part 6 addresses existing buildings undergoing additions, alterations, or repairs through Section 141.0. This section stipulates that when a space-conditioning system is altered or extended, any newly installed or replaced duct segments must meet certain sealing and insulation standards. Subsection 141.0(b)2D clarifies that if over 75 percent of the duct material is new, the entire duct system is effectively considered “new” for compliance purposes and must be tested for leakage under Section 120.4(g). Even when only a small portion of ductwork is added, if the system meets the single-zone criteria noted above, the combined new and existing duct system may be subject to a 15 percent leakage threshold. If that threshold cannot be achieved, a smoke test and sealing of all accessible leaks must be documented.

## **Evolution of Regulations Across Code Cycles**

### **Early 2000s to 2008**

In the early 2000s, the CMC already contained language requiring duct systems to be “substantially airtight.” However, neither the CMC nor Title 24, Part 6 imposed explicit duct leakage testing requirements for commercial buildings. Title 24, Part 6 addressed duct sealing primarily via prescriptive or broad mandatory measures—particularly if ducts were located in unconditioned

spaces—but did not prescribe a specific maximum leakage rate. Enforcement largely hinged on meeting minimal insulation R-values for ductwork and using approved sealing materials.

### **2008 Code Cycle**

The 2008 Title 24, Part 6 standards represented a turning point for commercial duct sealing by clarifying mandatory sealing methods. Nevertheless, formal leakage testing requirements were still limited. Commercial projects occasionally had to verify duct leakage if they underwent significant HVAC alterations, but in practice, testing was not uniformly enforced. The CMC continued to require airtight methods but no firm percentage-based testing requirement.

### **2013 Code Cycle**

While the 2013 Title 24, Part 6 reorganized envelope and mechanical sections, the specifics of duct leakage testing remained relatively unchanged from the 2008 cycle. Duct sealing became more clearly embedded in Sections 120.4–120.7, and projects using the prescriptive path for compliance had to account for duct leakage in energy models. However, there was still no comprehensive requirement that all nonresidential duct systems be pressure-tested. On the mechanical code side, “substantially airtight” duct system language continued, but enforceable testing mandates had yet to be introduced for most nonresidential buildings.

### **2016 Code Cycle**

The 2016 Title 24, Part 6 standards maintained the direction of the 2013 code, with emphasis on sealing all joints and seams for ducts in unconditioned or semi-conditioned spaces. Acceptance testing protocols in the Nonresidential Compliance Manual began to cover more mechanical equipment verification steps. Still, mandatory duct leakage testing applied primarily to residential or certain small commercial projects meeting specific criteria. The CMC of 2016 reiterated airtight duct construction but did not require a systematic leakage test for commercial projects, leaving enforcement somewhat to the discretion of local jurisdictions.

### **2019 Code Cycle**

In 2019, for the first time in commercial applications, the CMC introduced a requirement that at least 10 percent of a duct system be tested to achieve Leakage Class 6. In the 2019 edition, Title 24, Part 6 simultaneously expanded the prescriptive requirements of Section 140.4(l) and the additions and alterations rules in Section 141.0 to cover duct leakage verification for small commercial systems—defined as under 5,000 square feet, single-zone CAV, and ducts in unconditioned space. The 2019 cycle brought significantly tighter expectations for duct construction and introduced real testing requirements for many commercial projects, even though it still treated some duct sealing scenarios under the prescriptive approach rather than a blanket mandatory one.

### **2022 Code Cycle**

In the latest cycle, both the CMC and Title 24, Part 6 solidified duct sealing as a mandatory requirement for a broad range of commercial systems. The 2022 CMC continued the testing mandate from 2019, requiring that at least 10 percent of new duct systems be tested and pass Leakage Class 6. Meanwhile, Title 24, Part 6, Section 120.4(g) elevated duct sealing into mandatory measures for qualifying new systems. Under 2022 rules, new or significantly altered duct systems serving less than 5,000 square in a single-zone configuration must achieve 6 percent or less leakage—or meet 15 percent in certain alteration scenarios—under the supervision of a certified

Home Energy Rating System-rater or acceptance test technician. As a result, the 2022 cycle closed the gap between prescriptive and mandatory requirements for many small commercial projects, ensuring that owners and contractors must verify their ducts are truly sealed with measurable performance outcomes.

## Methods and Approach

### Literature Review and Case Study Analysis

Building on the first study's literature review and market findings, this second study combined a review of existing literature with analysis of case studies and examination of current regulations and standards. The literature review encompassed academic papers, industry reports, and other relevant publications with specific focus on commercial buildings. Insights gained informed the baseline assumptions regarding duct leakage levels, HVAC system configurations, and the selection of leakage and post-sealing levels and cost variables.

### Detailed Energy Modeling and Saving Analysis

The project team performed detailed energy modeling to assess the impact of duct sealing in small commercial buildings. Baseline models assumed duct systems have not been sealed beyond standard or outdated code requirements, with leakage percentages ranging from 10 to 30 percent. Selected cases reflect sealed ducts at various levels of sealing improvement compared to baseline levels. This analysis spanned across all 16 California climate zones to simulate and analyze energy performance before and after duct sealing in various small commercial building prototypes, such as small office, fast food restaurant, and small retail.

### Feasibility Evaluation and Information for a New Measure Package

Drawing on lessons from the first study's market characterization, and based on the collected data and analysis from the current study, the project team evaluated the feasibility and practicality of implementing duct sealing in small commercial buildings. This included assessing the applicability and effectiveness of the proposed solutions, potential realized savings, and market adoption factors. Together, these two projects support development of a new measure package by SDG&E for duct sealing in commercial buildings.

## Findings

### Case Study Analysis

Duct leakage remains a widespread challenge across commercial buildings, contributing significantly to wasted energy and higher operating costs. Prior research demonstrated that effective duct sealing can yield savings of 15 to 30 percent in HVAC energy consumption, demonstrating the importance of practical solutions that enhance efficiency and reduce long-term costs (Proctor Engineering et al., 2002; Quinnell et al., 2016). This section examines multiple case studies and draws from interviews with industry experts to review a range of duct sealing technologies in further detail than the first study. The discussion below begins broadly to capture the overall market landscape and then



narrows to examine the specific context of small commercial buildings. We emphasize CAV HVAC configurations, where the energy savings potential from duct sealing appears particularly promising.

## **Overview of Duct Leakage and Measurement Approaches**

Research has long demonstrated that poorly sealed ductwork can compromise system performance and drive up utility costs (Fisk et al., 2000). Recent investigations measured leakage levels in small and large commercial buildings, often revealing baseline leakage rates in the range of 10 to 20 percent and sometimes exceeding 30 percent of design airflow (Wray et al.; Quinnell et al., 2016). Such losses directly increase the energy demand required to maintain comfort conditions, whether for heating, cooling, or ventilation.

## **Measuring Duct Leakage**

A range of methods are available to measure duct leakage in commercial buildings, varying in precision, cost, and suitability depending on the application and performance goals.

**Pressurization tests (fan pressurization or duct blaster).** These methods involve sealing off the registers and using a calibrated fan to pressurize the duct system. Airflow measurements are taken at different static pressures to estimate total leakage. Case studies on light commercial rooftop units have shown that this technique can pinpoint leakage reductions from 36 percent to under 6 percent of fan flow (Proctor Engineering et al., 2002).

**Flow hood assessments.** In larger commercial settings, flow hoods combined with pitot traverses are sometimes used to compare total supplied versus measured flow at diffusers, estimating system leakage. Though less precise than pressurization, flow hood assessment often serves as an initial screening to identify whether duct sealing warrants closer investigation.

**Tracer gas methods.** Typically reserved for research or high-stakes environments like laboratories or healthcare facilities, this approach achieves very accurate measurements of duct leakage rates but requires specialized equipment.

**Physical inspection and thermal imaging.** Visual checks, smoke tests, and thermal images can help locate major holes or compromised seams. While not as quantitative, these approaches are useful to guide where more rigorous testing or sealing efforts should be focused.

## **Technology Options and Feasibility**

The evolution of duct sealing methods has produced multiple solutions, including manual taping with aluminum or butyl tape; mechanical fastening, which is sometimes paired with sheet-metal patches; mastic applications; and aerosol sealant sprays. Each technology carries unique benefits and limitations.

Manual approaches, such as applying mastic or reinforced tapes, can be very effective for large leaks but often require direct access to joints and seams. In practice, many leaks in older duct systems are hidden behind walls or in difficult-to-reach locations, limiting the overall impact of manual sealing.

By contrast, aerosol sealant technology automates the sealing process by delivering an atomized adhesive to all leak points as air escapes the ductwork. Multiple projects reported 70 to 90 percent reductions in leakage when aerosol methods were used (Diamond et al., 2003; Desai & Wu, 2022).

Industry professionals interviewed for this project noted that aerosol methods often succeed where manual inspection cannot reliably detect smaller, concealed leaks.

A large-scale demonstration involving over 400 light commercial rooftop systems achieved post-sealing leakage rates as low as 6 percent of fan flow, with a corresponding 25 percent reduction in cooling energy (Proctor Engineering et al., 2002). Studies in Minnesota and California documented the high effectiveness of aerosol methods but cautioned that larger gaps and missing blank-offs sometimes require mechanical repairs first (Quinnell et al., 2016; Harrington, 2014). Contractors cited that correct preparation—particularly protecting coils and dampers before aerosol injection—is a key factor in achieving durable, long-term performance.

For small commercial buildings—many of which were never required to pass rigorous leakage testing—initial feasibility often comes down to balancing cost with the potential for high-impact results. Buildings with simpler layouts, relatively short duct runs, and older systems are prime candidates for advanced sealing methods, particularly if the ductwork is partially inaccessible or poorly maintained.

### **Interview Insights and Lessons Learned**

Conversations with installing contractors, testing and balancing technicians, and property owners yielded several observations. Foremost among them was the recognition that smaller commercial buildings often cannot afford extended downtimes, making on-site labor efficiency paramount. Contractors noted that aerosol sealing can minimize the need to remove ceiling tiles or chase ductwork behind walls, which is critical in retail and office settings with minimal after-hours windows. Interviewees also highlighted that in single-zone or CAV systems, continuous fan operation exacerbates leakage-related energy losses, making any sealing intervention more valuable.

While installing contractors frequently cited success in cutting leakage by more than half, building owners emphasized the importance of cost justification. In short-term lease scenarios, payback periods beyond five to seven years are often seen as too long. Programs offering incentives or shared savings models help mitigate these cost barriers.

### **Cost Considerations**

Cost is often a deciding factor when weighing the benefits of duct sealing. Prior field efforts have cited expenses ranging from \$40,000 to \$50,000 to seal ducts in a retail setting with multiple rooftop units, though actual amounts vary widely based on building size, accessibility, system complexity, and off-hours labor requirements. Small commercial structures often rely on steady customer traffic throughout the day, so work must be done overnight or during weekends.

Interviewees specializing in both manual and aerosol methods agreed that aerosol sealing typically reduces labor in certain phases of the process—particularly for pinpointing and treating hidden leaks—yet may require added steps to protect sensitive HVAC components like heating coils and smoke dampers. Therefore, the resulting total cost depends on a combination of technology choices, building constraints, and the extent of protective measures required.

In smaller retail or office spaces where short tenant leases are common, landlord-tenant arrangements can complicate a direct return on investment. Landlords might be reluctant to invest in upgrades when utility costs are passed down to tenants, while tenants may be unwilling to fund



improvements that they cannot fully repay within their lease term. Incentive programs or well-documented payback projections often help overcome such barriers, particularly when projected savings can be clearly communicated.

### **Effectiveness and Durability in Practice**

Case studies consistently point to a significant drop in leakage—70 to 90 percent—when both preparatory repairs and aerosol sealing are undertaken (Desai & Wu, 2022; Diamond et al., 2003). Mechanical fastening plus mastic is also regarded as durable, particularly for large holes. However, manual methods alone may miss smaller leaks in inaccessible areas, yielding 40 to 50 percent improvement (Walker, 2001). In interviews, contractors also noted that some aerosol sealant products carry multi-year performance guarantees, offering reassurance of long-term durability. Durability appears closely tied to initial workmanship and the operating environment. In locations prone to vibration, large thermal swings, or moisture, the sealed surfaces can degrade if incompatible sealants are used. One installing contractor mentioned that water-based sealants crack quickly in exterior duct runs. This suggests that a tailored approach, such as combining manual pre-sealing with aerosol finishing, maximizes both short-term effectiveness and long-term reliability.

### **Energy and Cost Savings Potential**

A previous effort involving over 400 commercial rooftop systems achieved cooling energy savings of about 25 percent and heating energy savings of 15 percent, with peak demand reductions of up to 2.4 kilowatts (kW) per system (Proctor Engineering et al., 2002). Another investigation of mixed-use buildings found that sealing cut fan power usage by 40 percent in certain large commercial scenarios (Modera, 2005).

In small commercial buildings, single-zone CAV configurations run fans at near-constant speeds, so any leakage wastes energy during all occupied hours. Consequently, even modest leak reductions often produce meaningful utility cost savings within a relatively short payback period. A study in Minnesota recorded an average leakage reduction of 81 percent, resulting in significant heating and fan energy savings (Quinnell et al., 2016). While payback timelines varied, targeted screening of systems with higher leakage rates helped reduce the average payback to seven years.

### **Target Markets and Building Types**

Field data suggests that healthcare facilities, hotels, and schools frequently pursue duct sealing efforts due to large system loads and continuous or extended operating hours. However, smaller commercial establishments such as stand-alone retail shops and small offices also present a compelling market. These buildings often feature simpler, single-zone HVAC systems that lack advanced controls, are in continuous operation during business hours, and may have never been leakage-tested. Several experts noted that small commercial buildings often have simpler HVAC layouts, making it more straightforward to measure baseline conditions and verify improvements.

### **Market Drivers**

Key motivations for duct sealing include rising utility costs, occupant complaints over uneven temperatures, and heightened awareness about indoor air quality. Regulatory frameworks that require or encourage energy efficiency improvements can also be a motivation, though code-driven duct testing remains limited to certain projects. Building owners interviewed commonly cited the

influence of utility incentive programs, which help offset initial costs and address the uncertainties around payback periods. Yet several owners indicated they need clearer data on achievable leak reductions and tangible utility savings before proceeding.

### **NARROWING FOCUS: SMALL COMMERCIAL CAV SYSTEMS**

Integrating the above findings, the potential impact of duct sealing is particularly compelling in small commercial buildings equipped with CAV systems. Such installations often operate continuously, which amplifies the energy penalty when ducts leak. Due to the lower overall system complexity compared to large, multi-zone facilities, these buildings are also more responsive to cost-effective sealing interventions. Baseline testing is more straightforward in small commercial buildings where a simple flow hood measurement or pressurization test can quickly quantify leakage and determine viability. This simplicity and consistency in system configuration and operation make these building types especially suitable for a deemed measure approach, which is a central goal of this study.

In prior demonstration projects, many such establishments had never been leak-tested, resulting in baseline leakage rates that could exceed 20 percent of design airflow (Delp et al., 1998). By targeting these small commercial CAV systems, it is possible to significantly reduce fan, heating, and cooling energy.

## **Documented Baseline Leakage Rates**

Published case studies and field research consistently highlight the prevalence of moderate to severe leakage in commercial HVAC systems, often attributed to relaxed historical requirements and inconsistent workmanship.

### **Insights from Literature and Field Studies**

Many field projects have measured leakage rates in existing commercial duct systems. In a review of small commercial buildings, average supply-side leakage rates of 10 to 20 percent were common, with some locations reaching 30 to 35 percent (Delp et al., 1998; Wray et al.). Another study of 447 rooftop air-conditioning units reported an initial average leakage of 36 percent of fan flow (Proctor Engineering et al., 2002).

Duct sealing requirements have become stricter over time, meaning buildings constructed decades ago often exhibit higher leakage rates (Harrington, 2014). In systems predating modern codes, it was not unusual to find unsealed seams or poorly fitted duct connections, leading to leakage rates that substantially inflated energy usage.

Studies focusing on single-zone packaged rooftops suggest baseline leakage levels frequently exceed ten percent of system airflow (Delp et al., 1998). By contrast, larger multi-zone buildings may undergo partial testing in high-pressure areas, sometimes revealing more modest baseline leakage in those segments while still leaving downstream duct sections untested and potentially leaky.

## **Sealing Effectiveness Data**

In parallel with documenting baseline leakage, numerous studies have assessed the gains achieved through various sealing interventions. Based on the case study analysis, the project team found that the technology choice—manual taping, mechanical fastening, mastic, or aerosol spray—influences the final outcome.

### **Light Commercial Retrofits with Aerosol Spray**

One large-scale program in Southern California documented a drop from 36 percent to around 6 percent fan-flow leakage after sealing rooftop units with an aerosol method (Proctor Engineering et al., 2002). This improvement corresponded to an 80 percent leakage reduction with cooling energy savings in the range of 25 percent and heating savings of 15 percent.

### **Mixed Commercial and Industrial Buildings**

A pilot in Minnesota measured pre-sealing leakage rates from near-zero to over 10 percent across different properties, then observed an average 81 percent reduction in leaks post-sealing (Quinnell et al., 2016). Some cases achieved payback within seven years by prioritizing systems with the highest initial leakage.

### **Larger Facilities with Complex Duct Networks**

Studies in bigger commercial properties, including universities and hospitals, showed that even partial sealing campaigns—often combining manual repairs for large openings with aerosol technology for smaller gaps—lowered leakage to under 5 percent of fan flow (Mark Modera, 2005; Diamond et al., 2003).

Collectively, multiple case studies demonstrate that simple manual methods alone often reduce system leakage by 40 to 50 percent (Walker, 2001). Using advanced methods, particularly when preceded by patching major defects, can achieve a 70 to 90 percent leakage reduction (Desai & Wu, 2022; Harrington, 2014).

## **Energy Modeling Approach**

While the case study review illustrates the scale and importance of duct leakage challenges, developing a robust energy modeling framework for small commercial buildings requires a more granular understanding of the factors that drive leakage rates and savings potential. In the upcoming sections, the project team synthesizes multiple strands of existing research and field data—ranging from duct system design conventions to regulatory requirements—to build a foundation for modeling. This transition phase lays out the technical details needed for accurately simulating how duct sealing retrofits influence energy consumption and peak demand. Several focal areas stand out as particularly important for guiding the modeling design and assumptions.

### **Focal Areas**

#### **Codes and Regulations for Duct Sealing**

California's regulatory landscape has evolved over the past two decades, gradually imposing stricter duct sealing and testing requirements. By examining how historical codes differ from today's standards, the project team can better estimate the baseline leakage conditions in buildings of various vintages. Buildings constructed during periods of looser standards are more likely to exhibit high leakage rates, while those built or retrofitted under more stringent requirements tend to have lower default leakage values. Current duct sealing requirements and the evolution of regulation across code cycles are provided in the Background section of this report.

## **Duct System Configurations in Small Commercial Buildings**

Typical small commercial establishments tend to rely on packaged rooftop units or straightforward supply and exhaust duct networks. Understanding duct layouts helped the project team identify representative scenarios for energy modeling, including common duct routing and ceiling cavity and mechanical equipment characteristics. Such details ensure that simulated airflow paths reflect real-world conditions.

### **Thermal Barrier and Duct Location**

The location of ductwork relative to a building's thermal envelope critically affects how leakage translates into energy waste. Ducts outside the conditioned space often exacerbate cooling or heating loads, while ducts within conditioned zones may incur smaller thermal penalties. Recognizing these distinctions allows the modeling approach to differentiate between leakage-to-outside versus -inside, and to quantify their respective energy impacts.

### **Documented Baseline Leakage Rates**

Field measurements in commercial buildings have consistently shown that baseline leakage can range from minor levels of under 10 percent to more extreme scenarios exceeding 30 percent. The project team synthesized the relevant data and categorized findings by building type and era.

### **Published Sealing Effectiveness Data**

Empirical studies suggest that, with the implementation of the right sealing method, total leakage can be reduced substantially. The project team further explored these findings and translated them into realistic post-sealing assumptions for energy modeling.

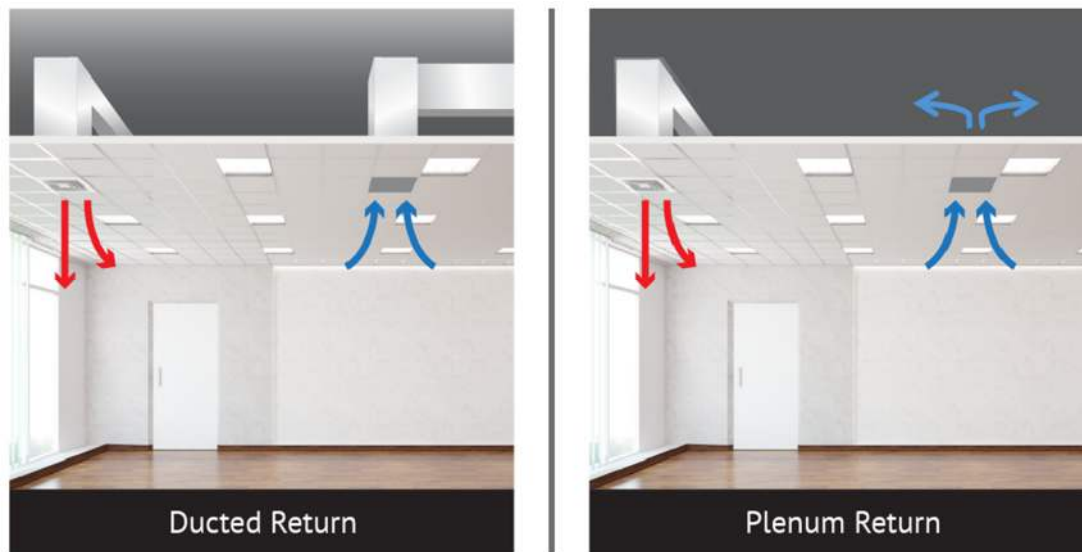
## **Duct Configuration Scenarios**

### **Fully Ducted Supply with Plenum Return**

In this arrangement, the HVAC unit delivers conditioned air through insulated supply ducts to the occupied zones. The return path relies on the ceiling space—or sometimes a dedicated overhead plenum—to collect return air, which then flows back to the HVAC unit through one or more return openings. Ceiling tiles are used to separate the occupied space from the plenum above, which results in a lower initial cost and easier routing in tight ceiling spaces.

### **Fully Ducted Supply and Return**

In fully ducted return systems, every return grille is connected back to the HVAC unit through its own set of return ducts. This configuration provides greater control over airflow but at a higher cost. This duct configuration offers better indoor air quality control because return air moves through sealed ductwork with a lower risk of drawing unwanted air from above-ceiling or unconditioned spaces. Figure 1 depicts fully ducted versus plenum return configurations.



**Figure 1: Ducted supply and return versus plenum return configuration.**

## Duct Configuration in Small Commercial Buildings

In designing HVAC systems for smaller commercial buildings—such as standalone retail units, small offices, and low-rise mixed-use facilities—engineers and contractors often rely on a ceiling plenum return. In this arrangement, conditioned supply air is delivered via ductwork to occupied spaces, while return air travels back to the HVAC equipment through the overhead ceiling cavity rather than dedicated return ducts. Multiple studies and reference building models confirm that this plenum approach remains dominant in small commercial settings (California Energy Commission, 2022; Deru et al., 2011).

Researchers at the Lawrence Berkeley National Laboratory (LBNL) have documented that, among buildings under 10,000 square feet, a large majority incorporate a plenum return, mostly because the method reduces materials, installation labor, and required ceiling space (Deru et al., 2011). These observations align with the prototypical building models developed by the Pacific Northwest National Laboratory (PNNL), which frequently assume plenum returns for small and medium commercial energy simulations (U.S. Department of Energy & PNNL).

Cost-effectiveness and ease of construction are among the most frequently cited motivations for adopting a plenum return, particularly in single-zone CAV systems. In California, for example, rooftop package units commonly serve small commercial suites using a supply duct plus overhead plenum return design (California Energy Commission, 2022). While the state’s energy code, Title 24, Part 6, does not require plenum returns per se, the Nonresidential Compliance Manual compiled by the California Energy Commission often references them as a typical or illustrative scenario in these building types (California Energy Commission, 2022). In practice, building owners and designers view plenum returns as a straightforward way to meet baseline ventilation needs without incurring the higher costs and space requirements of a fully ducted return. Publications from the American Society for Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) also note that small commercial owners typically prefer plenum returns due to lower installation expenses, faster project schedules, and simplified system layouts (ASHRAE, 2019).



## Thermal Barrier Configurations

In small commercial buildings, the location of the thermal barrier—the primary insulation boundary—can vary significantly. Broadly, there are three main scenarios:

- Roof-level insulation—above or below roof deck
- Ceiling-level insulation—laid on the dropped ceiling
- Hybrid or mixed—some insulation at roof, some at ceiling

Within small commercial buildings, the location of the thermal barrier—whether at the ceiling plane or at the roof deck—can substantially influence energy consumption, occupant comfort, and HVAC duct performance. Over the past few decades, building codes and industry practices have evolved to emphasize tighter envelopes and reduced duct leakage. However, many older small commercial properties retain legacy insulation strategies that place insulation only on the dropped ceiling, effectively leaving the plenum or attic unconditioned.

### Scenario 1: Roof-Deck Insulation (Modern or Comprehensive Retrofits)

In newer small commercial or extensively renovated buildings, insulation is more likely to reside at the roof deck, either on the interior, e.g., spray foam on the underside, or exterior, e.g., rigid board above the deck. This approach brings the entire ceiling plenum—or much of it—within or near the conditioned envelope, as shown below in Figure 2.



Figure 2: Roof-level insulation.

### REASONS AND FIELD INSIGHTS

- **Stringent energy codes.** Both California's Title 24, Part 6 and national standards, such as ASHRAE 90.1, encourage continuous insulation at the roof level to reduce thermal bridging and improve overall envelope tightness.
- **Reduced duct losses.** Locating ducts in a semi-conditioned or fully conditioned plenum ensures that any leakage has a smaller energy penalty noticeable drops in HVAC energy use when older ceiling-insulated systems retrofit to roof-level insulation, thereby minimizing extreme temperature differentials in the plenum.(Modera et al. 2014).
- **Compliance simplicity.** Modern code compliance manuals—e.g., the 2022 Title 24 Nonresidential Compliance Manual—often present roof-deck insulation as a straightforward pathway to meet mandatory minimum U-factors and infiltration targets.

## IMPACT ON ENERGY PERFORMANCE

By insulating at the roof, designers avoid the pitfalls of hot or cold air pockets forming above the ceiling tiles, lowering conduction losses and improving comfort. PNNL prototypes and other reference models for small office and retail projects routinely assume roof-deck insulation in post-2010 code-compliant buildings, reflecting industry trends toward a unified thermal envelope.

### Scenario 2: Ceiling-Level Insulation (Older Construction)

In many older small commercial buildings—particularly those constructed before the mid-2000s—insulation is typically laid above a dropped, or T-bar, ceiling, designating the ceiling plane as the primary thermal boundary, as shown in Figure 3. This approach often leaves the space above the ceiling outside or partially outside the conditioned envelope.



Figure 3: Ceiling-level insulation.

## REASONS AND FIELD INSIGHTS

- **Legacy code requirements.** Before newer energy codes gained traction, basic prescriptive measures allowed the use of minimal or moderate R-values at the ceiling plane, without enforcing consistent roof-deck insulation.
- **Cost and convenience.** Older projects favored rolling out batt or loose-fill insulation over ceiling tiles for quick installation and minimal interference with the roof assembly.

According to (Modera, 2005), field investigations in California light commercial buildings revealed that in older structures, “insulation was located only on the ceiling about 50 percent of the time, only on the roof deck 38 percent of the time, and in both places 12 percent of the time.” Furthermore, a significant fraction—38 percent—had ceiling tiles functioning as the primary air barrier, implying that the ducts above the ceiling were effectively outside the conditioned space.

(Modera, 2005) also emphasizes that ceiling plenum ducts in older light commercial buildings frequently leak into unconditioned or semi-conditioned spaces, inflating fan energy use. Where insulation remains exclusively at the ceiling, the temperature of the plenum can exceed outside ambient levels, exacerbating thermal losses from leaky duct segments.

## IMPACT ON ENERGY PERFORMANCE

Because the attic or plenum above the dropped ceiling is not thermally integrated with occupied



areas, the HVAC system must overcome higher gains or losses when duct leakage occurs. Studies by the LBNL indicate that ducts located above the ceiling can incur substantial cooling penalties in hot climates, as the plenum can reach extreme temperatures. Meanwhile, any supply air leakage or infiltration in that overhead space rarely benefits the occupied zone.

### **Scenario 3: Hybrid or Partial Upgrades**

Not all buildings fall neatly into “ceiling-only” or “roof-only” insulation categories. When an owner replaces just part of the roof or adds code-required rigid board above the deck yet retains older batt insulation on the dropped ceiling, a partial configuration similar to Figure 4 emerges.



**Figure 4: Hybrid insulation of ceiling and roof.**

### **REASONS AND FIELD INSIGHTS**

Building owners often tackle roof replacements or partial code compliance mandates without removing existing ceiling insulation. Over time, this can create a layered effect with some insulation at the roof deck and some left at the ceiling plane.

As noted in (Modera, 2005), if the ceiling remains more airtight than the roof assembly—for instance, due to existing older vents or rooftop penetrations—then even a newly insulated roof may not fully bring the plenum into the conditioned zone.

Hybrid setups were documented in “Hybrid Roofing Retrofits and the Insulation Boundary,” which highlights the difficulties of modeling infiltration and conduction in partially conditioned overhead spaces (ASHRAE, 2016).

### **IMPACT ON ENERGY PERFORMANCE**

Energy outcomes for hybrid approaches can be better than a purely ceiling-insulated system yet fall short of a fully roof-insulated design. With insulation installed in two planes, some portion of duct leakage or conduction may still occur in an effectively unconditioned zone. Proper sealing and air-barrier continuity are critical to ensure that partial upgrades yield meaningful savings.

## Energy Modeling

Building on the insights from the previous sections, this analysis focuses on developing a robust modeling framework for small commercial buildings with CAV systems. Drawing from the literature review, the project team concluded that many small commercial facilities deploy supply ducts and use the ceiling plenum as a return path. Additionally, code evolution over the past decade has increased the likelihood of the thermal barrier being placed at the roof deck in newer buildings, while older buildings commonly retain ceiling-level insulation. In the latter case, ducts are effectively located outside the conditioned envelope, which amplifies energy savings potential when duct leakage is reduced.

### Energy Modeling Tool and Scenarios

To quantify these effects, the project team used EnergyPlus—an industry-standard simulation engine—and the Database for Energy Efficient Resources (DEER) prototype models for commercial buildings, consistent with the utility program measure development protocol set by the CPUC. This study incorporated parametric modeling using Modelkit to explore duct leakage performance across 16 California climate zones for the existing vintage.

The project team defined two modeling scenarios to represent the distinct ways of simulating duct leakage from supply ducts in EnergyPlus, as shown in Table 1.

**Table 1: Modeling approaches.**

| Potential Modeling Approach | Duct Configuration Scenarios  | Thermal Barrier Configurations                | DEER Prototypes Compatibility |
|-----------------------------|-------------------------------|-----------------------------------------------|-------------------------------|
| Leakage to inside           | Plenum return                 | Roof-deck insulation                          | High                          |
| Leakage to outside          | Plenum return or fully ducted | Ceiling-plane insulation or ventilated plenum | High, with simplifications    |

### Leakage to Inside (SDLM)

In this approach, the project team treated the duct losses as a percentage of supply airflow leaking directly to the return airflow pathway in a short-circuit effect. This scenario assumes leakage occurs within the thermal envelope (“leakage to inside”), reflecting cases where the plenum or attic is within the thermal envelope but minimally separated from occupied zones. It is applicable to systems with ducted supply and direct plenum return. The project team used the Simplified Duct Leakage Method (SDLM) in EnergyPlus for leakage-to-inside modeling. In this method, “Nominal Upstream Leakage Fraction” in “ZoneHVAC: AirDistribution” class was modified with the percentage leakage fraction from base and measure cases. Based on EnergyPlus “Input-Output Reference,” SDLM considers that supply air leaks to a return plenum in a commercial variable-air-volume (VAV) or CAV system. So, this approach assumes that leakage occurs within the thermal envelope (“leakage to inside”) by supply

air leaking directly to the return airflow pathway in a short-circuit pathway. Figure 5 shows a snapshot of EnergyPlus IDF editor for this method.

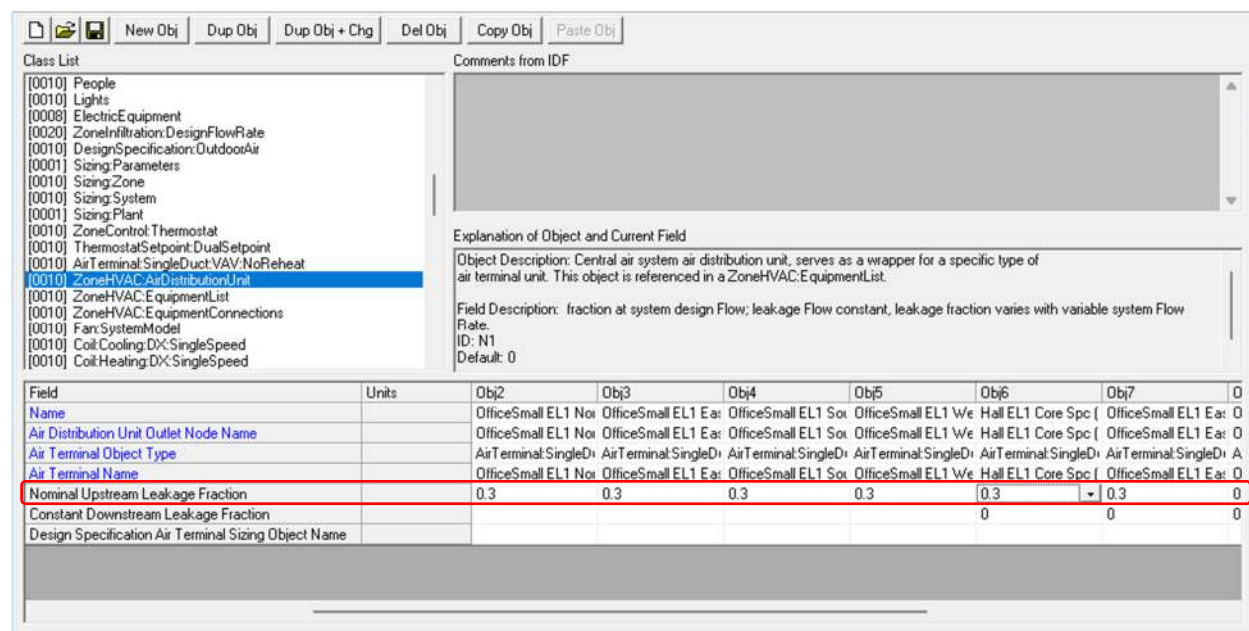


Figure 5: EnergyPlus IDF editor for leakage-to-inside or SDLM scenario.

The project team used Modelkit to manage parametric simulations, with relevant parameters—such as the “atu\_leak\_supply\_frac” variable—defined in the cases file. Please note that the project team first modified the “Air Distribution Type” to a CAV system. However, one limitation of this approach is that EnergyPlus imposes a maximum upstream leakage fraction of 0.3, or 30 percent, which restricts simulations from modeling leakage fractions greater than 30 percent of the supply air.

## Leakage to Outside (OA)

Here, the model assigns airflow to the ceiling plenum zone, treating it as a semi-conditioned or unconditioned space. This allows for capturing more realistic temperature and infiltration effects—particularly in older buildings where the plenum lies fully outside the conditioned envelope. This approach can represent buildings with plenums inside or outside the thermal envelope.

Since the leakage occurs to the outside in this scenario, it is reasonable to assume that the leaked air will be replaced by outdoor air to maintain the consistency of the airflow in the duct system.

Unlike SDLM, the leakage-to-outside scenario does not have a predesigned modeling method in EnergyPlus. To implement this approach, the project team modified parameters in the "Controller:OutdoorAir" class. First, the project team set the "Minimum Limit Type" to "ProportionalMinimum," meaning the minimum outdoor airflow rate varies in proportion to the total system airflow rate. Additionally, the project team defined a "Minimum Fraction of Outdoor Air Schedule," which is a fractional schedule that multiplies the current system mixed air flow rate to determine the minimum outdoor air (OA) flow rate. Figure 6 shows a snapshot of EnergyPlus IDF editor for this method.

With this configuration, the project team ensured that the leaked airflow percentage is compensated by outdoor air as the duct system already experiences leakage to the outside. The limitation of this method is that it is not able to model the zones with more than 30 percent of the OA fraction.

In both the leakage-to-inside and leakage-to-outside scenarios, we assumed that the supply airflow remains unchanged before and after duct sealing. The leaked air is considered to be replaced by indoor air in the case of leakage-to-plenum (inside), and by outdoor air in the case of leakage-to-outside. In both cases, the energy penalty is estimated as an additional thermal load imposed on the system to account for the leakage. In real-world conditions, duct leakage may result in reduced supply airflow to the conditioned space, which can somewhat affect thermal comfort. However, since this study does not model comfort impacts due to reduced airflow, the assumption of constant supply airflow represents a reasonable simplification for energy modeling purposes.

**Class List**

- [0010] Fan:SystemModel
- [0010] Coil:Cooling:DX:SingleSpeed
- [0010] Coil:Heating:DX:SingleSpeed
- [0010] AirLoopHVAC:UnitarySystem
- [0010] **Controller:OutdoorAir**
- [0010] AirLoopHVAC:ControllerList
- [0010] AirLoopHVAC
- [0010] AirLoopHVAC:OutdoorAirSystem:EquipmentList
- [0010] AirLoopHVAC:OutdoorAirSystem
- [0010] OutdoorAir:Mixer
- [0010] AirLoopHVAC:ZoneSplitter
- [0010] AirLoopHVAC:SupplyPath
- [0010] AirLoopHVAC:ZoneMixer
- [0010] AirLoopHVAC:ReturnPath
- [0025] Branch
- [0012] BranchList
- [0002] Connector:Splitter
- [0002] Connector:Mixer

**Comments from IDF**

**Explanation of Object and Current Field**

Object Description: Controller to set the outdoor air flow rate for an air loop. Control options include fixed, proportional, scheduled, economizer, and demand-controlled ventilation.

Field Description:  
ID: A1  
Enter a alphanumeric value  
This field is required.

| Field                                         | Units | Obj1                                                          | Obj2                | Obj3                | Obj4                |
|-----------------------------------------------|-------|---------------------------------------------------------------|---------------------|---------------------|---------------------|
| Economizer Maximum Limit Enthalpy             | J/kg  |                                                               |                     |                     |                     |
| Economizer Maximum Limit Dewpoint Temperature | C     |                                                               |                     |                     |                     |
| Electronic Enthalpy Limit Curve Name          |       |                                                               |                     |                     |                     |
| Economizer Minimum Limit Dry-Bulb Temperature | C     | 4.44444444E+00                                                | 4.44444444E+00      | 4.44444444E+00      | 4.44444444E+00      |
| Lockout Type                                  |       | Lockout/WithHeating                                           | Lockout/WithHeating | Lockout/WithHeating | Lockout/WithHeating |
| Minimum Limit Type                            |       | ProportionalMinimum                                           | ProportionalMinimum | ProportionalMinimum | ProportionalMinimum |
| Minimum Outdoor Air Schedule Name             |       | Hall EL1 Core Spc (G.C5) SZ-CAV Outdoor Air Schedule          | OfficeSmall EL1 No  | OfficeSmall EL1 Ea  | OfficeSmall EL1     |
| Minimum Fraction of Outdoor Air Schedule Name |       | Hall EL1 Core Spc (G.C5) SZ-CAV Outdoor Air Fraction Schedule | OfficeSmall EL1 No  | OfficeSmall EL1 Ea  | OfficeSmall EL1     |
| Maximum Fraction of Outdoor Air Schedule Name |       |                                                               |                     |                     |                     |
| Mechanical Ventilation Controller Name        |       |                                                               |                     |                     |                     |
| Time of Day Economizer Control Schedule Name  |       |                                                               |                     |                     |                     |

Figure 6: EnergyPlus IDF editor for leakage-to-outside (OutdoorAir Controller) scenario.

## Measure Offering Design

Based on initial reviews of energy savings, the project team ran models with various leakage percentages using both modeling methodologies, combining different base and measure case leakages to create the offering scenarios. Due to EnergyPlus limitations, the highest initial leakage value modelled was 30 percent, while the lowest leakage value was 5 percent. The high, low, and improvement percentage of leakage is supported by the previous CalNEXT market study and the pre- and post-testing required to claim savings.

The modeling was focused on the small business building types identified in the CalNEXT market study using existing vintage DEER prototypes. Additionally, we modeled all unitary HVAC system types currently available in the DEER prototypes.

Table 2: Measure offering leakage scenarios.

| Leakage Type       | Base Leakage | Measure Leakage | Improvement |
|--------------------|--------------|-----------------|-------------|
| Leakage to inside  | 30%          | 25%             | 5%          |
| Leakage to inside  | 30%          | 20%             | 10%         |
| Leakage to inside  | 30%          | 15%             | 15%         |
| Leakage to inside  | 30%          | 10%             | 20%         |
| Leakage to inside  | 30%          | 5%              | 25%         |
| Leakage to inside  | 25%          | 20%             | 5%          |
| Leakage to inside  | 25%          | 15%             | 10%         |
| Leakage to inside  | 25%          | 10%             | 15%         |
| Leakage to inside  | 25%          | 5%              | 20%         |
| Leakage to inside  | 20%          | 15%             | 5%          |
| Leakage to inside  | 20%          | 10%             | 10%         |
| Leakage to inside  | 20%          | 5%              | 15%         |
| Leakage to inside  | 15%          | 10%             | 5%          |
| Leakage to inside  | 15%          | 5%              | 10%         |
| Leakage to inside  | 10%          | 5%              | 5%          |
| Leakage to outside | 30%          | 25%             | 5%          |
| Leakage to outside | 30%          | 20%             | 10%         |
| Leakage to outside | 30%          | 15%             | 15%         |
| Leakage to outside | 30%          | 10%             | 20%         |
| Leakage to outside | 30%          | 5%              | 25%         |

| Leakage Type       | Base Leakage | Measure Leakage | Improvement |
|--------------------|--------------|-----------------|-------------|
| Leakage to outside | 25%          | 20%             | 5%          |
| Leakage to outside | 25%          | 15%             | 10%         |
| Leakage to outside | 25%          | 10%             | 15%         |
| Leakage to outside | 25%          | 5%              | 20%         |
| Leakage to outside | 20%          | 15%             | 5%          |
| Leakage to outside | 20%          | 10%             | 10%         |
| Leakage to outside | 20%          | 5%              | 15%         |
| Leakage to outside | 15%          | 10%             | 5%          |
| Leakage to outside | 15%          | 5%              | 10%         |
| Leakage to outside | 10%          | 5%              | 5%          |

## Energy Savings

In this section, the project team presents and analyzes the results for various building prototypes, HVAC systems, and air leakage methods across California's 16 climate zones. The building prototypes evaluated in this study include small commercial buildings: small office buildings (OfS), fast food restaurants (RFF), dine-in restaurants (RSD), and retail stores (RtS).

The team evaluated two types of air leakage: leakage to inside (SDLM) and leakage to outside (OA). We assessed these across different HVAC system types, including direct expansion heat pump (DXHP), direct expansion cooling with gas furnace (DXGF), direct expansion cooling with no heating (DXOH), and no cooling with gas furnace heating (NCGF).

The results are presented by showing the percentage of total energy savings for both regulated and unregulated loads; the percentage of HVAC savings for heating, cooling, and fan; and the percentage of total saving based on percent improvement for each method and HVAC type across California's 16 climate zones. The project team combined the electric and gas savings as total energy savings for the purpose of comparison. Appendix A includes the results for gas and electric savings, savings per square foot of conditioned area, and percentage of HVAC savings based on percent improvement.

### Small Office Building (OfS)

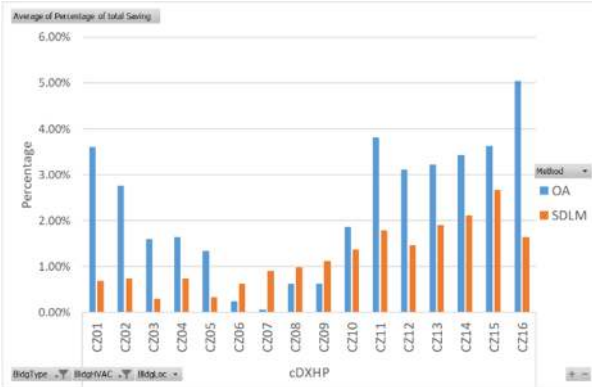
#### PERCENTAGE OF TOTAL ENERGY SAVINGS

Figure 7 illustrates the percentage of total energy savings for the small office building, comparing different HVAC systems across 16 climate zones. Subfigures (a), (b), (c), and (d) display energy

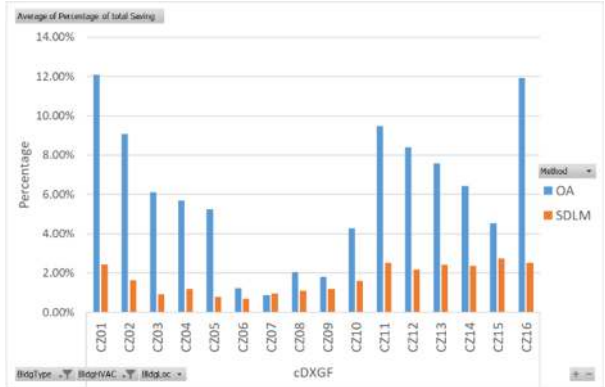


savings for the DXHP, DXGF, DXOH, and NCGF systems, respectively. As mentioned, SDLM refers to the leakage-to-inside method, while OA represents the leakage-to-outside method. The graphs show that, across all HVAC systems, the leakage-to-outside method generally results in greater energy savings across most climate zones. This is primarily due to the increased heating and cooling loads required to compensate for the unconditioned outdoor air entering the building, compared to the recirculated conditioned air in the leakage-to-inside method.

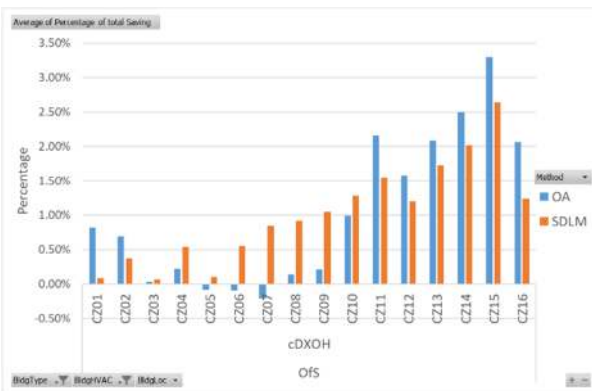
The difference in energy savings between the two leakage methods is more pronounced in systems that provide both heating and cooling—DXHP and DXGF—compared to systems that offer either heating or cooling—DXOH and NCGF. Additionally, across all system types, energy savings tend to be lower in mild or coastal climate zones than in more extreme inland zones. This is expected, as there is less heating and cooling energy to offset in milder climates. Gas furnace system types—such as DXGF and NCGF—tend to show greater energy savings compared to their equivalent heat pump systems—DXHP and DXOH. This is primarily because gas furnaces are generally less energy efficient than heat pumps, so improvements in duct sealing have a more substantial impact. As a result, even a small percentage of leakage reduction leads to greater energy savings in these less-efficient systems.



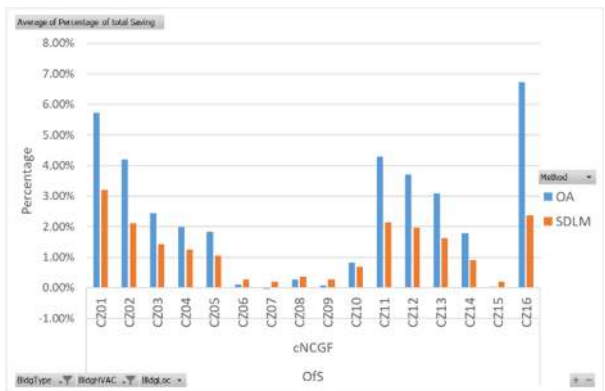
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



(d) No cooling with gas furnace heating (NCGF)

Figure 7: Percentage of total energy savings for different HVAC types and leakage methods (OfS).

Table 3 presents the average percentage of total energy savings across 16 climate zones for each leakage scenario. In other words, the values in the table represent the average percentage of blue and orange bars shown in Figure 7. There are significant average savings for DXGF in OA method (6.06 percent) compared to SDLM (1.71 percent).

Table 3: Average percentage of total energy savings across 16 climate zones for each leak scenario (OfS).

| Leak Scenario         | DXHP  | DXGF  | DXOH  | NCGF  |
|-----------------------|-------|-------|-------|-------|
| OA (leak to outside)  | 2.29% | 6.06% | 1.03% | 2.32% |
| SDLM (leak to inside) | 1.21% | 1.71% | 1.01% | 1.25  |

## PERCENTAGE OF HVAC ENERGY SAVINGS

This section compares the savings percentages for different leakage methods at the HVAC level. The project team expects higher savings here compared to the total energy savings presented in the previous section. The savings ratios for various methods across different HVAC types are like those in the previous section, but with higher values. Figure 8 shows the percentage of HVAC savings for different leakage scenarios across 16 climate zones and different HVAC systems, and Table 4 presents the average of the savings for each leakage scenario in each HVAC type across 16 climate zones.

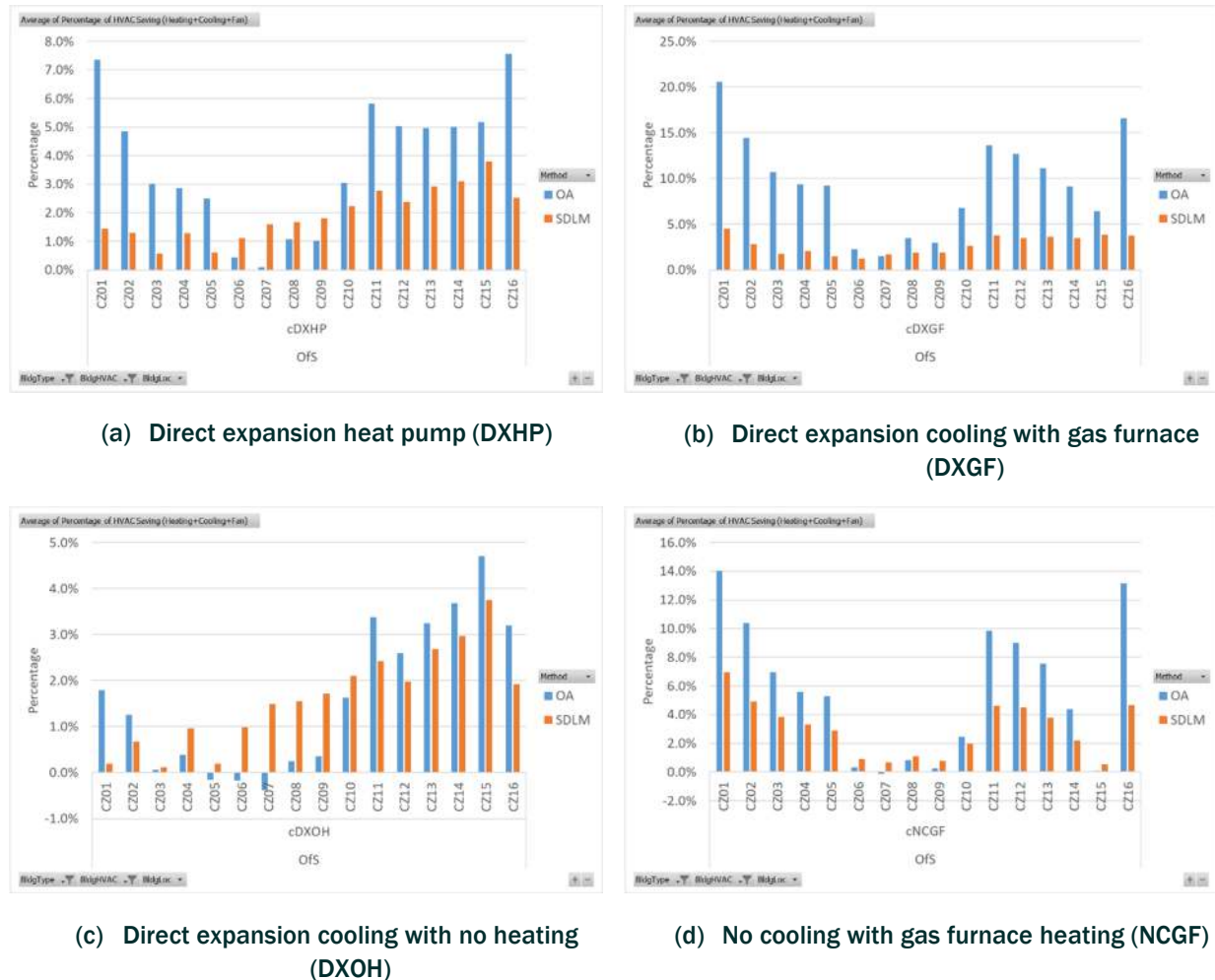


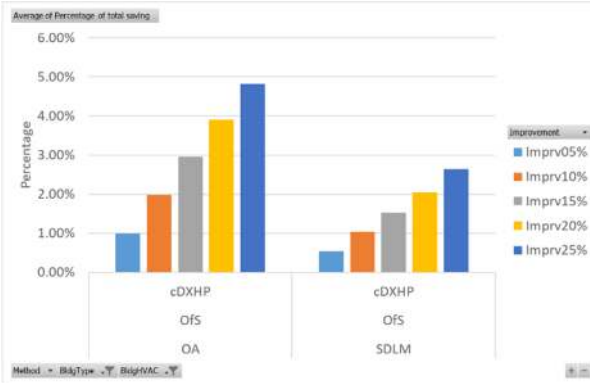
Figure 8: Percentage of HVAC energy savings for different HVAC types and leakage methods (OfS).

Table 4: Average percentage of HVAC energy savings across 16 climate zones for each leak scenario (OfS)

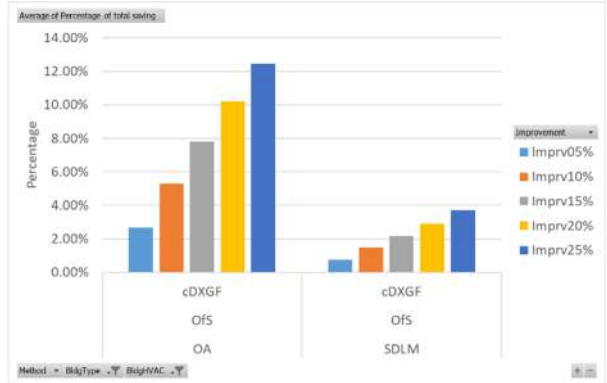
| Leak Scenario         | DXHP | DXGF | DXOH | NCGF |
|-----------------------|------|------|------|------|
| OA (leak to outside)  | 3.7% | 9.4% | 1.6% | 5.6% |
| SDLM (leak to inside) | 1.9% | 2.7% | 1.6% | 3.0% |

#### PERCENTAGE OF TOTAL SAVINGS BASED ON PERCENT IMPROVEMENT

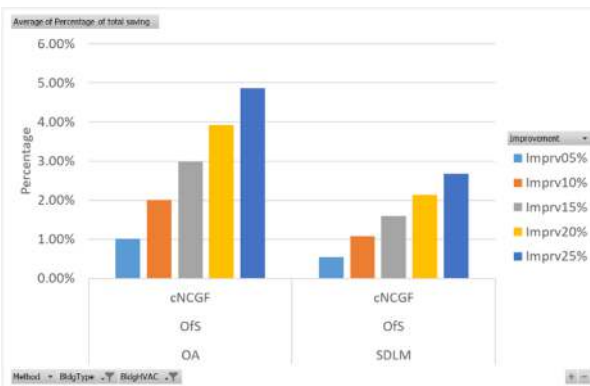
Figure 9 presents the percentage of total energy savings as a function of percent improvement of total leakage for different HVAC types and leakage methods in an office building. There is a linear relationship between percent improvement (x-axis) and total energy savings (y-axis). In the leakage-to-outside (OA) scenario, the slope of this linear trend is steeper than for the leakage-to-inside (SDLM) scenario. For all HVAC types, the leakage-to-outside scenario results in greater energy savings, except for NCGF, which shows nearly identical savings for both leakage scenarios.



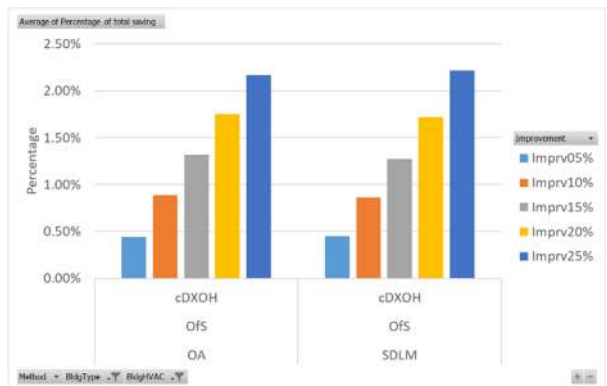
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



(d) No cooling with gas furnace heating (NCGF)

Figure 9: Percentage of total energy savings based on percent improvement for different HVAC types and leakage methods (Ofs).

## Restaurant Fast Food (RFF)

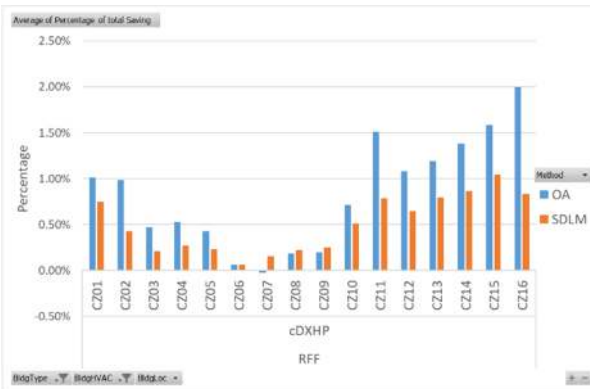
### PERCENTAGE OF TOTAL ENERGY SAVINGS

Figure 10 illustrates the percentage of total energy savings for each leakage scenario and HVAC type across 16 climate zones for a fast food restaurant prototype. Subfigures (a), (b), (c), and (d) present results for the following HVAC systems, respectively: DXHP, DXGF, DXOH, and NCGF.

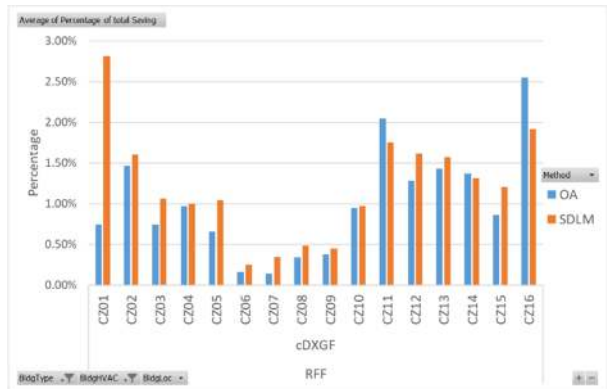
When comparing the energy savings patterns between the two leakage scenarios across different HVAC systems, the project team noticed that, for the NCGF system, which does not include cooling, the SDLM (leakage-to-inside) scenario results in greater energy savings than the OA (leakage-to-outside) method. Conversely, in the DXOH system, which lacks heating, the OA scenario yields higher savings compared to SDLM. The project team attributes this difference to the high internal heat gains typical in restaurant settings, making them cooling-dominated environments.

Another observation is that, regardless of system types, the leakage-to-inside method has yields greater savings than the leakage-to-outside method in mild, coastal climates, such as Climate Zone

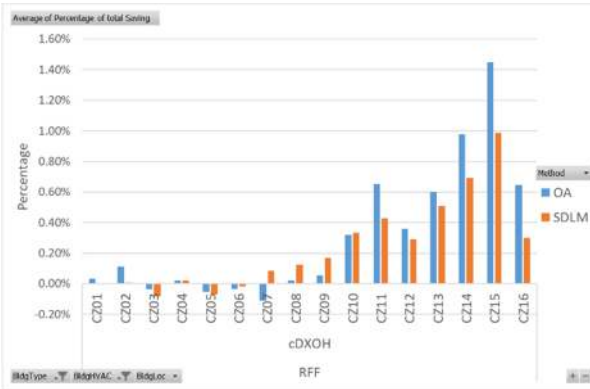
6 through Climate Zone 9; this makes sense due to mild outside temperatures and high economizer run times.



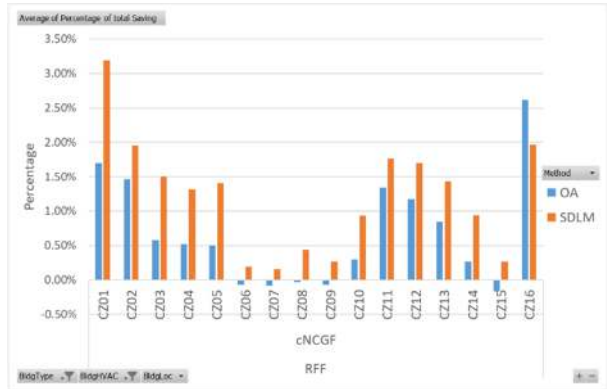
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



(d) No cooling with gas furnace heating (NCGF)

Figure 10: Percentage of total energy savings for different HVAC types and leakage methods (RFF).

Table 5: Average percentage of total energy savings across 16 climate zones for each leak scenario (RFF).

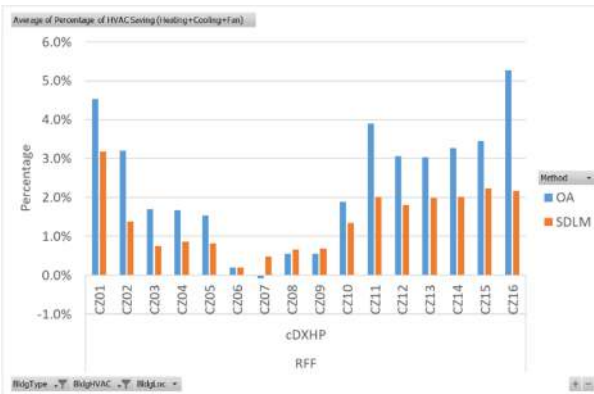
| Leak Scenario         | DXHP | DXGF | DXOH | NCGF |
|-----------------------|------|------|------|------|
| OA (leak to outside)  | 2.4% | 2.6% | 0.8% | 2.7% |
| SDLM (leak to inside) | 1.4% | 3.3% | 0.6% | 4.2% |



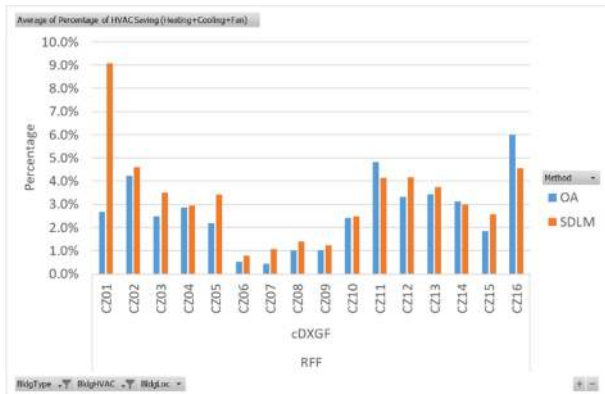
## PERCENTAGE OF HVAC ENERGY SAVINGS

Figure 11 compares the HVAC energy savings percentages for different leakage and HVAC types.

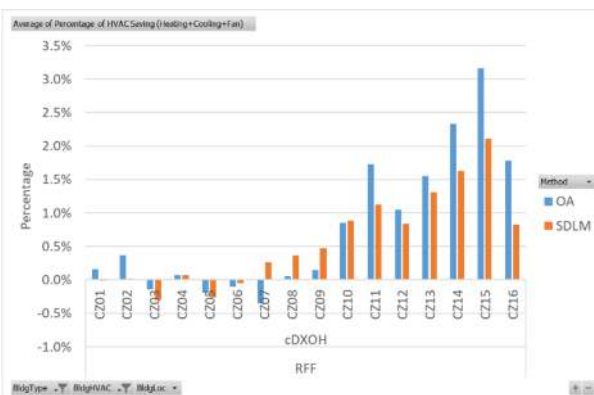
Table 6 shows the average value of HVAC savings for each leakage scenario across 16 climate zones for each HVAC type.



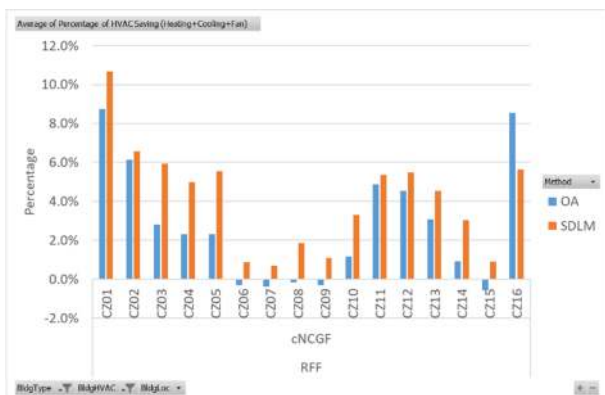
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



(d) No cooling with gas furnace heating (NCGF)

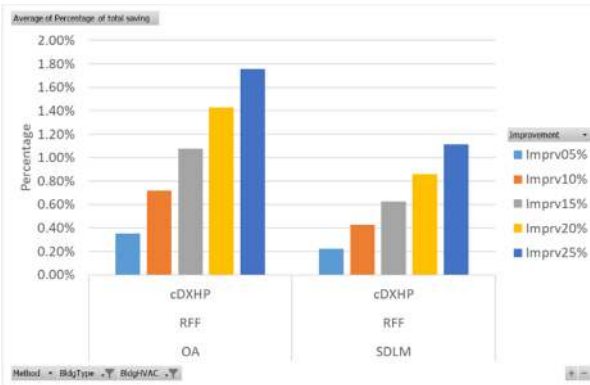
Figure 11: Percentage of HVAC energy savings for different HVAC types and leakage methods (RFF).

Table 6: Average percentage of HVAC energy savings across 16 climate zones for each leak scenario (RFF).

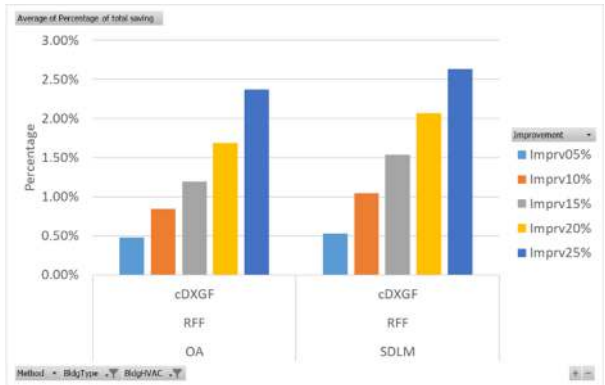
| Leak Scenario         | DXHP  | DXGF  | DXOH  | NCGF  |
|-----------------------|-------|-------|-------|-------|
| OA (leak to outside)  | 0.83% | 1.01% | 0.31% | 0.68% |
| SDLM (leak to inside) | 0.5%  | 1.21% | 0.24% | 1.21% |

## PERCENTAGE OF TOTAL SAVINGS BASED ON PERCENT IMPROVEMENT

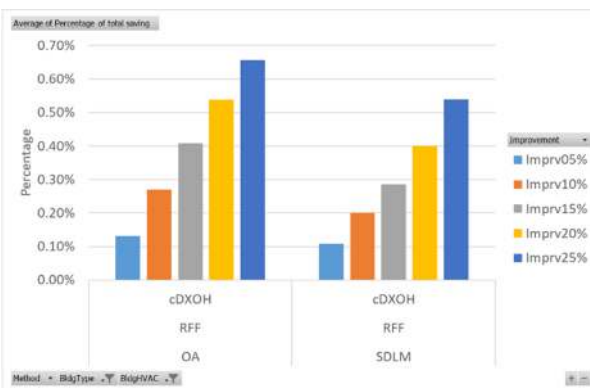
Figure 12 illustrates the relationship between percent improvement and total energy savings across various HVAC types and leakage methods in the RFF building type. For DXHP and DXOH, the leakage-to-outside percentage savings increases more with percentage improvement compared to the leakage-to-inside method. The DXGF system, however, shows nearly identical savings for both leakage scenarios.



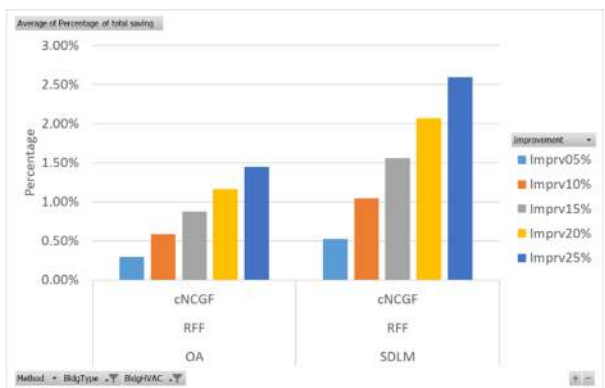
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



(d) No cooling with gas furnace heating (NCGF)

Figure 12: Percentage of total savings based on percent improvement for different HVAC types and leakage methods (RFF).

## Retail Store (RtS)

### PERCENTAGE OF TOTAL ENERGY SAVINGS

Figure 13 shows the total energy savings for various leakage scenarios and HVAC system types across 16 climate zones for retail stores (RtS). The subfigures (a), (b), (c), and (d) display the outcomes for the following HVAC systems, respectively: DXHP, DXGF, DXOH, and NCGF.

For this prototype, the leakage-to-outside method yields greater energy savings than the leakage-to-inside method for the DXGF and DXHP systems in most climate zones. Like the RFF case, the NCGF system shows that the SDLM approach results in higher savings compared to the OA method. For the

DXOH system, in cooling-dominated climate zones—like Climate Zone 1 and Climate Zone 16—the leakage-to-outside method again provides more savings than the leakage-to-inside method. In the remaining climate zones, the savings from both methods are relatively similar. As observed in other building types, the leakage-to-inside method offers greater savings in mild or coastal climate zones, such as Climate Zone 6 through Climate Zone 9.

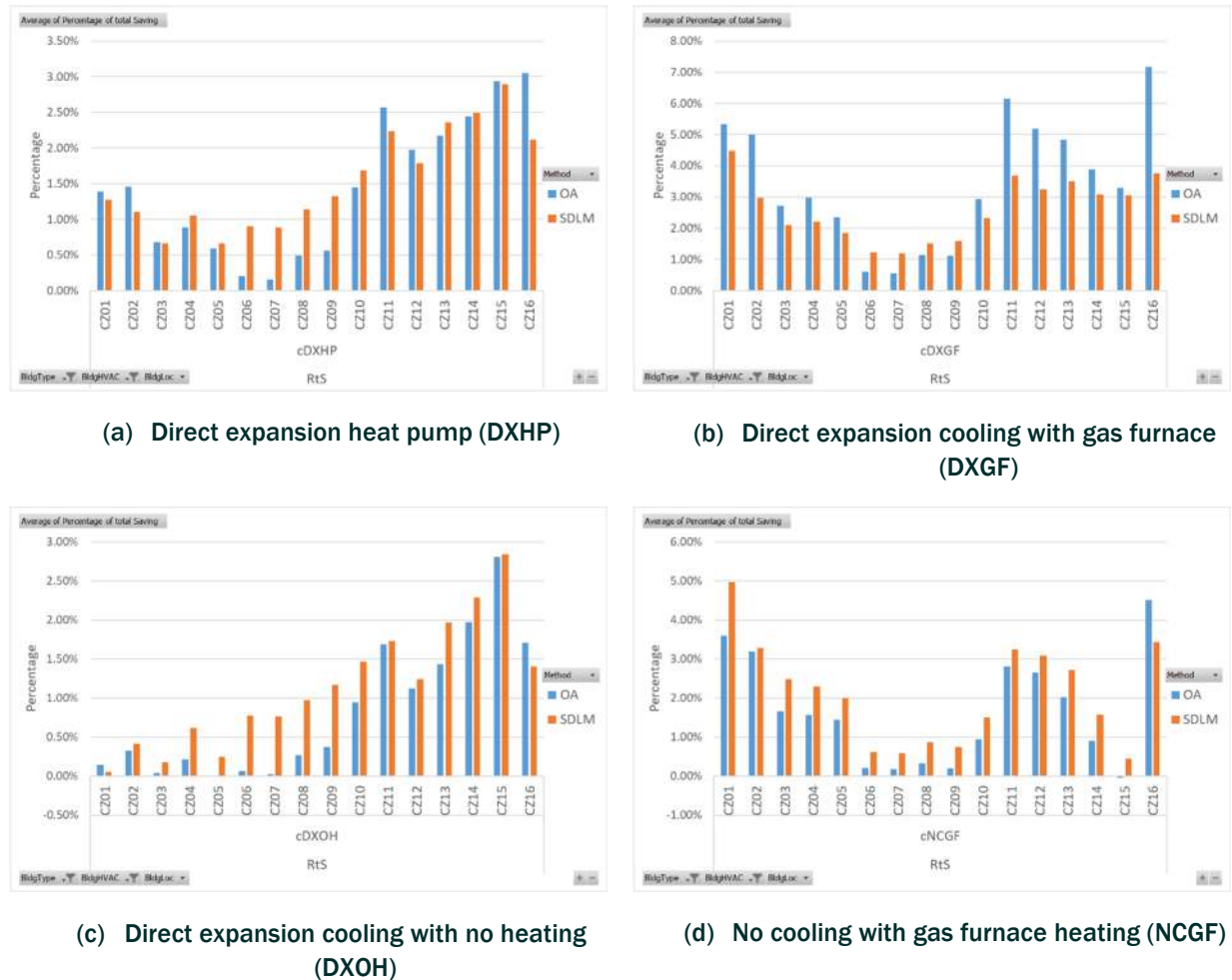
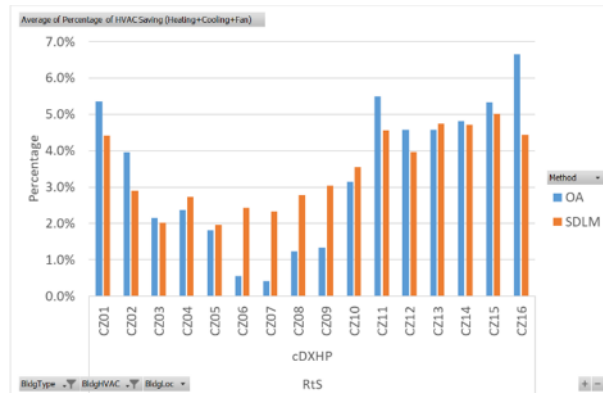


Figure 13: Percentage of total energy savings for different HVAC types and leakage methods (RtS).

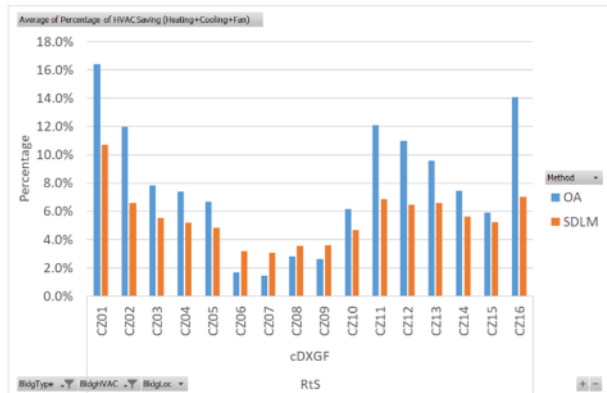
Table 7: Average percentage of total energy savings across 16 climate zones for each leak scenario (RtS).

| Leak Scenario         | DXHP  | DXGF  | DXOH  | NCGF  |
|-----------------------|-------|-------|-------|-------|
| OA (leak to outside)  | 1.44% | 3.45% | 0.82% | 1.64% |
| SDLM (leak to inside) | 1.54% | 2.61% | 1.13% | 2.12% |

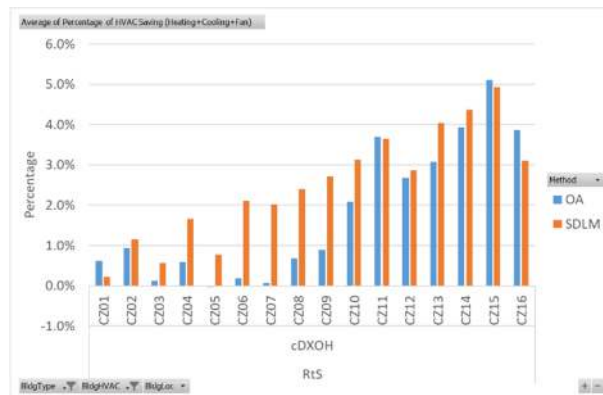
## PERCENTAGE OF HVAC ENERGY SAVINGS



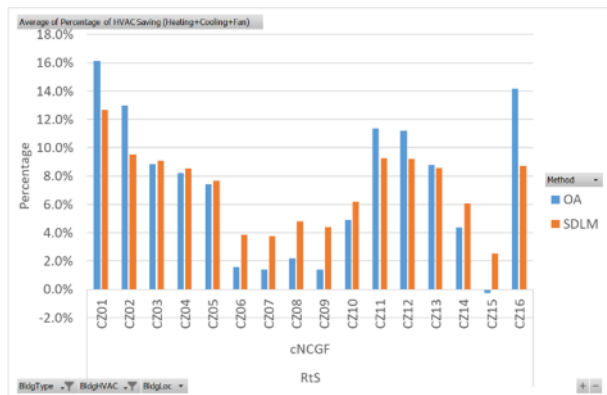
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



(d) No cooling with gas furnace heating (NCGF)

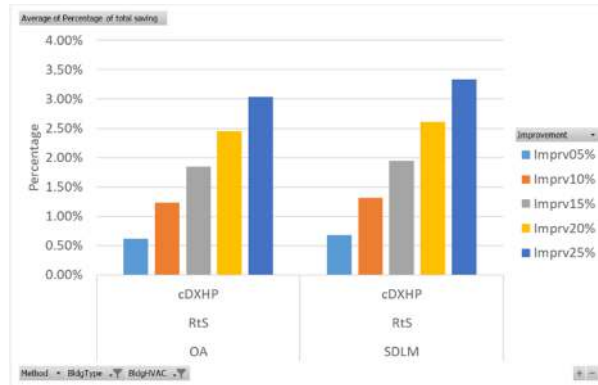
Figure 14: Percentage of HVAC energy savings for different HVAC types and leakage methods (RtS).

Table 8: Average percentage of HVAC energy savings across 16 climate zones for each leak scenario (RtS).

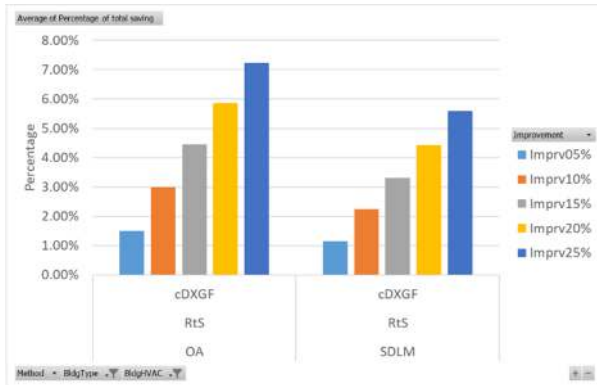
| Leak Scenario         | DXHP | DXGF | DXOH | NCGF |
|-----------------------|------|------|------|------|
| OA (Leak to outside)  | 3.4% | 7.8% | 1.8% | 7.2% |
| SDLM (Leak to inside) | 3.5% | 5.5% | 2.5% | 7.2% |

## PERCENTAGE OF TOTAL SAVINGS BASED ON PERCENT IMPROVEMENT

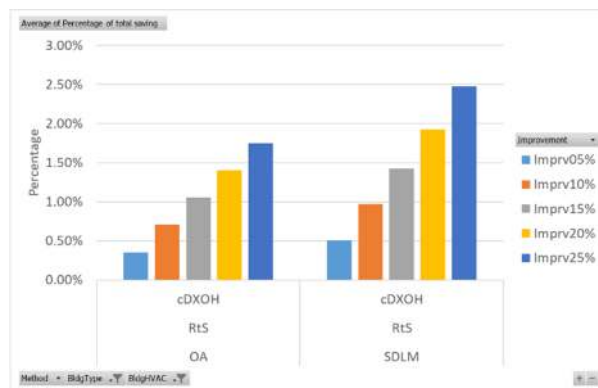
Figure 15 shows the energy savings percentage based on the percent improvement across various HVAC types and leakage methods in the RtS building type. For DXGF, the leakage-to-outside percentage savings increases more with percentage improvement compared to the leakage-to-inside method. The DXHP system, however, shows nearly identical savings for both leakage scenarios. For NCGF and DXOH, SDLM shows more savings than the OA method.



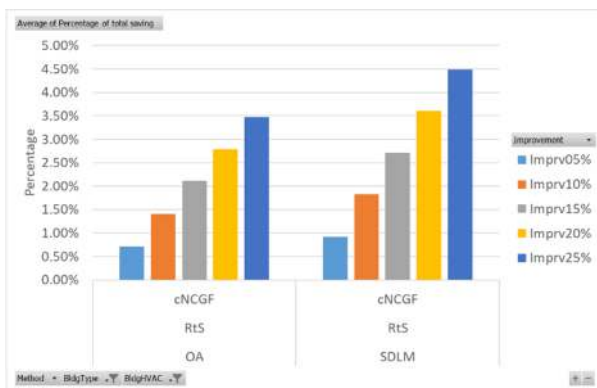
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



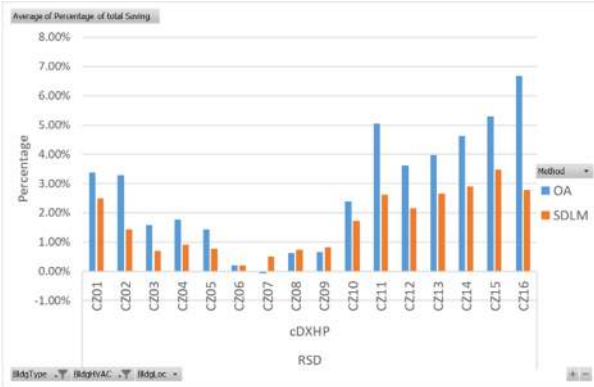
(d) No cooling with gas furnace heating (NCGF)

Figure 15: Percentage of total energy savings based on percent improvement for different HVAC types and leakage methods (RtS).

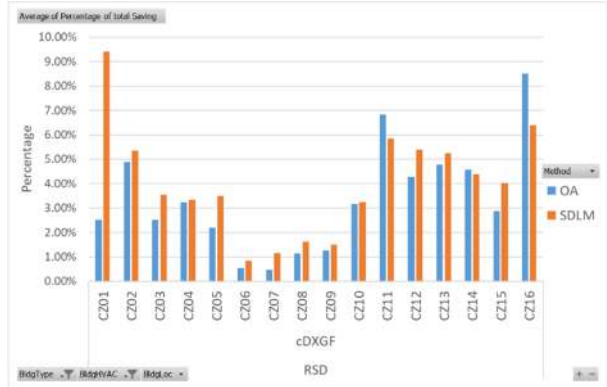
## Restaurant Dining (RSD)

### PERCENTAGE OF TOTAL ENERGY SAVINGS

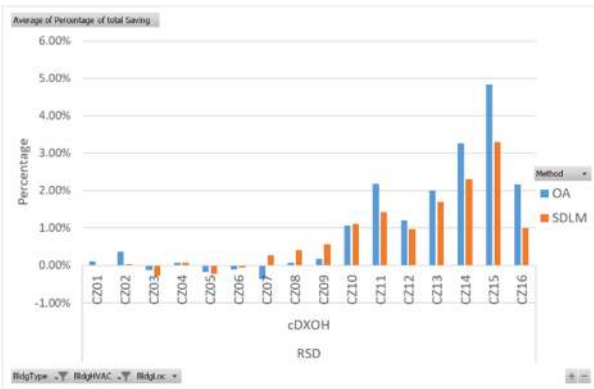
For the restaurant dining prototype, the project team estimated energy savings by scaling the results from the restaurant fast food (RFF) prototype based on the ratio of conditioned area. The outdoor air fraction in the main zone (dining area) remained high for most of the year, preventing the leakage-to-outside method from functioning effectively for this prototype.



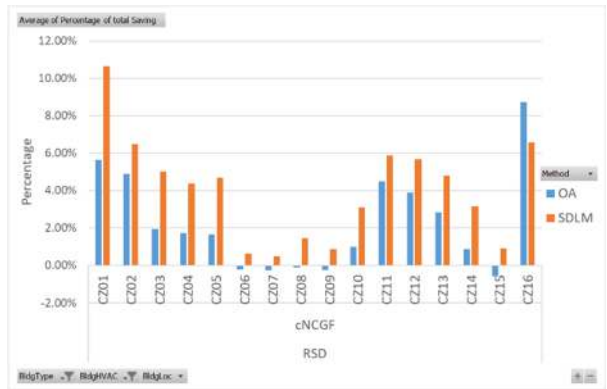
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



(d) No cooling with gas furnace heating (NCGF)

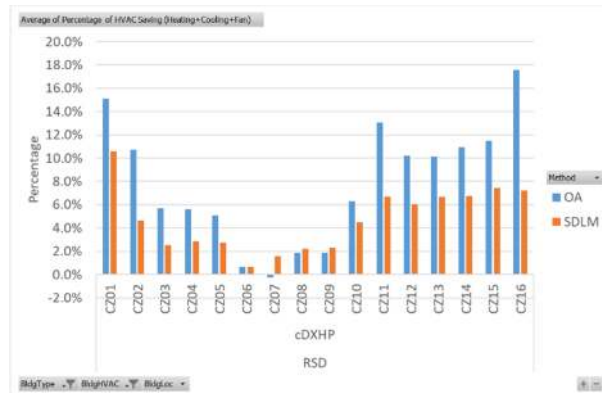
Figure 16: Percentage of total energy savings for different HVAC types and leakage methods (RSD).

Table 9: Average percentage of total energy savings across 16 climate zones for each leak scenario (RSD).

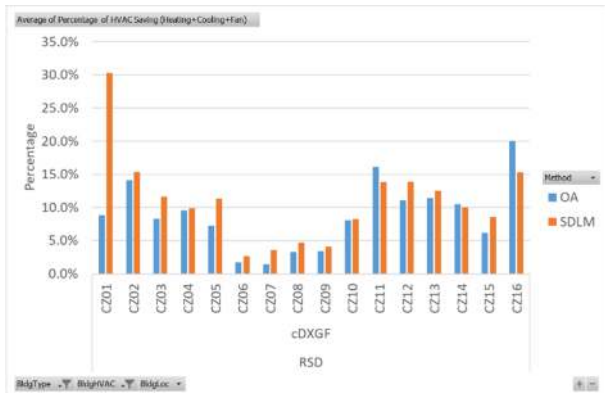
| Leak Scenario         | DXHP  | DXGF  | DXOH  | NCGF  |
|-----------------------|-------|-------|-------|-------|
| OA (leak to outside)  | 2.78% | 3.36% | 1.04% | 2.27% |
| SDLM (leak to inside) | 1.68% | 4.05% | 0.79% | 4.05% |



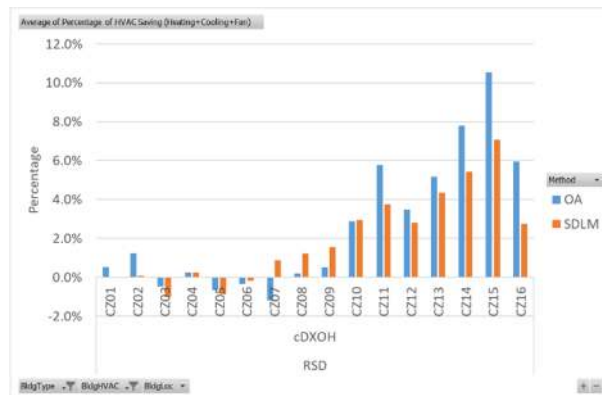
## PERCENTAGE OF HVAC ENERGY SAVINGS



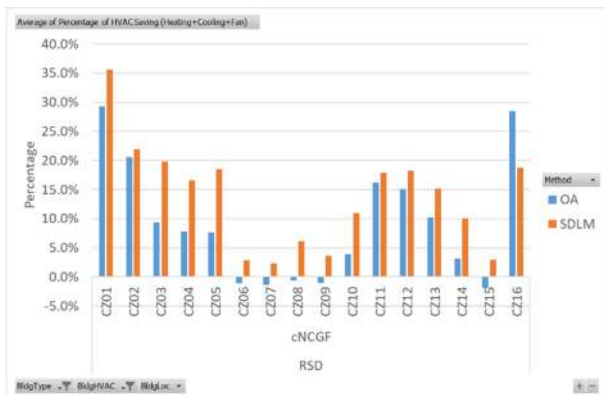
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



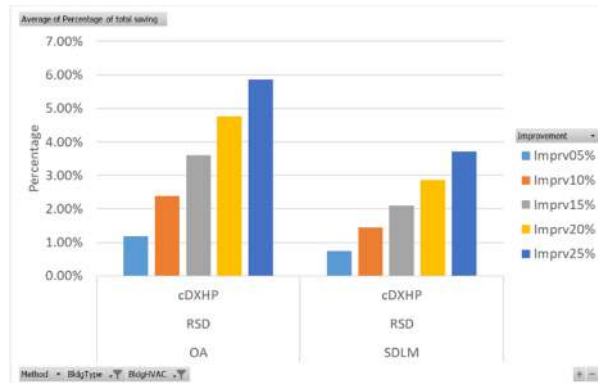
(d) No cooling with gas furnace heating (NCGF)

Figure 17: Percentage of HVAC energy savings for different HVAC types and leakage methods (RSD).

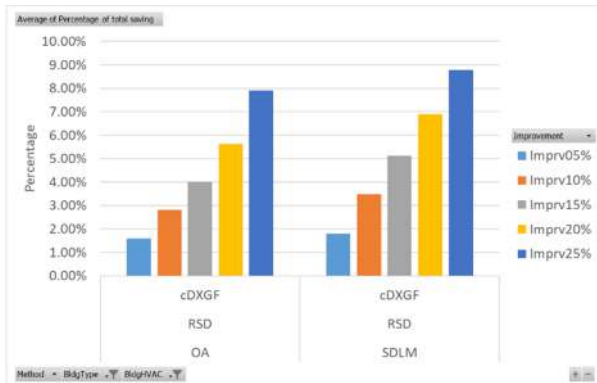
Table 10: Average percentage of HVAC energy savings across 16 climate zones for each leak scenario (RSD).

| Leak Scenario         | DXHP | DXGF | DXOH | NCGF  |
|-----------------------|------|------|------|-------|
| OA (leak to outside)  | 7.9% | 8.8% | 2.6% | 9.1%  |
| SDLM (leak to inside) | 4.7% | 11%  | 1.9% | 13.8% |

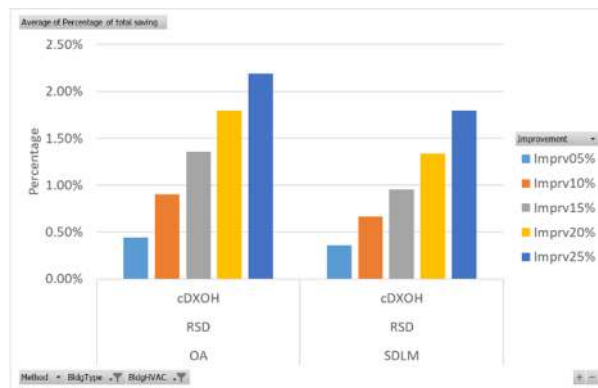
## PERCENTAGE OF TOTAL SAVING BASED ON PERCENT IMPROVEMENT



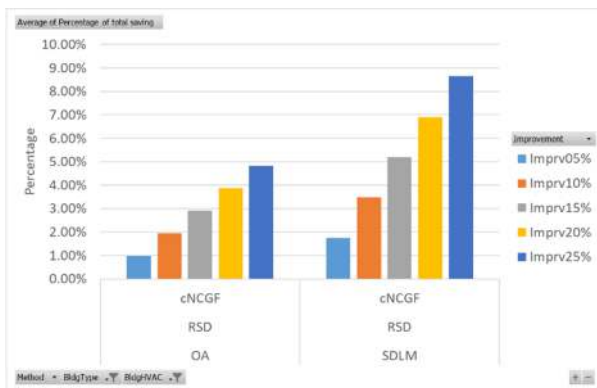
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



(d) No cooling with gas furnace heating (NCGF)

Figure 18. Percentage of total savings based on percent improvement for different HVAC types and leakage methods (RSD).

## Cost Impacts and Feasibility Analysis

Building on the detailed market characterization study and preliminary draft report, the project team further explored the cost aspects of duct sealing technologies, specifically for small commercial buildings. Initial findings revealed that manual sealing typically has lower material costs but higher labor expenses, especially when duct access is challenging. Aerosol sealing methods require higher upfront investment but significantly reduce labor costs by automating the sealing process, making them advantageous for systems with complex ductwork or limited accessibility.

To contextualize the cost dynamics further, it is important to understand the core components that drive pricing for both manual and aerosol duct sealing approaches. Table 11 outlines the typical cost

components and how they vary between the two methods, presenting a side-by-side view of differences in labor intensity, material costs, and operational disruption.

**Table 11: Cost components for manual and aerosol spray duct sealing.**

| Cost Element              | Manual Sealing                                                          | Aerosol Sealing                                                                             |
|---------------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Direct labor              | Technicians access each joint; 40–60% of total job cost                 | Prep and damper blocking; 30–45% of total cost (automated injection shortens sealing phase) |
| Materials and consumables | Mastic/tape, mesh, brushes                                              | Proprietary sealant and tubing kit                                                          |
| Cost                      | ~ US \$0.5–1.5/ft <sup>2</sup> price varies based on duct accessibility | ~ US \$1/ft <sup>2</sup>                                                                    |
| Leakage testing           | Duct-blaster or blower door (hourly TAB rate: \$200–\$500)              | Integrated test in AeroSeal                                                                 |
| Business-hours premium    | Higher if ceiling tiles removed                                         | Usually lower, minimal ceiling disturbance                                                  |

The Minnesota CARD (2016) study illustrates cost differences. For a 6,000-square-foot office, aerosol sealing costs were about \$6,000, or \$1.00 per square foot, yielding an 86 percent leakage reduction and annual savings of \$800, which translates to a seven-year payback. Manual sealing costs in this study were approximately half—\$0.50 per square foot, or around \$3,000—achieving a 45 percent leakage reduction with annual savings of \$450, resulting in a slightly longer payback of 7 to 10 years.

The results of a (2022 Title 24 CASE) field pilot confirm aerosol sealing at approximately \$1.00 per square foot, achieving 70 to 90 percent leakage reductions, HVAC energy savings of 10 to 25 percent, and payback periods of 2 to 7 years. Table 12 summarizes the findings of relevant studies in small commercial buildings.

Table 12: Literature-derived cost and payback ranges.

| Case and Source                                                                     | Sealing Method | Upfront Cost                                  | Leakage Reduction | Annual Energy Bill Savings | Simple Payback |
|-------------------------------------------------------------------------------------|----------------|-----------------------------------------------|-------------------|----------------------------|----------------|
| Southern California strip-retail demo, 3–5 rooftop units (Proctor Engineering 2002) | Aerosol        | US \$40,000–50,000 (multiple units)           | ↓ ~ 80%           | 23–28% HVAC kWh            | 5–8 yr         |
| Minnesota CARD office, 6,000 ft <sup>2</sup> (2016)                                 | Aerosol        | ~ US \$1.00/ft <sup>2</sup> floor (~ \$6,000) | ↓ 86%             | \$800/y                    | 7 yr           |
| Minnesota CARD manual mastic/tape on similar rooftop system                         | Manual         | ~ US \$0.50/ft <sup>2</sup> (~ \$3 k)         | ↓ 45%             | \$450/y                    | 7–10 yr        |
| California Title 24 CASE field pilots (schools and small offices, 2023)             | Aerosol        | ~ US \$1.00/ft <sup>2</sup>                   | ↓ 70–90%          | 10–25% HVAC kWh            | 2–7 yr         |

Practically, for a typical 5,000-square-foot commercial building, manual sealing costs range from \$2,500 to \$4,500 and aerosol methods typically cost between \$5,000 and \$6,000. Although initially more expensive, aerosol sealing delivers superior energy savings—15 to 30 percent (Figure 17) of HVAC energy consumption—compared to 10 to 15 percent from manual methods.

Figure 17 shows total system power savings (combination of heating converted from therms to kW, and cooling power), as opposed to cooling power savings only. In heating-dominated zones such as CZ01 and CZ16, the larger savings percentages are primarily driven by reduced heating loads (gas savings). This trend (30% saving) is consistent across two prototypes (RSD and RTS). Furthermore, the difference between the OA method and SDLM saving percentage in CZ01, occurs as a result of a known limitation of the OA method. Any method that adds OA inherently interacts with the existing mechanical ventilation and economizer controls. When the economizer is active, it can override outdoor air control, which reduces the savings potential captured by the OA method compared to SDLM. In case "d" (where there is no

cooling) the economizer is not activated with savings of 30% and 35% for SDLM and OA methods. For the “No cooling with gas furnace heating (NCGF)” case, the savings are also not fan-only. The chart represents all HVAC energy (heating + fan), and since there is no cooling in this system type, the savings primarily reflect reductions in heating energy use, with some fan contribution.

To estimate the dollar value of HVAC energy savings, the project team applied a consistent set of assumptions for utility rates and end-use energy benchmarks. Based on the commercial reference building models used in this modeling study across California’s 16 climate zones, the project team determined that a typical small commercial building uses about 20 kWh per square foot per year of electricity and 0.38 therms per square foot per year of natural gas. For a 5,000-square-foot building, this results in an annual energy use of roughly 100,000 kWh and 1,900 therms.

Assuming HVAC accounts for 40 percent of total building energy use, this yields approximately 40,000 kWh and 760 therms of HVAC energy consumption annually. Using blended California utility rates of \$0.24 per kWh and \$1.50 per therm, the baseline HVAC energy cost is estimated at \$10,750 per year (EIA, 2025).

Based on energy modeling results, for an office building with a direct expansion cooling and gas furnace (DXGF) system—which is typical of existing office buildings in California—duct sealing can achieve HVAC energy savings ranging from 12 to 18 percent when leakage is to outside of thermal zone. Applying this range of HVAC energy savings to typical small commercial building energy profiles results in estimated annual utility cost savings between approximately \$1,290 and \$1,930, depending on the specific sealing method employed and the initial duct leakage conditions, as shown in Table 13 below.

**Table 13: Estimated costs, savings, and payback window for a 5,000-square-foot commercial building.**

| Metric                | Manual Sealing     | Aerosol Sealing    |
|-----------------------|--------------------|--------------------|
| Typical capital cost  | US \$2,500–\$5,000 | US \$5,000–\$6,000 |
| Expected leakage cut  | 40–50%             | 70–90%             |
| HVAC energy savings*  | 12% → US \$1,290   | 18% → US \$1,930   |
| Simple payback window | 2–4 yr             | 2–3 yr             |

\*Savings assume California blended rates of 0.24 \$/kWh and 1.50 \$/therm and average HVAC savings for an office building (DXGF) based on energy modeling results.

California's utility rates for small commercial customers are among the highest in the nation, with average electricity rates exceeding \$0.24/kWh, significantly above the national commercial average of \$0.12/kWh (EIA, 2025). Natural gas prices similarly exceed national averages. This difference has a direct impact on the cost-effectiveness of duct sealing measures. In regions with lower energy costs, savings from sealing interventions can be modest in dollar terms, often resulting in longer payback periods. However, in California, even relatively modest percentage reductions in HVAC energy use translate into substantial monetary savings.

This elevated rate environment shortens the payback period for both manual and aerosol sealing methods compared to what was reported in historical studies conducted in lower-cost energy markets. As such, duct sealing presents a particularly attractive investment opportunity in California's small commercial sector, supporting the case for including targeted incentives and robust screening tools in utility energy efficiency programs.

## Conclusions

The project team set out to quantify the energy savings potential and cost analysis of duct sealing technologies in small commercial buildings across California, and that analysis showed substantial opportunities for energy savings in most California climate zones. HVAC energy savings were notably higher in leakage-to-outside scenarios, especially for some systems, such as direct expansion systems combined with gas furnaces (DXGF), and in climate zones characterized by more extreme temperature conditions.

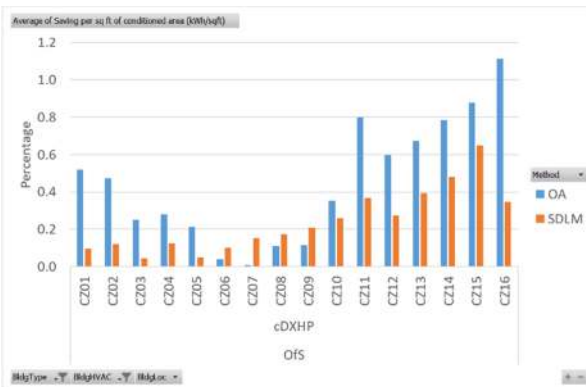
The findings highlight that duct sealing is not only technically effective but also economically advantageous in most California climates. The cost-effectiveness analysis demonstrates relatively short payback periods for aerosol sealing methods, making it a viable option for targeted incentive programs. These insights provide a robust basis for utilities and policymakers to prioritize duct sealing in efficiency programs, particularly leveraging performance-based incentives and preliminary diagnostic evaluations to optimize energy savings and reduce operational costs in small commercial buildings.

## Appendix A

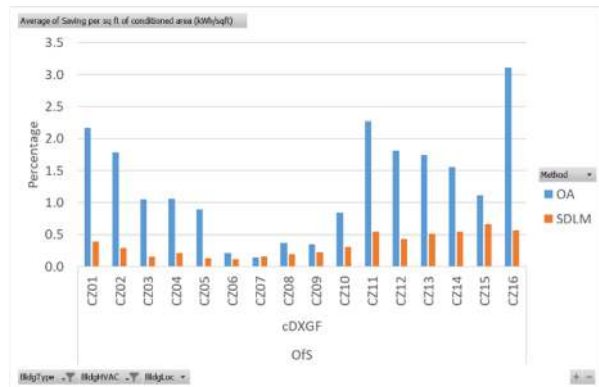
In this appendix, we describe savings per square foot of a conditioned area, savings by end use for natural gas (therms) and electricity (kWh), and the percentage of HVAC savings for each building prototype. Please note that the conditioned area refers to the zones served in the model using the leakage method.

### Small Office Building (OfS)

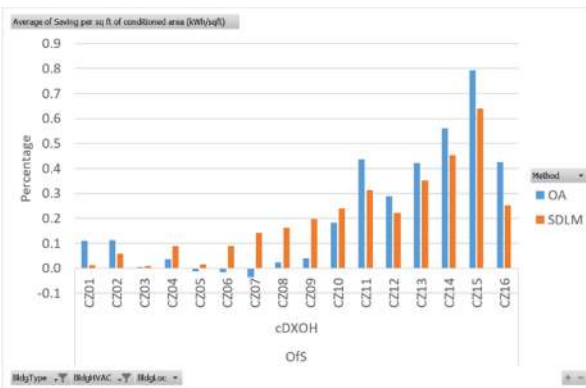
For the OfS prototype, the conditioned area is 7,934 square feet.



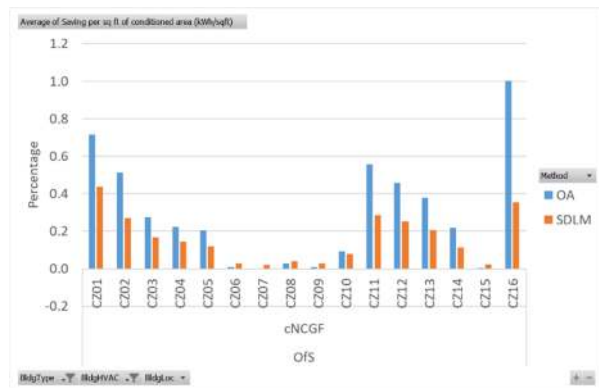
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



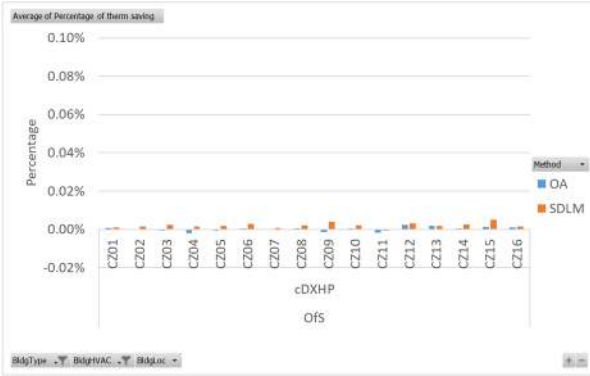
(c) Direct expansion cooling with no heating (DXOH)



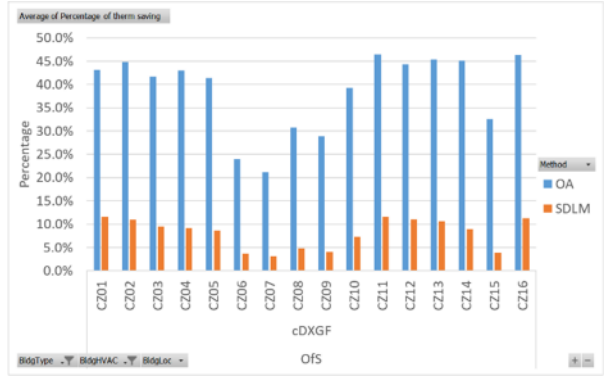
(d) No cooling with gas furnace heating (NCGF)

Figure 19: Energy savings per square foot of conditioned area for different HVAC types and leakage methods (OfS).

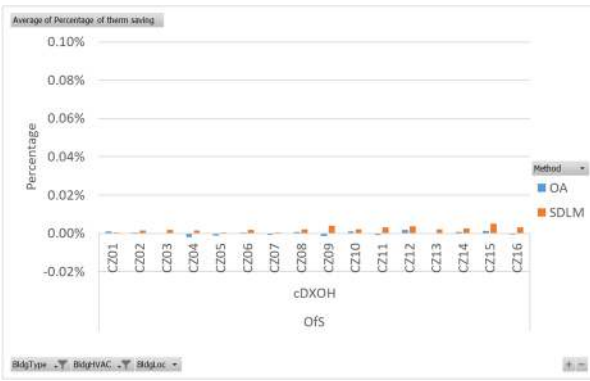




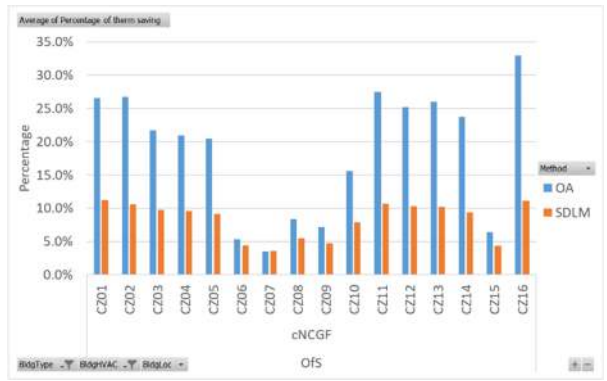
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)

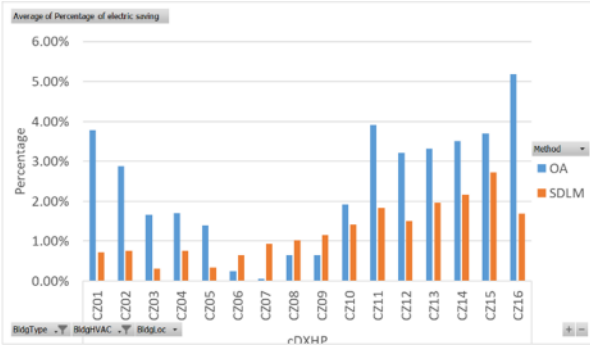


(c) Direct expansion cooling with no heating (DXOH)

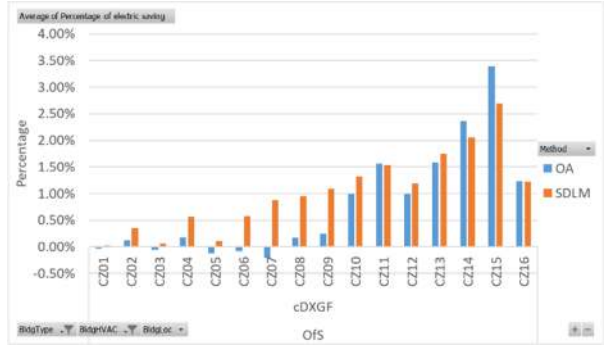


(d) No cooling with gas furnace heating (NCGF)

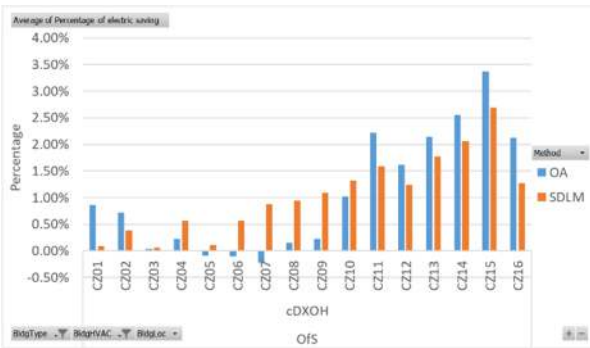
Figure 20: Percentage of natural gas (therm) savings for different HVAC types and leakage methods (OfS).



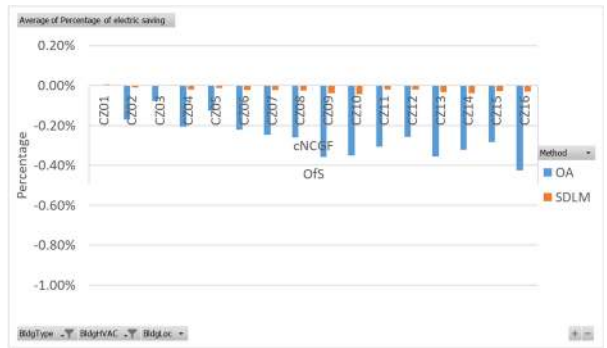
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)

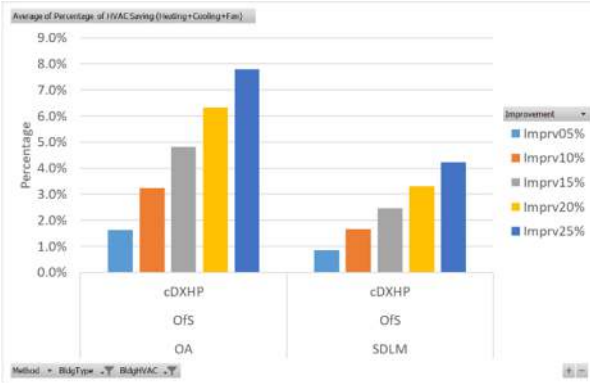


(c) Direct expansion cooling with no heating (DXOH)

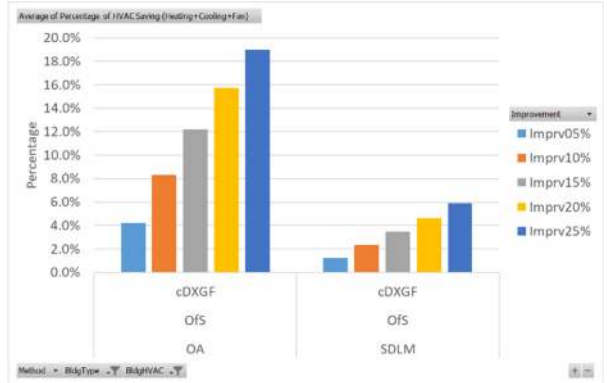


(d) No cooling with gas furnace heating (NCGF)

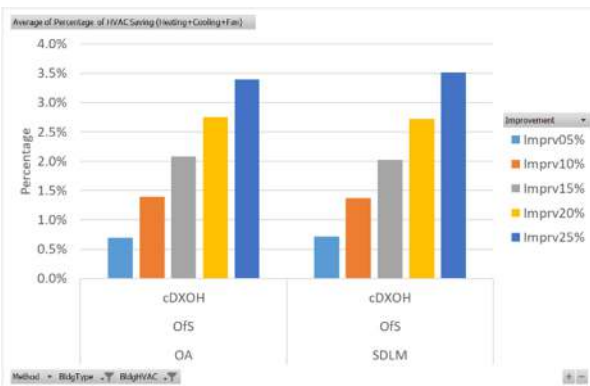
Figure 21: Percentage of electric (kWh) savings for different HVAC types and leakage methods (OfS).



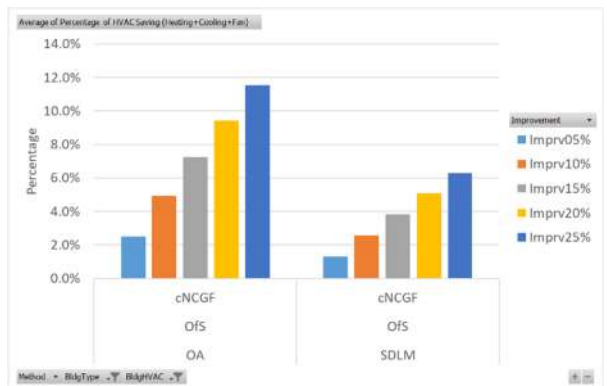
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)

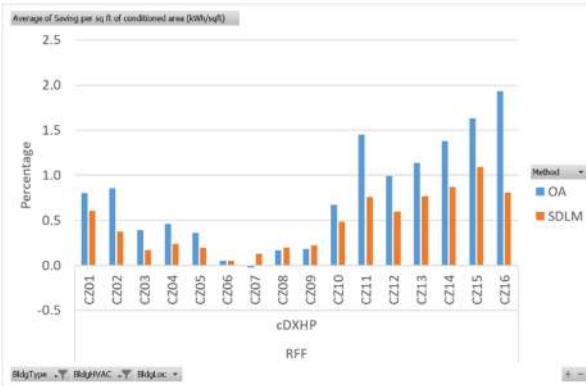


(d) No cooling with gas furnace heating (NCGF)

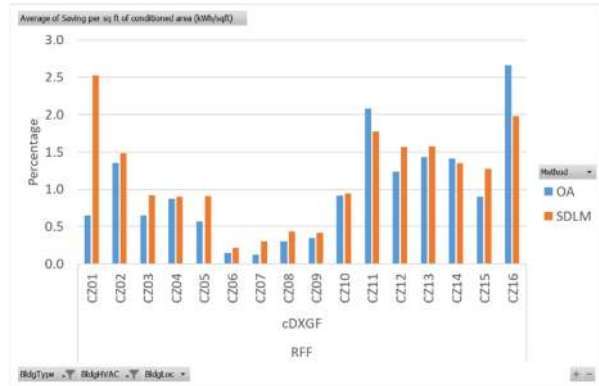
Figure 22: Percentage of HVAC savings based on percent improvement for different HVAC types and leakage methods (OfS).

## Restaurant Fast Food (RFF)

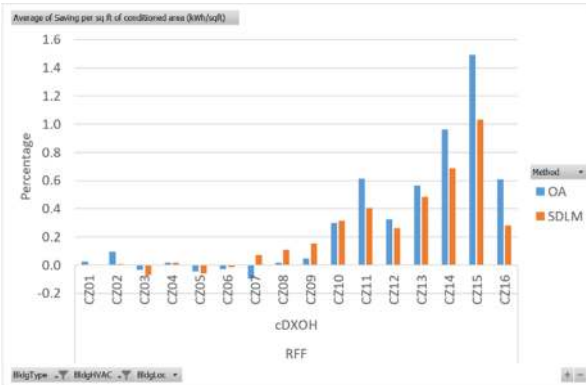
The conditioned area is 1,198.9 square feet for the RFF prototype.



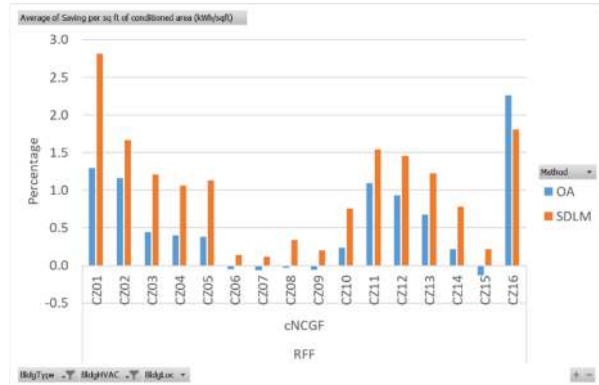
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)

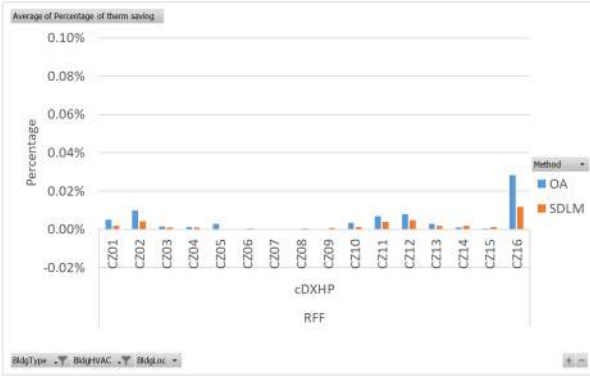


(c) Direct expansion cooling with no heating (DXOH)

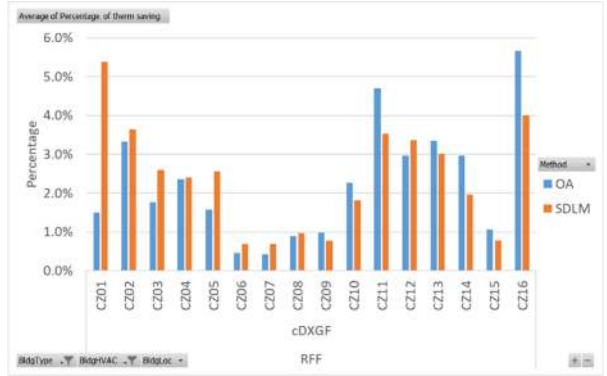


(d) No cooling with gas furnace heating (NCGF)

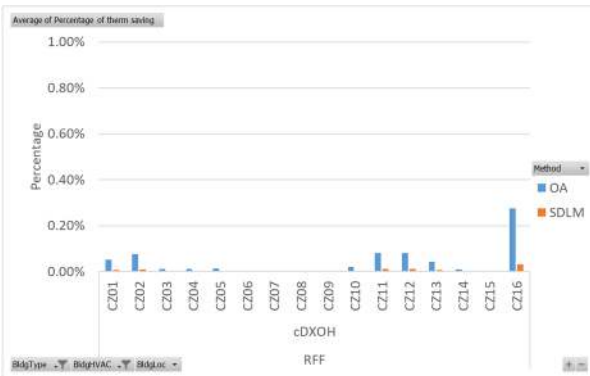
Figure 23: Total energy savings per square foot of conditioned area for different HVAC types and leakage methods (RFF).



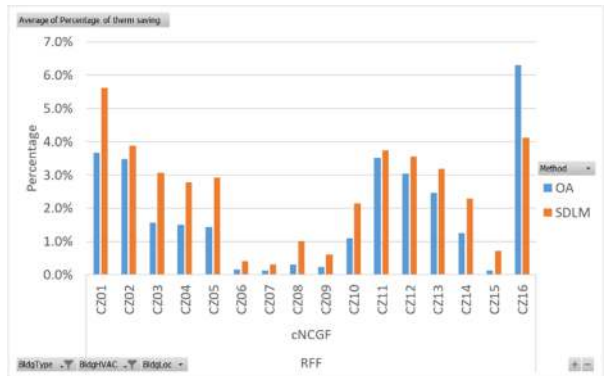
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)

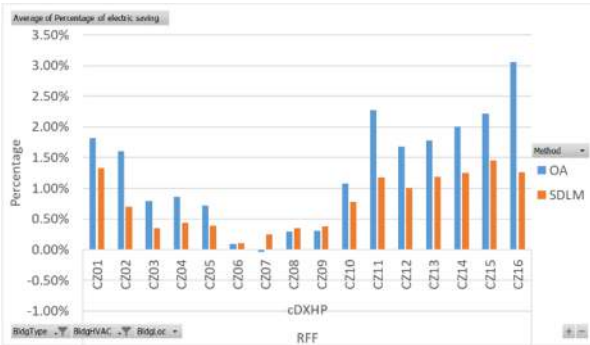


(c) Direct expansion cooling with no heating (DXOH)

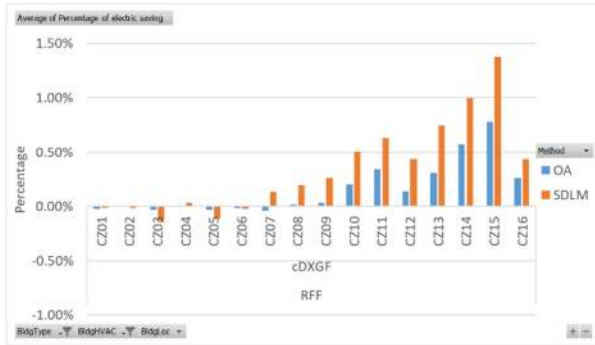


(d) No cooling with gas furnace heating (NCGF)

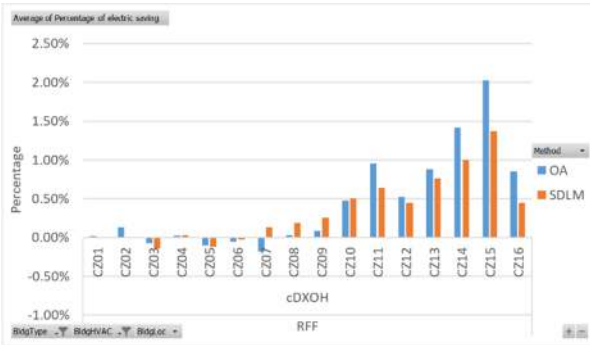
Figure 24: Percentage of natural gas (therm) savings for different HVAC types and leakage methods (RFF).



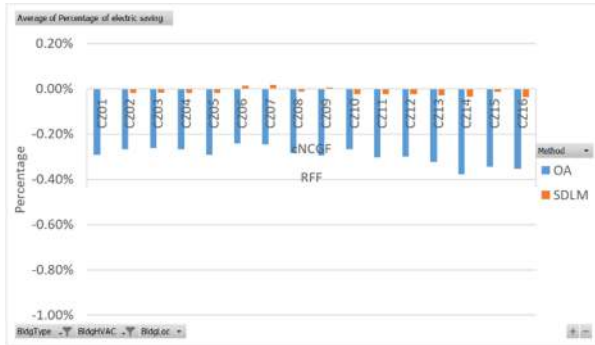
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)

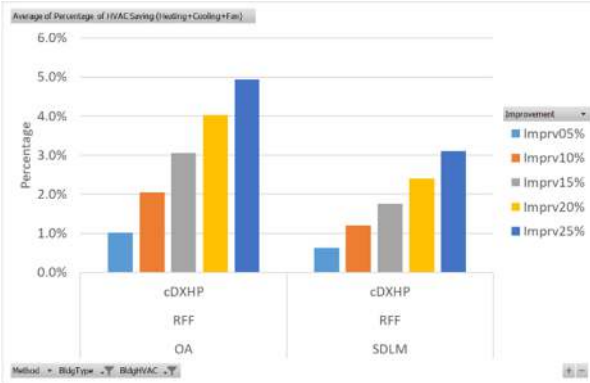


(c) Direct expansion cooling with no heating (DXOH)

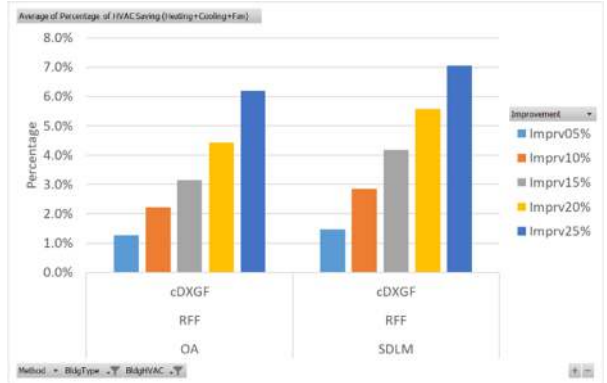


(d) No cooling with gas furnace heating (NCGF)

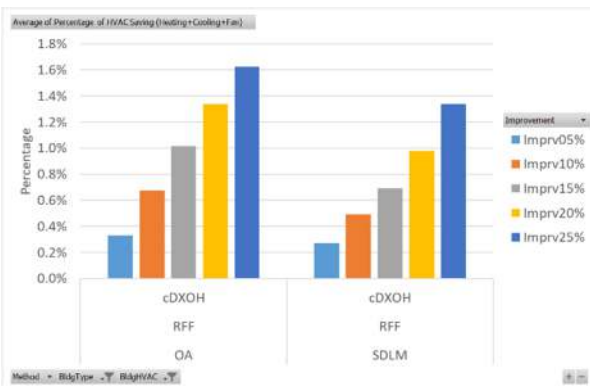
Figure 25: Percentage of electric (kWh) savings for different HVAC types and leakage methods (RFF).



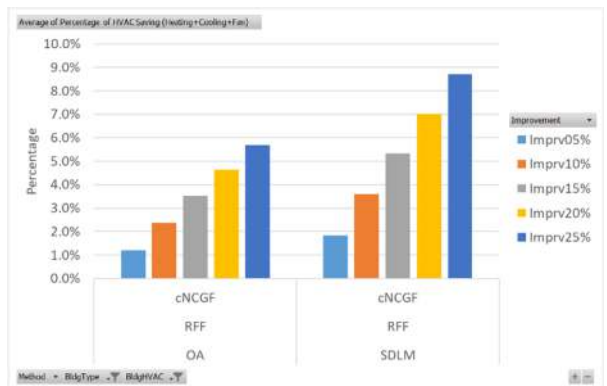
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



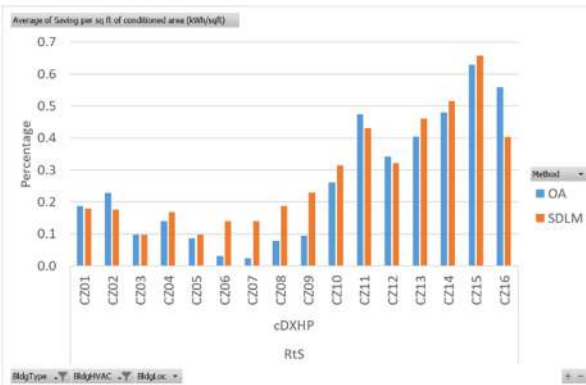
(d) No cooling with gas furnace heating (NCGF)

Figure 26: Percentage of HVAC savings based on percent improvement for different HVAC types and leakage methods (RFF).

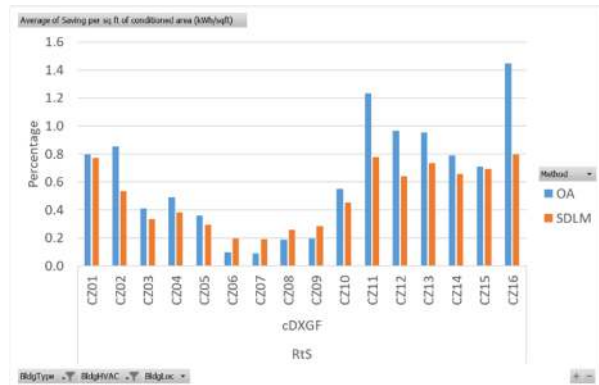


## Retail Store (RtS)

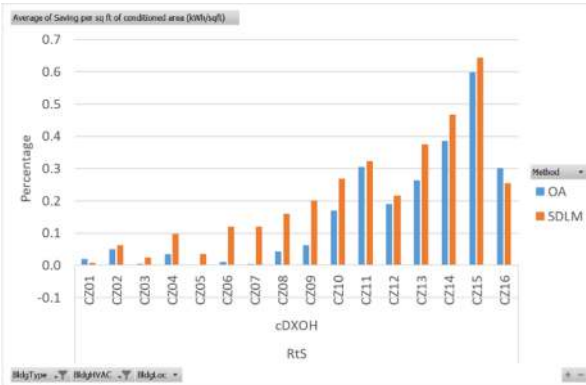
The conditioned area is 8,001.2 square feet for the RtS prototype.



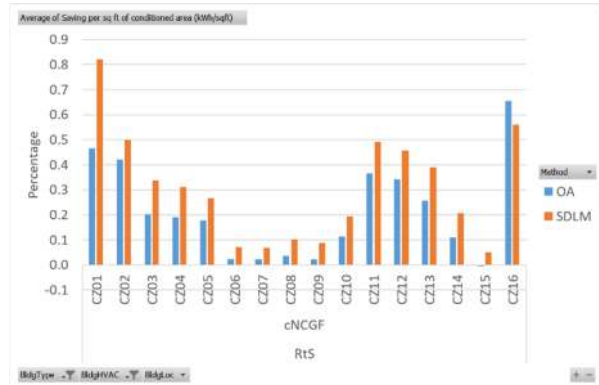
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)

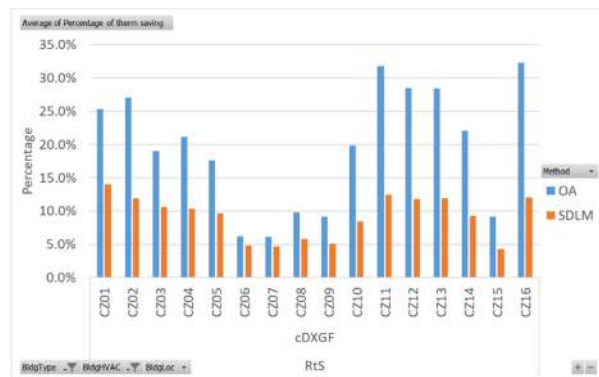
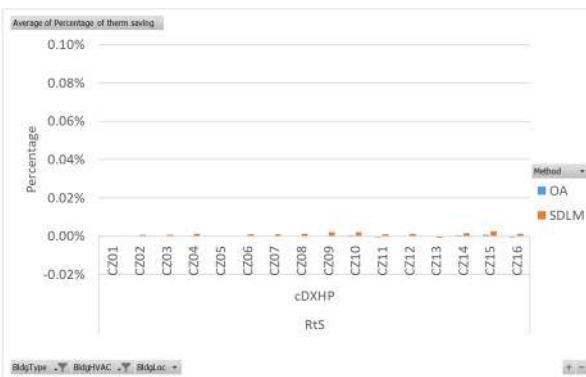


(c) Direct expansion cooling with no heating (DXOH)

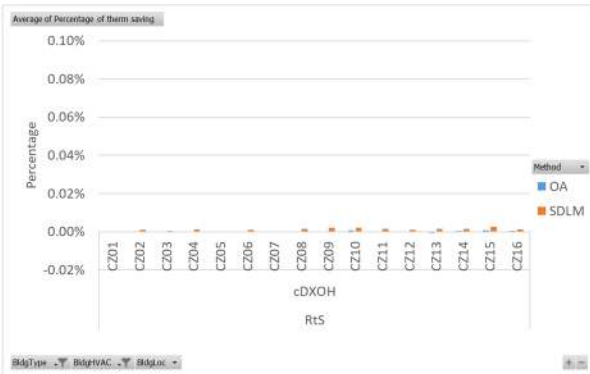


(d) No cooling with gas furnace heating (NCGF)

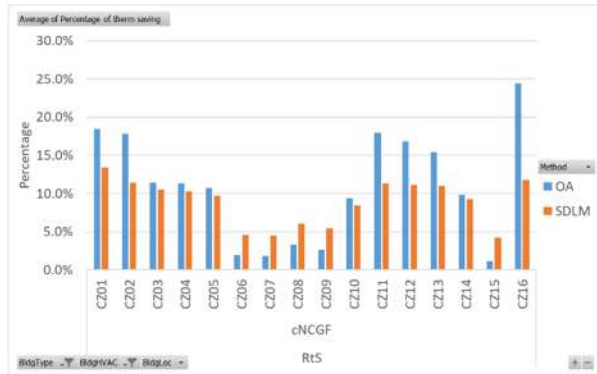
Figure 27: Total energy savings per square feet per conditioned area for different HVAC types and leakage methods (RtS).



(a) Direct expansion heat pump (DXHP)



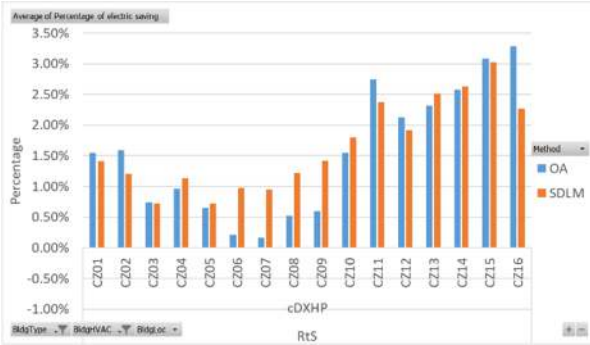
(b) Direct expansion cooling with gas furnace (DXGF)



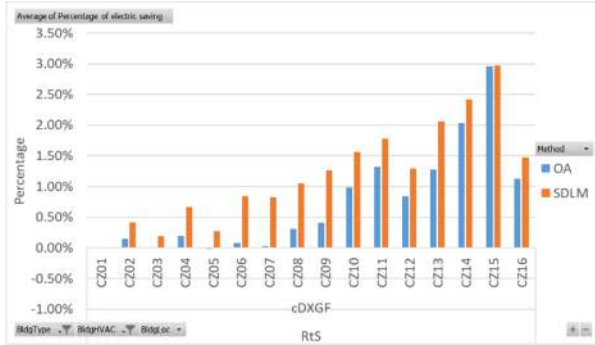
(c) Direct expansion cooling with no heating (DXOH)

(d) No cooling with gas furnace heating (NCGF)

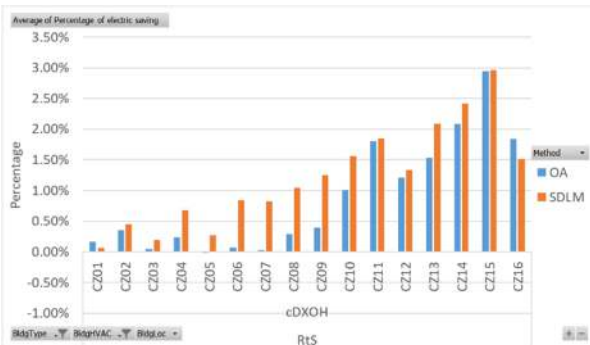
Figure 28: Percentage of natural gas (therm) savings for different HVAC types and leakage methods (RtS).



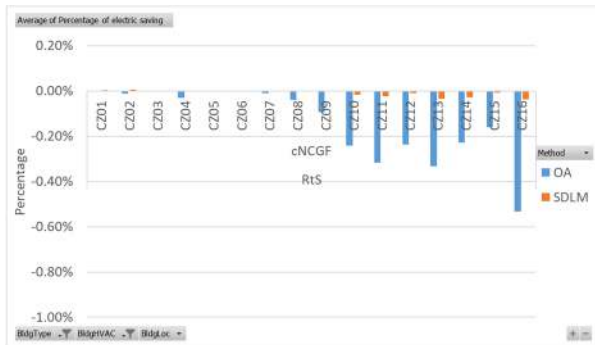
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)

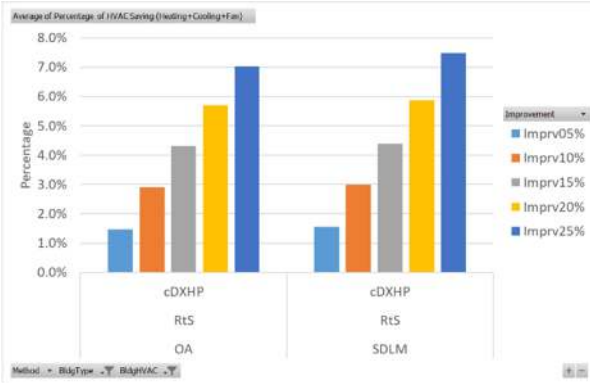


(c) Direct expansion cooling with no heating (DXOH)

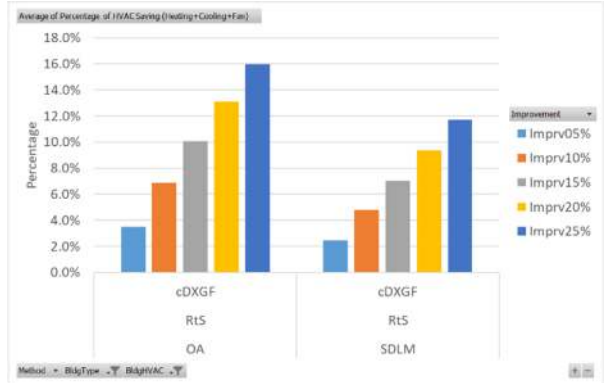


(d) No cooling with gas furnace heating (NCGF)

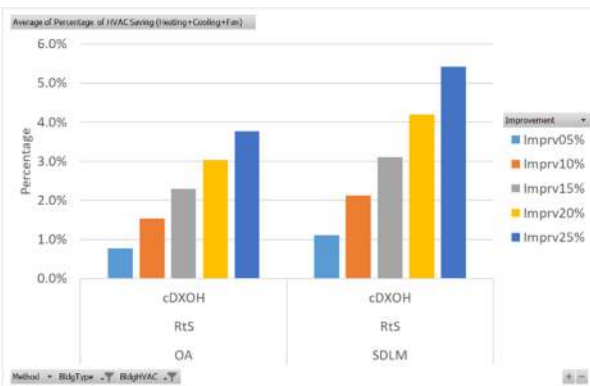
Figure 29: Percentage of electric (kWh) savings for different HVAC types and leakage methods (RtS).



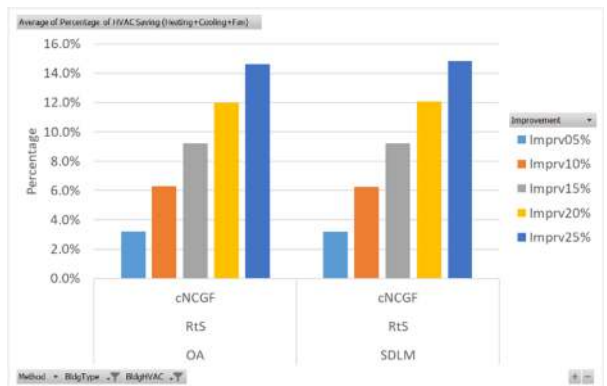
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)

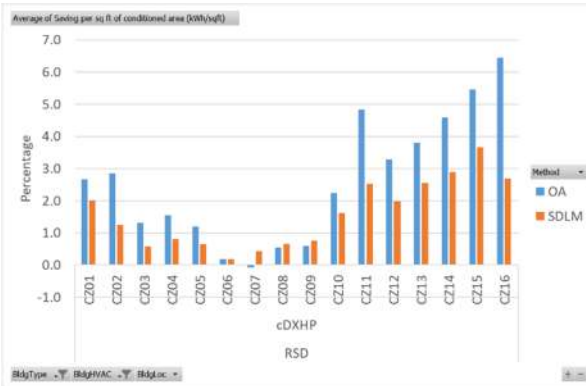


(d) No cooling with gas furnace heating (NCGF)

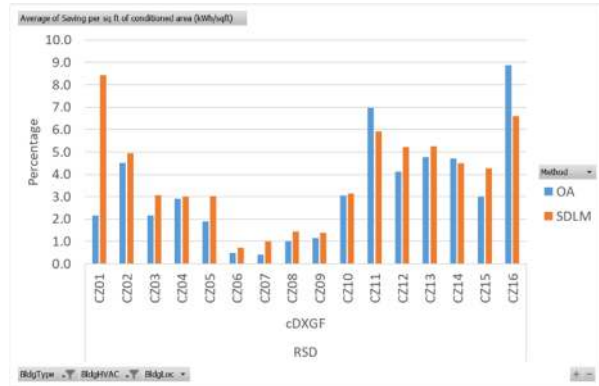
Figure 30: Percentage of HVAC savings based on percent improvement for different HVAC types and leakage methods (RtS).

## Restaurant Dining (RSD)

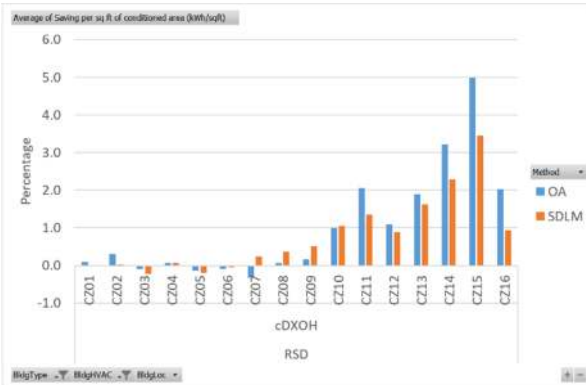
The conditioned area is 3,999.65 square feet for the RSD prototype.



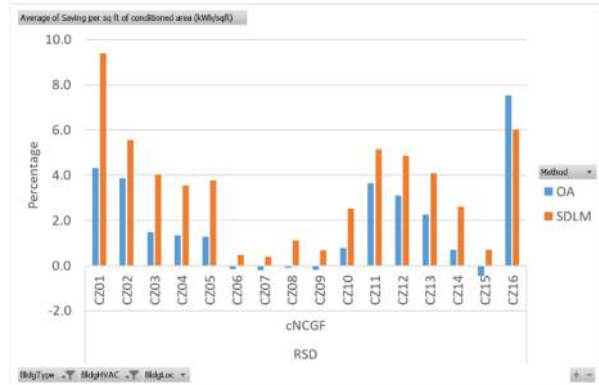
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)

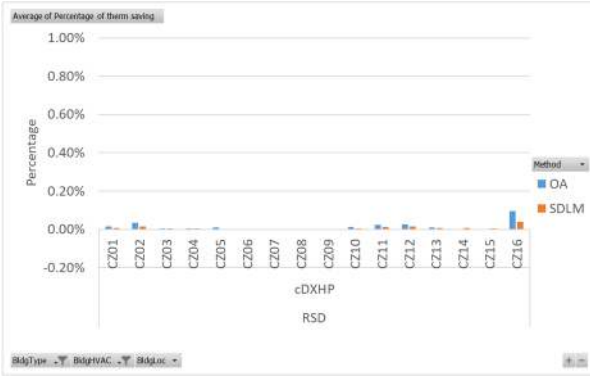


(c) Direct expansion cooling with no heating (DXOH)

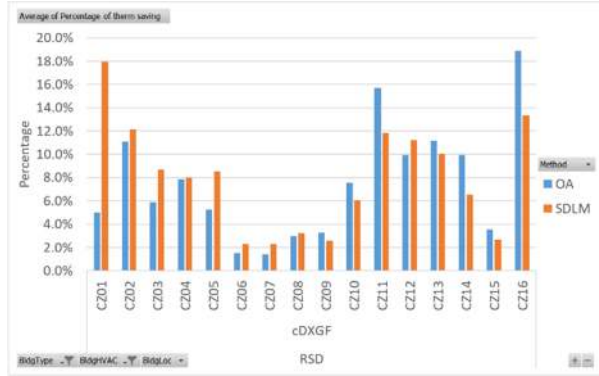


(d) No cooling with gas furnace heating (NCGF)

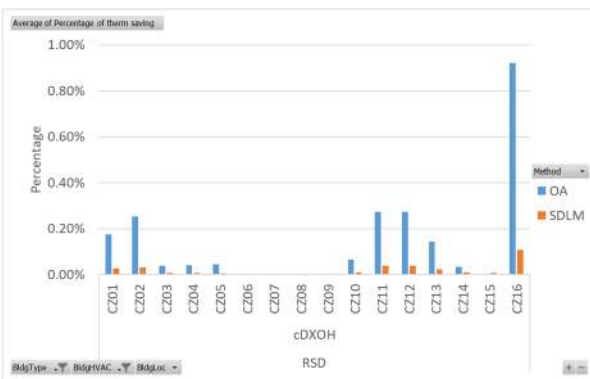
Figure 31: Total energy savings per square feet per conditioned area for different HVAC types and leakage methods (RSD).



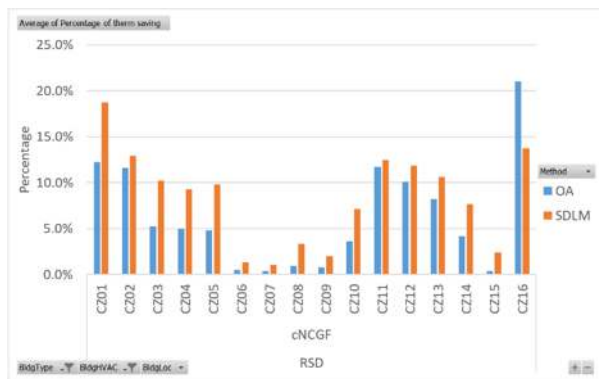
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)

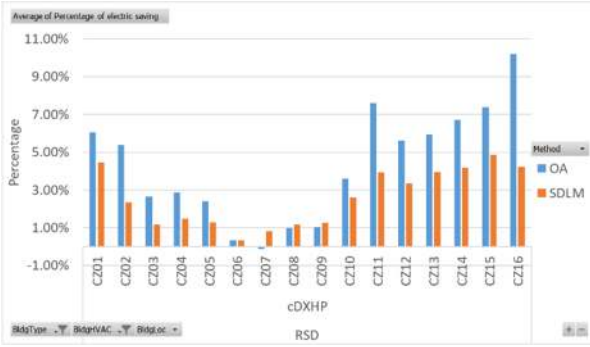


(c) Direct expansion cooling with no heating (DXOH)

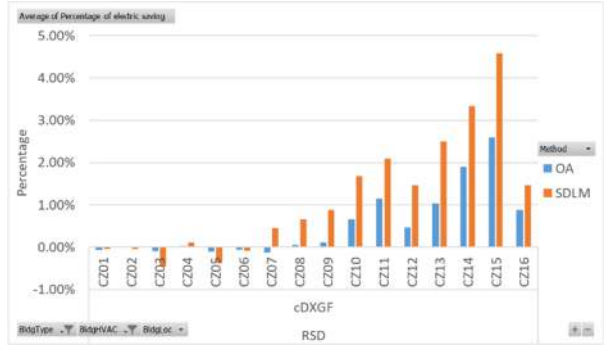


(d) No cooling with gas furnace heating (NCGF)

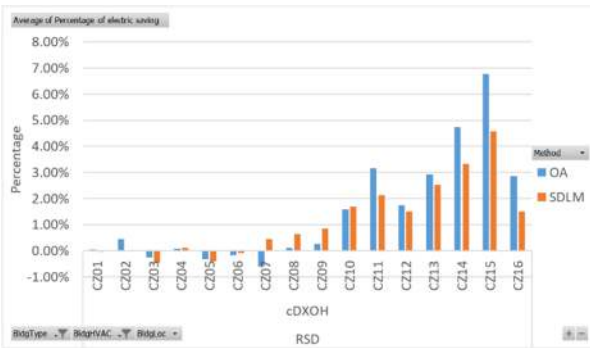
Figure 32: Percentage of natural gas (therm) savings for different HVAC types and leakage methods (RSD).



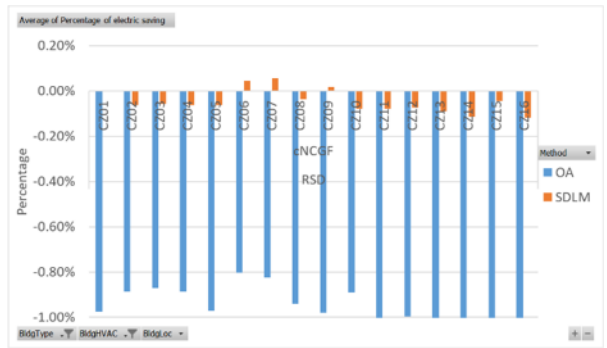
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



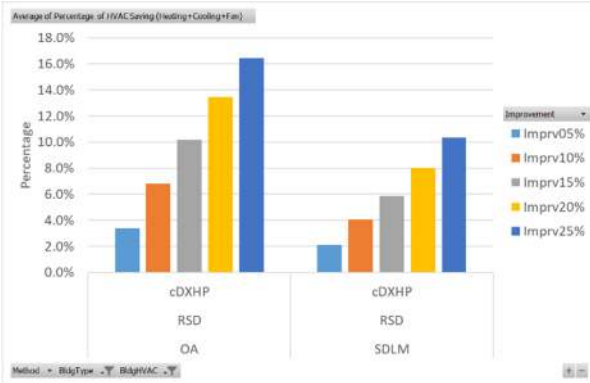
(c) Direct expansion cooling with no heating (DXOH)



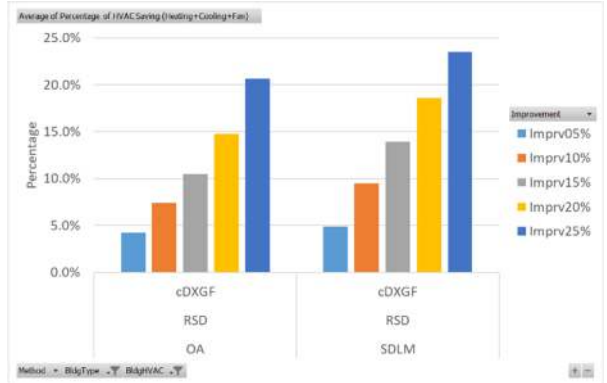
(d) No cooling with gas furnace heating (NCGF)

Figure 33: Percentage of electric (kWh) savings for different HVAC types and leakage methods (RSD).

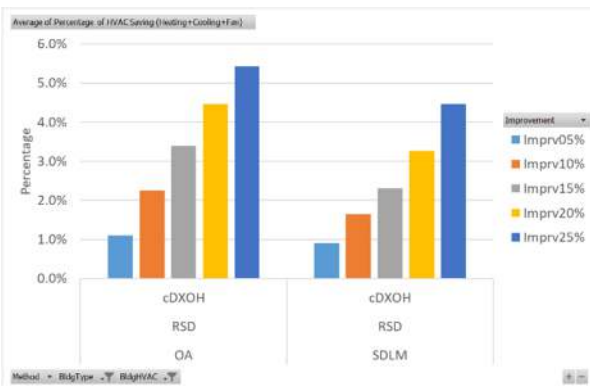




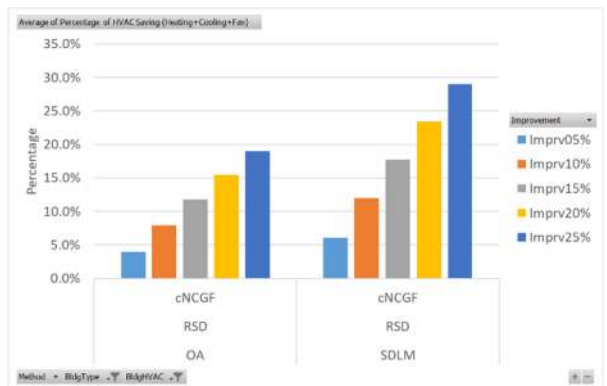
(a) Direct expansion heat pump (DXHP)



(b) Direct expansion cooling with gas furnace (DXGF)



(c) Direct expansion cooling with no heating (DXOH)



(d) No cooling with gas furnace heating (NCGF)

Figure 34: Percentage of HVAC savings based on percent improvement for different HVAC types and leakage methods (RSD).

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