U.S. DEPARTMENT OF ENERGY

PNNL-19227

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March 2010

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Prepared for Bonneville Power Administration
by Pacific Northwest National Laboratory
for the UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

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[†] Navigant Consulting Inc. contributed to the Market Assessment and Incremental Cost Estimate sections of the report

Executive Summary

Pacific Northwest National Laboratory (PNNL), with co-funding from the Bonneville Power Administration (BPA) and Building Technologies (DOE-BT) Program of the U.S. Department of Energy (DOE), conducted a research and development (R&D) activity that is targeted at addressing the energy efficiency goals outlined in the Bonneville Power Administration (BPA) Roadmap. PNNL study investigated an integrated heating, ventilation and air conditioning (HVAC) system option referred to in this study as the low-lift cooling system (LLCS) that potentially offers an increase in HVAC energy performance relative to American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 90.1-2004.

The LLCS PNNL evaluated consists of five interrelated elements:

1. Peak-load shifting by active or passive thermal energy storage (TES).
2. Dedicated outdoor air supply with enthalpy heat recovery from exhaust air (DOAS).
3. Radiant heating and cooling panels or floor system (RCP).
4. Low-lift vapor compression cooling equipment.
5. Advanced controls at the HVAC equipment and HVAC system (supervisory) levels.

The analysis shows that significant *cooling system efficiency gains* can be achieved by integrating a *low-lift cooling system*. The cooling energy savings for a standard-performance building range from 47% to 84% and, for a high-performance building, from 17% to 66%.

Building Prototypes and Climate Locations Used for Low-Lift Energy Savings Analysis
PNNL chose to use the modified DOE Benchmarks Prototype EnergyPlus input files (referred to as ASHRAE Benchmarks) for this analysis because the DOE prototypes were enhanced, largely as a result of the greater review provided by industry members. Also, note that these modifications will eventually be incorporated into the DOE Benchmarks. For standalone retail, supermarket and healthcare "outpatient" building types, the original DOE Benchmarks were used; for the rest of the building types, the ASHRAE Benchmarks are used. The 21 climate locations were selected by mapping each county in the Pacific Northwest to the TMY2 (typical meteorological year version 2) weather location that best approximated the climate in that county. To translate per-building savings into Pacific Northwest regional savings, PNNL employed the building weights that were developed by the Northwest Power Planning Council.

To estimate the energy consumption of a prototype building with baseline HVAC system (or some subset of it), a detailed simulation model is needed. The existing mainstream detailed simulation models (DOE-2 and EnergyPlus) currently lack the capability to simulate the full LLCS. Although EnergyPlus can model many of the elements, it currently lacks the requisite elements of a low-lift chiller, thermal storage and advanced controls that are needed to optimize the operation.

PNNL calculated the energy consumption estimates and savings in two steps: 1) estimated the building thermal loads for 12 different building types (two performance levels) and 21 climate locations using EnergyPlus simulations; and 2) simulated the systems - using the thermal loads as a basis, - with a set of component models that were developed as part of the DOE funded effort (Jiang et al. 2008, Katipamula et al. 2010) in the Matlab[3] environment.

Market Assessment

PNNL contracted with Navigant Consulting Inc. (NCI) to conduct an assessment of the potential market for the LLCS.[4] The NCI market assessment consisted of four steps: 1) review of the proposed technology and models, 2) identification of potential benefits and barriers to market penetration, 3) validation of those benefits and barriers through surveys and discussions with stakeholders and 4) recommended initiatives that might be taken to accelerate market adoption of the proposed low-lift solutions.

Based on stakeholder feedback about the individual technologies comprising the LLCS, NCI made the following recommendations and actions for PNNL to take to accelerate market adoption (Figure E-1)

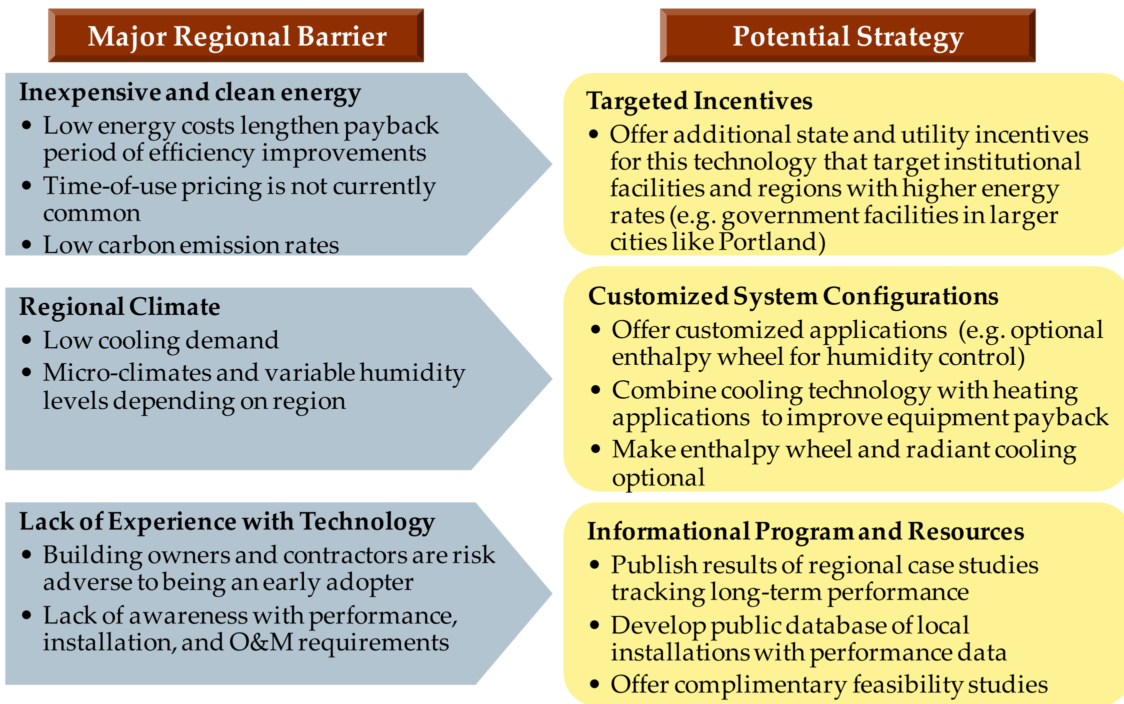

Figure E-1 Major Regional Barriers Identified and Potential Strategy to Overcome Barrier

NCI concluded that the LLCS is an attractive option worthy of further research, development and deployment (RD&D). They noted that the stakeholders were generally very receptive, and that there did not seem to be any "deal-breakers." *Stakeholders seem to be most interested in packaged solutions, rather than individual technologies*. It also appears that the timing is good, because more and more stakeholders are realizing the importance of energy efficiency, and are

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[3] Matlab is a high-level programming language and interactive environment used to develop and perform computational applications faster than with traditional programming languages such as C, C++, and Fortran.

[4] Navigant also provides technical support and analysis to DOE's HVAC/R program.

becoming *interested in green buildings*. One of the most important steps moving forward will be case studies and demonstrations of benefits, including cost and energy savings. Many of the findings are consistent with PNNL's own experience. NCI's recommendation provides useful insight to BPA because *these recommendations generally apply to most integrated technology options* that are going to be used in high performance and net-zero energy buildings.

PNNL concurs with the limitation and barriers noted by NCI for the use of active TES. Although PNNL has investigated the active TES option, PNNL does not think that active TES is essential to realize the savings potential. A significant fraction of the savings that can be attributed to TES can be achieved by passive TES (using thermal mass). PNNL has not yet evaluated passive TES as an option because of simulation limitations.

Another issue identified by NCI (although noted as minor), is the need for advanced controls that are user-friendly and tailored to the needs of building operator and maintenance personnel. To achieve high efficiencies, the high performance and net-zero energy buildings will use highly integrated systems, which will need advanced controls and diagnostic tools that can help even an unsophisticated operator to manage the buildings efficiently.

Incremental Cost Estimates for Low-Lift System

One of the objectives of this study was to conduct an economic analysis of the LLCS. In line with the zero energy buildings goal of five-year paybacks by 2025, PNNL decided to estimate simple payback, rather than conducting a detailed life-cycle cost analysis. For simple payback, both incremental cost and energy savings estimates are needed.

Estimating incremental cost of emerging technology is difficult because of limited availability of information that is available in the open literature. To estimate the incremental cost for the components that make up the LLCS, PNNL retained the services of NCI.

NCI's core findings are as follows:

- Office buildings may be the most ideal first application for low-lift cooling technologies/systems, particularly those using multi-zone rooftop systems.
- The large cost of the multi-zone rooftop systems (with respect to a similar-sized chiller) allows for a favorable cost comparison for low-lift chiller systems in medium office buildings.
- Large office buildings show a low incremental cost per square foot, as a result of small increases in chiller costs, and large savings from the smaller ductwork required by the DOAS system.
- Radiant cooling drives the cost incremental for all of the building types. A large portion of these costs is associated with the labor required for installation.
- The cost advantage resulting from reduction of the ductwork for large buildings is a large factor and needs to be validated further.

In addition, there are additional items to consider:

- Some components of the low-lift system, particularly the radiant cooling system, can be considered emerging technologies. There is often a 10-20% premium associated with emerging technologies that may gradually decline as the technology is commoditized.
- Potential additional benefits of the low-lift system include reducing the amount of materials used in construction, particularly the ductwork material.

These are the best estimates given the scope of the work and time frame. PNNL believes that these costs are conservative for a number of reasons:

1. Limited availability of cost information for the emerging technologies.
2. Emerging technologies generally have a premium when introduced but generally the cost goes down significantly as the market is transformed (e.g., compact fluorescent lamps).
3. Low-lift chiller size has not been optimized to reflect the lower size needed when used with the passive thermal storage option.
4. Redundant heating systems have been added for the building with a low-lift system, which may not be needed.

Widespread use of these technologies and when the building is designed and optimized for the LLCS could lower the cost between 20 and 30% from the NCI estimates.

Energy Savings

Estimating the potential technical energy savings for this technology in the Pacific Northwest (PNW) is fairly involved, because of the number of variables involved:

- 21 climate zones
- 12 building types
- 8 different cases of the LLCS, in addition to the baseline reference case (described below)
- 2 different levels of overall building performance - standard and high performance, with lower thermal loads.
- 2 different chiller performance curves (ideal chiller and prototype chiller).

Details of this analysis, including by specific building type, are included in the main report, but the key overall findings are provided in Tables E-1 and E-2. This analysis shows that significant *cooling system efficiency gains* can be achieved by integrating *low-lift cooling technologies*: variable-speed compressor and transport motor controls, radiant cooling with dedicated ventilation air transport and dehumidification, and cool storage. The cooling energy savings for a standard-performance building range from 47% to 84% and, for a high-performance building, from 17% to 66%. These estimates, which include cooling, fans and pumps, are scaled up from the savings from the prototype buildings used in the analysis. Table E-1 summarizes the annual technical energy savings potential in the Pacific Northwest for the *full* LLCS, compared to the building using a conventional HVAC system. Note that these estimates are for new construction and building-types and climate locations for which the full LLCS is applicable. The aggregate percent savings across all climate locations and building types (weighted by new construction volume) is about 74% for standard-performance buildings and 64% for the high-performance buildings. Table E-2 summarizes the annual technical energy savings potential in the Pacific

Northwest for the *full* LLCS, compared to a building with a better system - one that uses a conventional air distribution system with a two-speed chiller.

Table E-1 Summary of Annual *Technical Site* Electricity and Peak[5] Savings Potential in Pacific Northwest for the Low-Lift Cooling System Compared to Conventional HVAC system (assuming 100% Penetration)

Building Performance Level	Cooling and Fan and Pump Electricity Savings		
	million kWh/year	Peak Reduction aMW	Percentage Electricity Savings
Standard	**54.0**	6.2	74.1%
High Performance	**15.5**	1.8	63.5%

aMW = average Mega Watts

Table E-2 Summary of Annual *Technical Site* Electricity and Peak Savings Potential in Pacific Northwest for the Low-Lift Cooling System Compared to two-Speed Chiller as the Baseline (assuming 100% Penetration)

Building Performance Level	Cooling and Fan and Pump Electricity Savings		
	million kWh/year	Peak Reduction aMW	Percentage Electricity Savings
Standard	**42.1**	4.8	71.1%
High Performance	**11.3**	1.3	61.0%

Although parts of the LLCS are applicable for a large portion of the existing commercial building stock and the full LLCS may be applicable to a fraction of the existing building stock, the savings for existing buildings are not considered in this study because the primary market – as with most advanced HVAC systems involving systems engineering in building design – is new construction. In this sense, the technical potential presented here is conservative.

For baseline buildings that are compliant with ASHRAE 90.1-2004, the full LLCS saves about 54 million kWh of site electricity use *in 1 year* with the full LLCS being applied to total new construction in 2010 new commercial building stock. The peak savings associated with it is roughly 6.2 average MW. The annual site electricity savings are about 15.5 million kWh for high-performance buildings. Assuming the new construction growth rates remain the same for the next 10 years (through the year 2020), the total technical site energy savings potential (again assuming 100% penetration) for the baseline building would be 625 million kWh in 2020 (Figure E-2). To reiterate, all of these savings are in site energy terms; to calculate the "busbar" savings, the previous estimates should be multiplied by factor of 1.0725 (using the average transmission loss of 7.625%).[6] The total savings potential – relative to the baseline building – is therefore 670 million kWh in 2020.

[5] Average megawatt (aMW) of electricity is an average measure of the total energy delivered in one year -- 8,760,000 kilowatt-hours per year.

[6] http://www.bpa.gov/Energy/N/pdf/October_2009_Implementation_Manual_FINAL.pdf page 2.

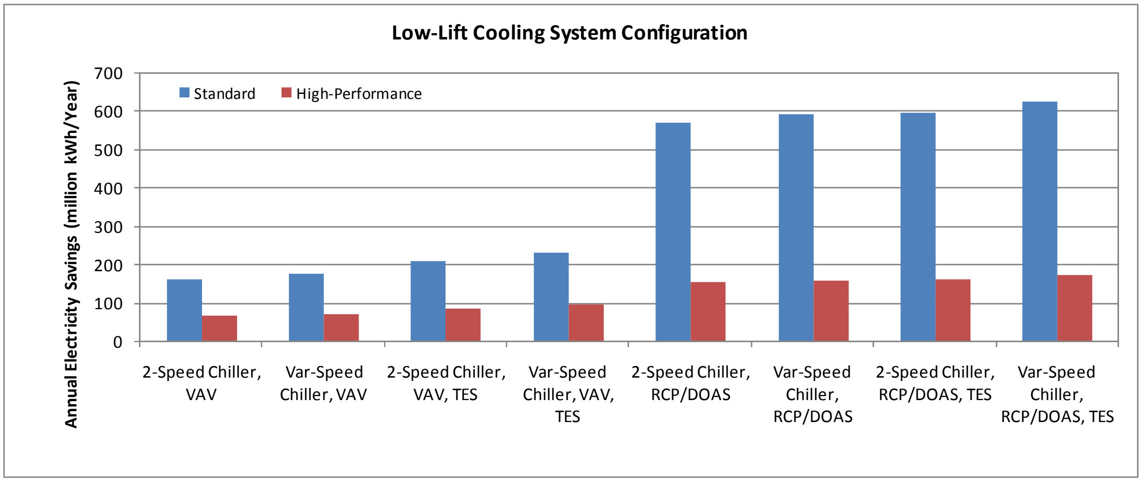

Figure E-2 Pacific Northwest Region Technical Site Electricity Savings in 2020 over the Standard HVAC System for Different System Configurations for 2020 Assuming 100% Penetration over 10 Years of New Construction

As noted above, the analysis of LLCS cases includes eight different combinations, with Case 8 being the full application of the LLCS and Case 0 being the baseline. These EnergyPlus simulations are:

1. Case 0: the EnergyPlus base HVAC configuration case (different of each building)

2. Case 1: two-speed chiller with variable air volume (VAV) or constant air volume (CAV) air handling unit (AHU), depending on building type – the low-lift base case HVAC configuration

3. Case 2: low-lift variable-speed chiller and VAV AHU – this configuration uses the low-lift base case (Case 1), but with variable-speed low-lift chiller, pump and fan equipment

4. Case 3: two-speed chiller with RCP/DOAS – this configuration assumes the low-lift base case (Case 1) without VAV or CAV AHU, with a hydronic distribution system serving radiant cooling/heating panels and a DOAS for ventilation

5. Case 4: low-lift variable-speed chiller, VAV AHU and TES – this is the Case 2 system modified to use an idealized discrete TES

6. Case 5: two-speed chiller with VAV AHU and TES – this is the low-lift base case (Case 1) system modified to use an idealized discrete TES

7. Case 6: low-lift variable-speed chiller with RCP/DOAS – combines the alternatives provided separately in Case 2 and Case 3 (low-lift variable-speed chiller and RCP/DOAS)

8. Case 7: two-speed chiller with RCP/DOAS and TES - this is the Case 3 system modified to use an idealized discrete TES

9. Case 8: low-lift variable-speed chiller with RCP/DOAS and TES – this is the complete envisioned low-lift option incorporating low-lift variable-speed chiller, RCP/DOAS and idealized discrete TES

To provide some flavor for the level of analytical resolution contained in this report, please consider the following illustration for application of these cases for standard-performance medium office building. Depicted in Figure E-3 is simulated electricity consumption per year, for the eight cases, for 21 Pacific Northwest locations. Similar analysis was conducted for the other building types, and then aggregated to provide the regional savings presented earlier.

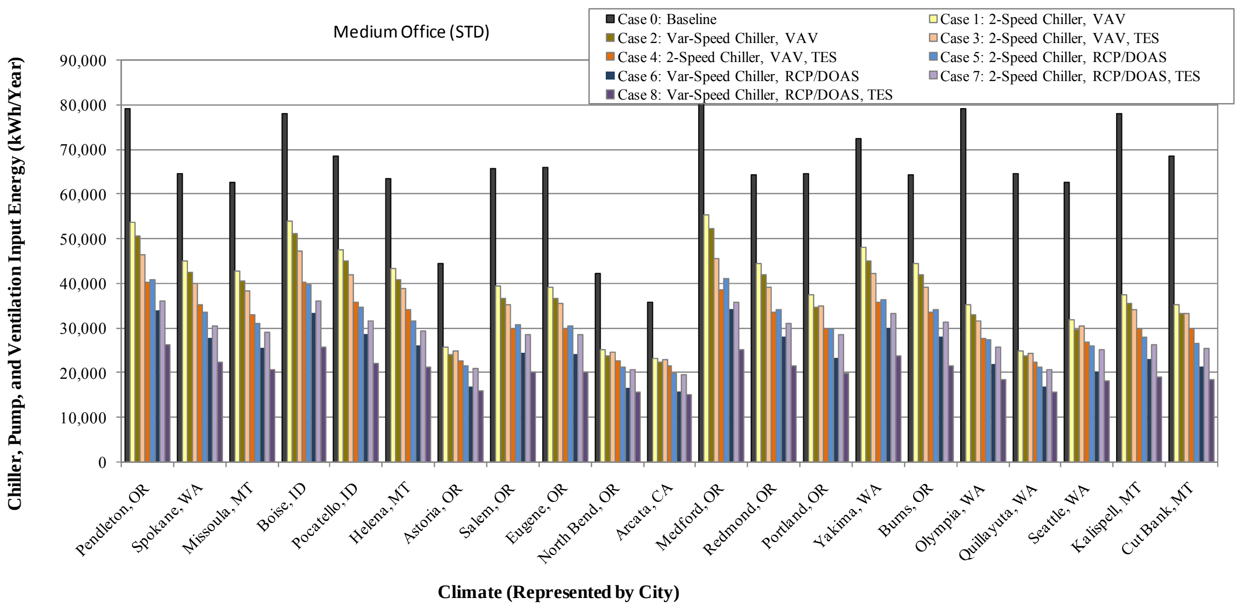

Figure E-3 Comparison of Annual Chiller and Distribution Energy Consumption for Standard Performance Medium Office Building for Various System Configurations in 21 Locations

Economic Analysis

Unless the benefits (energy cost savings) are significant compared to the incremental cost of the LLCS, it is unlikely that these technologies will find widespread acceptance. NCI's incremental cost estimates are for Case 7 – variable-speed low-lift chiller, radiant cooling, and dedicated outdoor-air system. The national average incremental costs for four building types (medium office, large office, supermarket and secondary schools) were estimated to be $0, $383,000, $276,000, $624,000, respectively (cost estimates shown previously in Table E-1 are for Houston). The medium size office buildings typicalyl use a multi-zone packaged system, which is relative more expensive than single-zone packaged units, so cost of these systems is much closer to the variable speed chiller cost. After adjusting the national costs to the various climate regions and using energy savings estimates, simple payback was estimated, as shown in Table E-5. Because the incremental cost of the medium office is negative, the LLCS has a zero payback. The range of paybacks for the large office and secondary school buildings are between 8 and 30 years, which is probably a little bit high even for an emerging technology. Although the technology is applicable to supermarkets, it is difficult to complete with the relatively inexpensive single-zone packaged units. It appears that in the Pacific Northwest, this LLCS may not be favorable, in the absent of innovation breakthroughs in technology or provision of other incentives.

The aggregate payback (weighted by the new construction volume) for large office and secondary schools is reasonable, 17 and 23 years, respectively.

Table E-4 Simple Payback by Building Type for each Climate Location

	Office Medium	Office Large	Supermarket	Secondary School
Spokane, WA	0	10.0	28.8	20.6
Pendleton, OR	0	13.5	27.9	16.7
Missoula, MT	0	12.2	17.1	14.9
Boise, ID	0	14.0	32.9	21.7
Pocatello, ID	0	8.3	24.4	23.8
Helena, MT	0	7.8	14.7	14.8
Astoria, OR	0	22.3	39.3	26.7
Salem, OR	0	17.1	33.3	20.4
Eugene, OR	0	16.9	33.5	20.2
North Bend, OR	0	24.9	40.3	28.7
Arcata, CA	0	25.5	24.1	19.0
Medford, OR	0	17.2	29.7	16.7
Redmond, OR	0	15.6	27.0	19.6
Portland, OR	0	17.6	34.5	20.9
Yakima, WA	0	15.6	30.6	20.3
Burns, OR	0	13.2	26.9	19.0
Olympia, WA	0	19.4	37.0	24.3
Quillayuta, WA	0	24.3	42.2	29.1
Seattle, WA	0	18.5	41.5	25.6
Kalispell, MT	0	14.2	17.2	16.5
Cut Bank, MT	0	10.4	14.9	17.0
Aggregate Payback	0	17.3	37.5	23.4

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Content

Figures

Tables

Acronyms and Abbreviations

A/C	air conditioning
AEDG	Advanced Energy Design Guide
AHU	air handler unit
ANSI	American National Standards Institute
ARI	American Refrigeration Institute
ARTI	Air-Conditioning and Refrigeration Technology Institute
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BPA	Bonneville Power Adminstration
BT	Building Technologies Program
CBECS	Commercial Building Energy Consumption Survey
C/C	cooling coil
CFC	chlorofluorocarbons
cfm	cubic feet per minute
COP	coefficient of performance
CV	constant volume air distribution system
CRTF	comprehensive room transfer function
CTF	conduction transfer function
DCV	demand-controlled ventilation
DDC	direct digital control
DOAS	dedicated outdoor air conditioning system
DOE	U.S. Department of Energy
DV	displacement ventilation
DX	direct expansion
ECM	electrically commutated motors
EER	energy efficiency ratio
EIA	Energy Information Administration
ELWT	Evaporator Leaving Water Temperature
EWFR	Evaporator Water Flow Rate
ERV	energy recovery ventilation
EUI	energy use intensity
FLEOH	full-load-equivalent operating hours
FDD	fault detection and diagnostics
GIS	geographical information systems
gpm	gallons per minute
GSA	General Services Administration
H/C	heating coil
HP	heat pump
HPB	high-performance building
HX	heat exchanger
HSTF	heat source transfer function
HVAC	heating, ventilation and air conditioning
IAQ	indoor air quality
IESNA	Illuminating Engineering Society of North America
kBh	thousand Btu per hour

kWh	kilowatt hours
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in Energy and Environmental Design
LLC	low-lift cooling
LLCS	low-lift cooling system
MCH	McGraw-Hill Construction
NCI	Navigant Consulting Inc.
NWPC	Northwest Power Planning Council
NZEB	Net-Zero Energy Building
NREL	National Renewable Energy Laboratory
ODB	outdoor dry-bulb temperature
OEM	original equipment manufacturer
PBA	principal building activity
PCM	phase change materials
PNNL	Pacific Northwest National Laboratory
PLR	part load ratio
PSZ	package single zone
QUAD	quadrillion (10^{15}) British Thermal Units (Btus)
R&D	research and development
RCP	radiant cooling panel
RTP	real-time pricing (electric utility rate)
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
SHR	sensible heat ratio
SP	special projects (working groups within ASHRAE)
TES	thermal energy storage
TOU	time of use (utility rate)
UA	conductance coefficient
UFAD	under-floor air distribution
VAV	variable air volume
VFD	variable frequency drive
VRV	variable refrigerant volume
VS	variable-speed
VSD	variable-speed drive
W/cfm	Watts per cubic feet per minute (measure of fan power efficiency)
W/sf	Watts per square foot
WWR	window-to-wall Ratio
ZEB	zero energy building

Introduction

Design of cost-effective high-performance buildings has focused mainly on lighting, window and other envelope measures. Efforts directed at improving the heating, ventilating and air conditioning (HVAC) performance have tended to pursue, and in many cases achieved, incremental efficiency improvements. There are a number of potential integrated solutions that can provide significant HVAC efficiency improvements. Pacific Northwest National Laboratory (PNNL), with co-funding from Bonneville Power Administration (BPA) and the Building Technologies (DOE-BT) Program of the U.S. Department of Energy (DOE), conducted this research and development (R&D) activity to address the energy efficiency goals outlined in the BPA Roadmap.[7] The R&D effort evaluated one integrated HVAC design option.

The objective of this R&D project is to show that integrated HVAC design options have the potential to reduce the HVAC energy consumption *significantly* in the Pacific Northwest region through utilization of synergies between emerging HVAC technologies and advanced controls. The integrated technology, referred to as low-lift cooling system (LLCS) in the report, evaluated as part of this project leverages increased part-load efficiencies of equipment and the operational efficiency of the building as an integrated system. The LLCS consists of:

1. Peak-load shifting by means of active or passive (pre-cooling of building mass) thermal energy storage (TES).[8]
2. Dedicated outdoor air system (DOAS) and enthalpy heat recovery from exhaust air.
3. Radiant heating and cooling (RCP) panels or floor system.
4. Low-lift[9] vapor compression cooling equipment.
5. Advanced controls at the HVAC equipment and HVAC system (supervisory) levels.

This report describes the work performed for the BPA portion of the work. For the DOE portion of the work refer to Katipamula el al. (2010), Jiang et al. (2008), Armstrong et al. (2009a, b). The objectives of the work are:

1. selecting a manufacturing partner to build the low-lift chiller prototype
2. developing a specification for a “low-lift” electrically driven vapor compression chiller system
3. building a prototype to meet the specification
4. conducting a market assessment in the Pacific Northwest region to understand the barriers and perceived benefits of the LLCS
5. developing incremental cost estimates for the low-lift system compared to conventional chiller

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[7] http://www.bpa.gov/corporate/business/innovation/docs/2006/RM-06_EnergyEfficiency-Final.pdf

[8] In this report *active* denotes peak-shifting by means of a discrete TES such as a stratified water tank; *passive* refers to pre-cooling of the intrinsic mass (building fabric and contents) by forced air or hydronic radiant cooling using a chiller and/or air-, water-, or refrigerant-side free cooling.

[9] The American Refrigeration Institute defines chiller part-load rating conditions as 50°F chilled water supply and 80°F outdoor dry-bulb temperature; we consider *low-lift conditions* to be 60-65°F chilled water supply, ~80°F outdoor dry-bulb temperature (day) and ~70°F outdoor dry-bulb temperature (night).

6. developing performance maps for the prototype and comparing them to the conventional vapor compression system
7. quantifying the energy, emissions and peak load reduction benefits from widespread use of the proposed technology options in the BPA's service territory

The savings estimates reported are based on thermal loads from the EnergyPlus simulations and the energy consumption estimates from the component models developed as part of the DOE funded effort. In addition, the savings are based on the use of a larger set of building types (12) and climate locations (21).

The report provides a brief background about the technology option (Background); followed by a section that describes the prototype chiller specification and its performance (Prototype Chiller Development and Performance Characterization). The EnergyPlus prototype templates that were used to generate the thermal loads are described in the Commercial Building Benchmarks section. The market assessment to identify potential barriers and perceived benefits from the use the LLCS was conducted by Navigant Consulting Inc. (NCI) under subcontract to PNNL. The summary of the market assessment is described in Market Assessment of Low-Lift Cooling System section. In addition to market assessment, PNNL also had NCI develop incremental cost estimates for the low-lift option; summary of that work is described in the section Incremental Cost Estimates for the Low-Lift Cooling System. The methodology used to estimate the energy use for the various low-lift combinations is described in Energy Use Estimation Methodology section. The energy savings for various combinations of low-lift technologies compared to the base case and simple backpack estimates for selected building types are presented in Energy Savings Estimates for the Various LLCS Combinations section. The methodology used to estimate the technical potential energy savings in the Pacific Northwest is described in Pacific Northwest Regional Energy Savings Estimation Methodology section. The technical potential savings for the Pacific Northwest and estimates for energy savings estimates for year 2020 are presented in Pacific Northwest Regional Technical Energy Savings Potential section. The economic analysis, including the simple payback calculation is described in Economic Analysis section. The discussion and recommendations are provided in the Discussion and Recommendations section.

Background

All the component technologies that comprise the LLCS have been in use, to some extent, for a number of years but not in the U.S. These efforts, even those that combined radiant panel distribution and/or night pre-cooling concepts however, have continued to assume a more or less conventional cooling plant. Conversely, efforts to optimize chiller and TES operations have generally assumed a conventional air-distribution system. Although these technologies can and have been used independently to provide incremental savings, when used together, they achieve significant energy savings by integrating HVAC equipment, distribution and control in a highly synergistic manner. Peak shifting and active and passive thermal energy storage are proven technologies that improve chiller load factor and can increase chiller efficiency. DOAS with enthalpy recovery[10] provide more efficient latent cooling so that radiant cooling can be used to satisfy sensible cooling loads. Radiant cooling further increases chiller efficiency by allowing the higher temperature of the radiant panel/ceiling, and hence of the chilled water supplied, to be only a few degrees below room temperature. Compared to all-air systems, the fan energy use of a RCP/DOAS is dramatically reduced. When advanced controls are integrated with the above technologies, additional energy and peak demand savings can be achieved by coordinating variable-speed compressors, fans and pumps for maximum efficiency, by anticipating and shifting daytime cooling loads, and by eliminating simultaneous heating and cooling.

It is recognized that substantial efficiency improvements in office, retail and other building types can be achieved with advanced envelopes (e.g., reduced conduction and infiltration, improved windows), lighting technologies/controls, and plug load power density reductions. These technologies are basic to continued advances in overall energy efficiency. As the envelope reaches a very high level of performance and ventilation load is taken up by a DOAS, the remaining cooling load will be dominated by internal gains: lights, plugs, and people. Most building types will have—and all building core zones have always had—cooling load patterns that do not vary much from week to week and even from summer to winter seasons. This is the ideal situation for a baseload cooling system with modest storage—analogous to a light, streamlined hybrid vehicle with a small and very efficient engine.

With the assumed low design load (high performance envelope and low lighting and equipment power densities) for cooling loads that can be satisfied with higher chilled water and supply air temperatures (60 to 65^{o}F) and, with roughly half of the cooling delivered at night, the lowest life-cycle-cost plant will be one that is optimized for low condensing temperature (75^{o}F or less) as well. Hydronic radiant cooling distribution can only be used in conjunction with DOAS equipment to address latent load. One can thus consider a LLCS to address the cooling and ventilation piece of the zero energy building (ZEB) puzzle as an integration of three key elements:

1. Efficient low-lift (75^{o}F condenser, 60^{o}F evaporator) variable-speed cooling plant.
2. Intrinsic building mass and controls to halve the typical cooling plant load factor.
3. RCP/DOAS with enthalpy recovery and efficient distribution.

[10] Uses outdoor-exhaust air enthalpy difference to pre-heat and humidify or pre-cool and pre-dry outdoor air.

Efficient pre-cooling of building mass, enabled by advanced controls and efficient distribution, has two potential effects on chiller cost and performance: 1) the plant operates at much lower average discharge pressure, and 2) shifting load away from the peak can reduce the required cooling plant capacity. Other high performance building characteristics involving the envelope, windows and shading, lighting and controls, and office equipment can be expected to reduce peak cooling loads by at least 50%. With the reduction in plant capacity, further improvements in chiller plant efficiency can be justified (refer to Jiang et al. 2008 for details).

The theoretical potential for high efficiency, low-lift vapor-compression cooling is well understood. The source and sink temperatures between which a thermodynamic cycle operates are determined by conditions and by approach temperatures in the load-side and rejection-side heat exchangers. The Carnot and Lorentz ideal cycle efficiencies represent fundamental upper bounds on performance to which current products and standards do not come anywhere near. Industry has argued that further improvements are not cost effective. However, the value engineering analyses that reach these conclusions typically assume current design practices such as not using thermal storage, using the same heat exchanger for sensible and latent cooling, using fixed-speed motors and sizing for peak load. Most cool storage installations to date have been justified by time-of-use electric rates; none have, to our knowledge, used chillers optimized for low-lift operation or for very efficient operation at less than half rated capacity. The main reasons for this are: 1) the double approach temperature penalty inherent in most discrete cool storage configurations, 2) a dearth of low-lift, high part-load efficiency chillers in the marketplace, and 3) low probability of finding an owner willing to try two or three new, mutually dependent cooling technologies in the same building.

As the results show, the proposed LLCS is applicable to many commercial building types and climates where mechanical cooling equipment is considered necessary (cooling applications that cannot be 100% satisfied by natural ventilation or air- or water-side economizer operation). This market represents well over half of the entire U.S. commercial building sector even if we count only applications that benefit from all elements of the LLCS.

Prototype Chiller Development and Performance Characterization

One of the objectives of the project was to work with a manufacturing partner and develop a prototype low-lift optimized air-cooled chiller. After talking to a number of manufacturers, PNNL chose to work with McQuay International to develop the prototype chiller. The specifications for the prototype chiller were prepared by PNNL staff and consultants. PNNL then worked with the manufacturing partner to negotiate the final prototype chiller specification. The following section provides the details of the prototype chiller.

Specification of Prototype Low-Lift Chiller

The chiller specifications are as follows:

1. **Chiller** type: Air cooled.

2. Power **supply**: three-phase 208 (+5% to -10%) volts 60 Hz.

3. **Cooling capacity**: A minimum desired nominal rated cooling capacity of 15 tons (90,000 Btu/h or 26 kW); the rated capacity should not exceed 15 tons (180,000 Btu/h or 52 kW).

4. **Heating capacity**: Optional, but if provided, a minimum desired nominal rated heating capacity of 90,000 Btu/h (26 kW).

5. **Number of compressors**: Two or more compressors, with one compressor fitted with variable-speed drive.

6. **Type of compressors**: Preferably at least one scroll compressor with variable-frequency drive (VFD) the other fixed-speed compressor(s) can also be scrolls. The intent is that the modulating compressor should have very high efficiency at low load and a low pressure ratio. With the combination of compressor sequencing and speed modulation of one compressor, the chiller will operate efficiently and reliably at as low as 20% of rated capacity. Motor-VFD efficiency of the variable-speed compressor shall be at least 90% above 20% rated speed.

7. **Water side heat exchanger**: Brazed plate type.

8. **Air side heat exchanged**: Cross fin coil type.

9. **Condenser fan**: Very efficient condenser fan, motor and adjustable-speed drive with 7:1 turn down (100%, 90%, 65%, 50%, 40%, 37%, 34%, 30%). Motor-VFD efficiency shall be at least 85% above 30% rated speed.

10. **Refrigerant type**: R410A.

11. **Refrigeration Control**: Electrical expansion valve.
12. **Subcooling:** A liquid receiver that provides sub-cooling to ensure the liquid entering the expansion valve is also subcooled.

13. **Defrost type**: Reverse cycle defrost.

14. **Temperature control**: Control with outlet water temperature.

15. **Chiller system (excluding chilled water pump)**: The chiller shall achieve a coefficient of performance (COP) of 3.0 or higher at rated conditions (i.e., 95°F outdoor dry-bulb and 44°F chilled water temperature). A COP of at least 4.0 or higher at 95°F outdoor dry-bulb and 68°F chilled water leaving temperature is also required.

16. **Internal controls** will provide independent optimal control of motor speeds and an electronic expansion valve such that:
    a. Suction superheat is always controlled to a reasonable value.
    b. At any given outdoor and chilled water return temperature, chilled water pump, and compressor specific power (kW/ton) are nearly monotonic with capacity from 100% to 30% of rated capacity (e.g., kW/ton at 50% cap should be greater than or equal to energy efficiency ratio [EER] at 60% capacity).
    c. At any given capacity and chilled water return temperature, condenser fan, and compressor specific power (kW/ton) must all fall monotonically with outdoor air dry-bulb from 100°F to 50°F (e.g., 1.0 kW/ton at 100°F should be 0.5 kW/ton at 50°F).
    d. At any given capacity and outdoor air dry-bulb temperature, condenser fan, and compressor specific power (kW/ton) must all fall monotonically as chilled water return temperature rises from 55°F to 75°F (e.g., at 80°F outdoor air dry-bulb temperature, 1.0 kW/ton at 55°F should fall to 0.6 kW/ton at 75°F).
    e. The control will allow user-defined chilled water pump speed vs. delta-T schedule (e.g., 2 gpm per °F temperature difference would be a typical simple linear relationship but a non-linear relationship should also be allowed for PNNL's testing purposes).

17. **Protective devices**: All standard protective devices including high-pressure switch, fan driver overload protector, over current relay, inverter overload protector, etc.

Quantifying the Performance of Prototype Chiller

The performance of the chiller was quantified in a controlled environment at the Intertek Laboratory in Cortland, NY. The details of the test conditions and measurement made to quantify the chiller performance are described below.

The chiller performance was first characterized at the American Refrigeration and Institute (ARI) test conditions, as shown in Table 1.

Table 1 ARI Performance Test

	For ARI Standard IPLV		
Chiller Step Number	Load (%)	ODB (^oF)	ELWT (^oF)
24	100	95	44
18	75	80	44
12	50	65	44
6	25	55	44
0	0	55	44

ODB: Outdoor dry-bulb temperature
ELWT: Evaporator leaving water temperature

In addition to the standard ARI test, the performance of the chiller was also characterized at the following test conditions.

Table 2 Additional Test to Characterize the Chiller Performance

Test No	Chiller Step	Load (%)	ODB (oF)	ELWT (oF)	EWFR (gal/min)
1	24	100	110	55	29.3
2	24	100	90	55	29.3
3	24	100	70	55	39.8
4	24	100	50	55	41.7
5	16	66	110	55	22.8
6	16	66	90	55	22.8
7	16	66	70	55	27.8
8	16	66	50	55	29.6
9	8	33	110	55	13.6
10	8	33	90	55	15.0
11	8	33	70	55	16.7
12	8	33	50	55	18.6
13	3	15	110	55	6.4
14	3	15	90	55	7.4
15	3	15	70	55	7.8
16	3	15	50	55	8.7
17	24	100	110	65	26.4
18	24	100	90	65	29.2
19	24	100	70	65	45.5
20	24	100	50	65	47.9
21	16	66	110	65	26.4
22	16	66	90	65	26.4
23	16	66	70	65	31.7
24	16	66	50	65	33.8
25	8	33	110	65	15.8
26	8	33	90	65	17.5
27	8	33	70	65	19.1
28	8	33	50	65	21.4
29	3	15	110	65	7.4
30	3	15	90	65	8.3
31	3	15	70	65	9.0

Test No	Chiller Step	Load (%)	ODB (oF)	ELWT (oF)	EWFR (gal/min)
32	3	15	50	65	10.0
33	8	33	75	70	19.6
34	8	33	70	65	38.2
35	18	75	70	55	25.0
36	12	50	70	55	23.7
37	6	25	55	55	15.1
38	16	66	75	44	23.4
39	8	33	55	44	15.6
40	3	15	55	44	7.4
41	3	15	110	55	6.4
42	3	15	90	58	7.4
43	3	15	70	62	7.8
44	3	15	50	65	8.7
45	6	25	110	55	11.4
46	6	25	90	58	13.4
47	6	25	70	62	14.7
48	6	25	50	65	16.4
49	13	55	90	65	25.5
50	8	33	50	65	15.6
51	12	50	70	65	23.7
52	9	38	90	65	23.7

EWFR: Entering water flow rate

For all tests the following data was collected at 1-minute intervals.

- Compressor discharge temperature
- Compressor discharge pressure
- Compressor suction temperature
- Compressor suction pressure
- Outdoor coil liquid temperature
- Outdoor coil liquid pressure
- Outdoor condenser fan temperature for each system
- Temperature difference across the condenser should be measured using a thermopile
- Total voltage per leg
- Total amps per leg
- Total kW
- Total kW for the two constant-speed compressors
- Total kW for the one variable-speed compressor
- Total kW for the condenser fans
- Condenser fan speed
- Variable-speed compressor speed
- Total water flow in gallon per minute (gpm) across evaporator
- Entering water temperature
- Leaving water temperature
- Condenser air inlet - approximately four locations
- Water pressure drop across evaporator for each system

- Refrigeration mass flow rate

Calculated data:
- Calculated superheat
- Calculated subcooling
- Calculated capacity
- Calculated EER.

There are two objectives to characterize the performance of the prototype chiller: 1) generate a chiller performance map that can be used in the simulations to estimate the chiller energy consumption at various part-load conditions and 2) compare the prototype chiller performance to the ideal low-lift optimized and a conventional chiller performance.

Three versions of the chiller model were developed to produce two ideal low-lift chiller performance maps. The first performance map is for the RCP system, which includes both compressor and refrigerant-side economizer operation. The chiller model for economizer operation uses the same components as the chiller for compressor operation except that the compressor is replaced by a flow-pressure characteristic of the compressor bypass branch used during economizer operation. At each performance evaluation, the two maps are evaluated and the mode of operation (compressor or economizer) is determined by which map evaluation returns the lower kW/ton number.

The variable air volume (VAV) system uses an air-side economizer so only one chiller model is needed to produce a chiller performance map. However, the map has three regions corresponding to a chilled water supply temperature reset schedule, which is a function of outdoor temperature. Two-speed operation of the compressor, condenser fan and chilled water pump is simulated by performance curves derived from the variable-speed performance map. The low- and high-speed specific power curves—functions of outdoor temperature only—are obtained by evaluating the variable-speed performance map at part-load fractions of 0.5 and 1.0.

Ideal Low-Lift RCP-Chiller Performance Map

A map of chiller system input power was produced for an indoor temperature, T_z, of 72°F on a grid of cooling load, Q, and outdoor temperature, T_x. A set of input power versus cooling load curves was generated for each outdoor temperature. A bi-cubic was fit to the surface because the bi-cubic accurately represents the chiller performance surface and is compatible with most simulation programs. The bi-cubic also satisfies the need of the 24-hour look-ahead controller for computational efficiency and for a power versus load function that is smooth to at least its first derivative.

Figure 1 shows the optimal chiller system performance map for indoor temperature T_z =72°F with outdoor temperature, T_x, ranging from 110°F to 50°F in 10°F increments. Note the inflections at low capacity fraction on the 50°F and 60°F outdoor temperature lines; the compressor is bypassed below these inflection points to make use of the refrigerant-side economizer. Table 3 documents the coefficients for the performance maps curves.

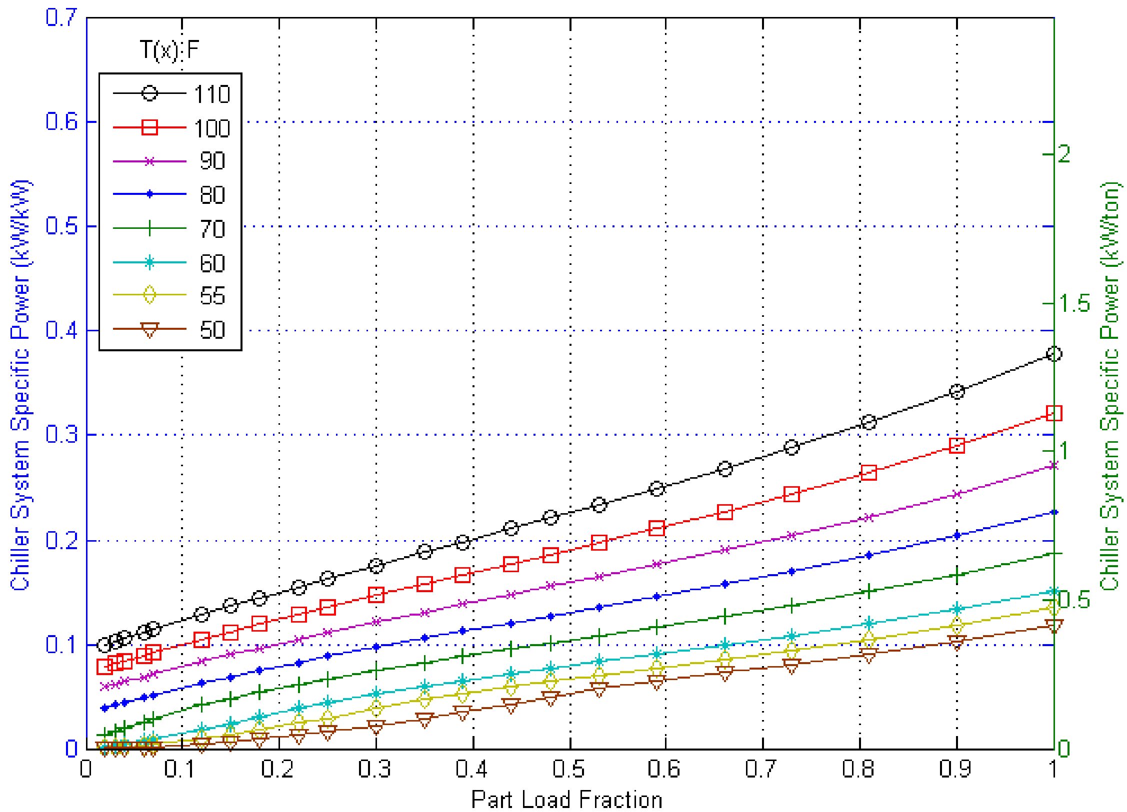

Figure 1 Ideal Low-Lift Chiller-RCP System Performance Map at Tz = 72°F with Tx ranging from 110°F (topmost curve) to 50°F in 10 R increments

Table 3 Coefficients for the Ideal Chiller Performance Map, x=Outdoor Dry-Bulb Temperature in Fahrenheit, y=part load fraction

	Ideal VAV	Ideal RCP		
		x<50°F	50°F<x<80°F	x>80°F
constant	-1.990E-01	-2.502E-01	-2.640E-01	-4.326E-01
x	4.905E-03	1.037E-02	7.730E-03	1.273E-02
y	3.190E-01	1.056E-01	3.961E-01	0.801471605
x2	-3.637E-05	-1.487E-04	-6.947E-05	-0.000109547
xy	-2.845E-03	-1.003E-03	-9.881E-03	-0.014008642
y2	-2.729E-01	-8.095E-02	-1.478E-01	-0.432111111
x3	1.452E-07	8.642E-07	3.378E-07	3.82373E-07
x2y	2.461E-05	1.843E-05	8.704E-05	8.08642E-05
xy2	1.225E-03	3.983E-04	1.400E-03	0.003972222
y3	1.183E-01	4.980E-02	5.180E-02	0.1

Ideal Low-Lift VAV-Chiller Performance Map

The chiller performance model for all-air (Constant Volume and VAV) applications differs from an RCS-plus-DOAS application with respect to chilled water supply temperature. The chilled water supply temperature reset schedule for all-air systems provided in Appendix G of ASHRAE 90.1-2000 was adopted, as shown in Figure 2. Because the chilled water supply temperature is a function of outdoor dry-bulb temperature, the chiller performance map may still be represented as a black-box function of specific power, *Q,* and $T_{x,}$, as shown in Figure 3. Two points should be noted: 1) the capacity of the cooling coil is assumed to be adequate, i.e., with the reset schedule of Figure 2, capacity is constrained by chilled water flow rate rather than coil proportionality constant, UA, and 2) for the all-air system, supply fan power is not included in the chiller coefficient of performance (COP) numbers represented in Figure 3. A separate model that relates fan power to hourly cooling and ventilation loads is used to compute annual fan energy.

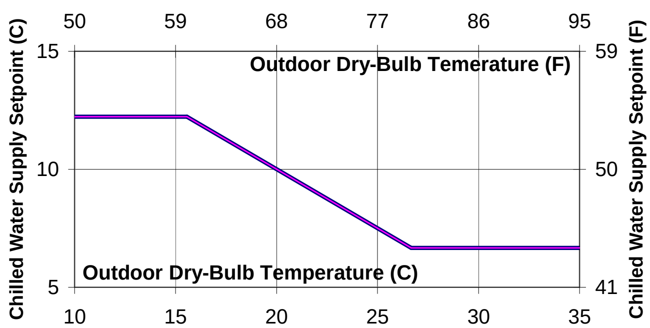

Figure 2 Chilled Water Reset Schedule (Appendix G, ASHRAE 90.1-2000)

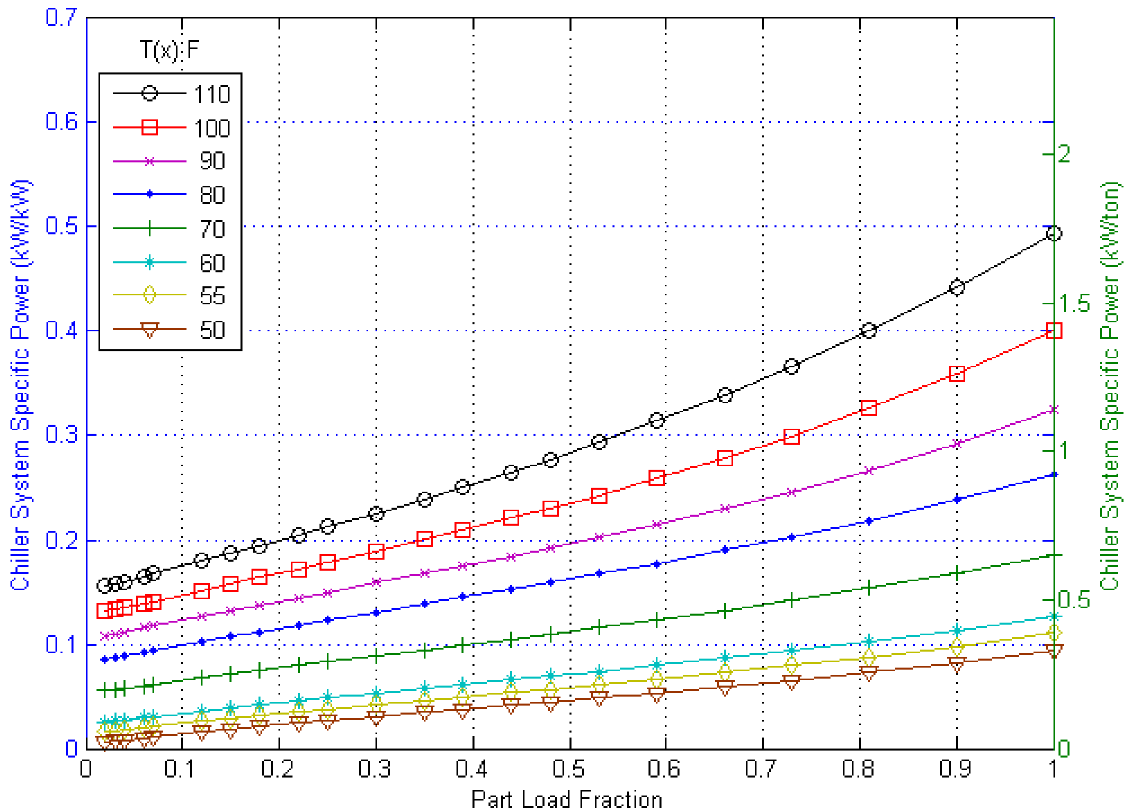

Figure 3 Ideal Low-Lift VAV-Chiller Performance Map with the Chilled Water Reset Schedule Shown in Figure 2

Prototype Low-Lift RCP-Chiller Chiller Performance Map

Figure 4 shows the prototype low-lift chiller system performance map for indoor temperature T_z =72°F with outdoor temperature, T_x, ranging from 110°F to 50°F in 10°F increments. Note the inflections at low capacity fraction on the 50°F and 60°F outdoor temperature lines; the compressor is bypassed below these inflection points to make use of the refrigerant-side economizer. Table 4 documents the coefficients for the performance maps curves.

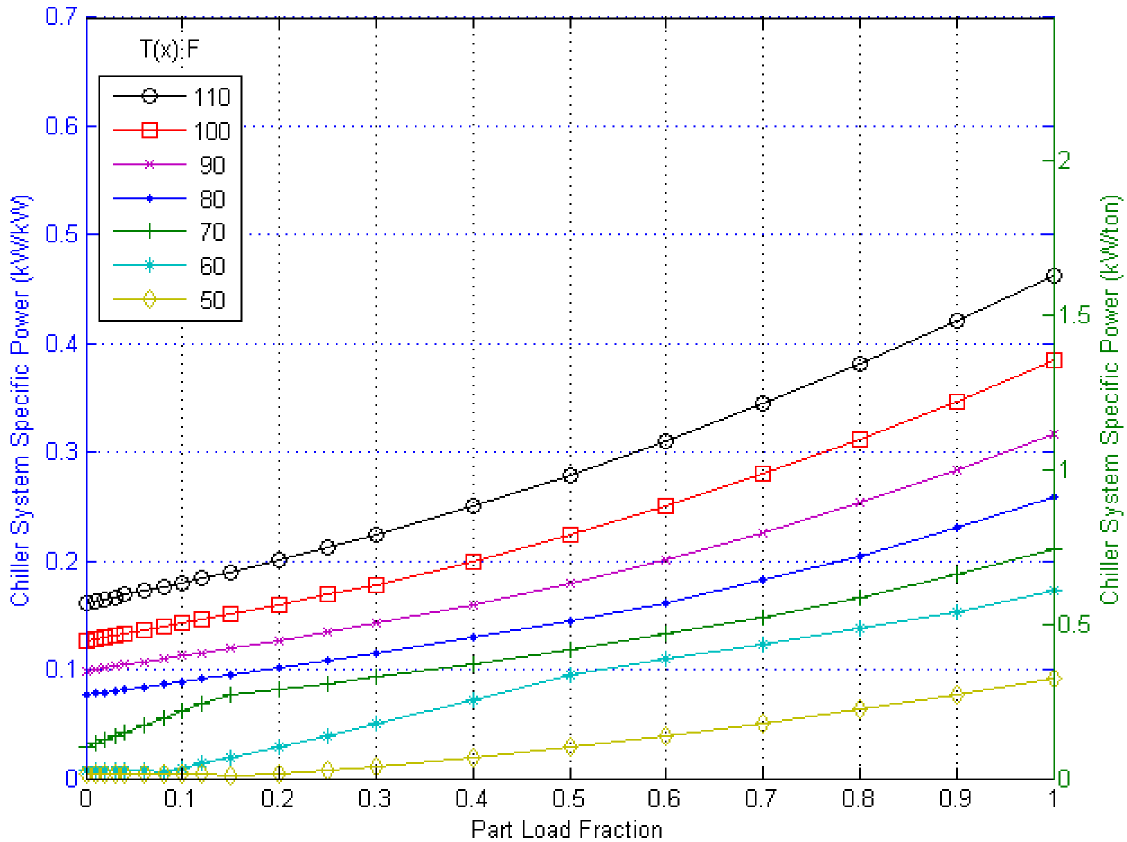

Figure 4 Prototype Low-Lift RCP-Chiller System Performance Map at T_z = 72°F with T_x ranging from 110°F (topmost curve) to 50°F in 10 R increments

Table 4 Prototype Chiller Performance Map Coefficient, x=Outdoor Dry-Bulb Temperature in Fahrenheit, y=part load fraction, z=Chilled Water Temperature in Fahrenheit

	Prototype RCP		Prototype VAV
	x>=z*	x<z	
constant	4.156E-01	6.485E-01	4.156E-01
x	1.229E-03	-2.356E-02	1.229E-03
z	-1.437E-02		-1.437E-02
y	3.282E-02	-6.879E-01	3.282E-02
x2	5.015E-05	2.101E-04	5.015E-05
z2	1.832E-04		1.832E-04
y2	5.603E-02	6.370E-02	5.603E-02
xz	-1.150E-04		-1.150E-04
xy	2.946E-03	1.442E-02	2.946E-03
yz	-2.441E-03		-2.441E-03

*for RCP z=75 – y x 15; for VAV z = 44 if x>=80°F, z = 44+0.5x(80-x) if 60°F> x < 80°F, z = 54 if x <= 60°F;

Prototype Low-Lift VAV-Chiller Performance Map

The prototype low-lift chiller performance model for all-air (CV and VAV) applications differs from an RCS-plus-DOAS application with respect to chilled water supply temperature. Because the chilled water supply temperature is a function of outdoor dry-bulb temperature, the chiller performance map may still be represented as a black-box function of specific power, *Q*, and T_x as shown in Figure 5.

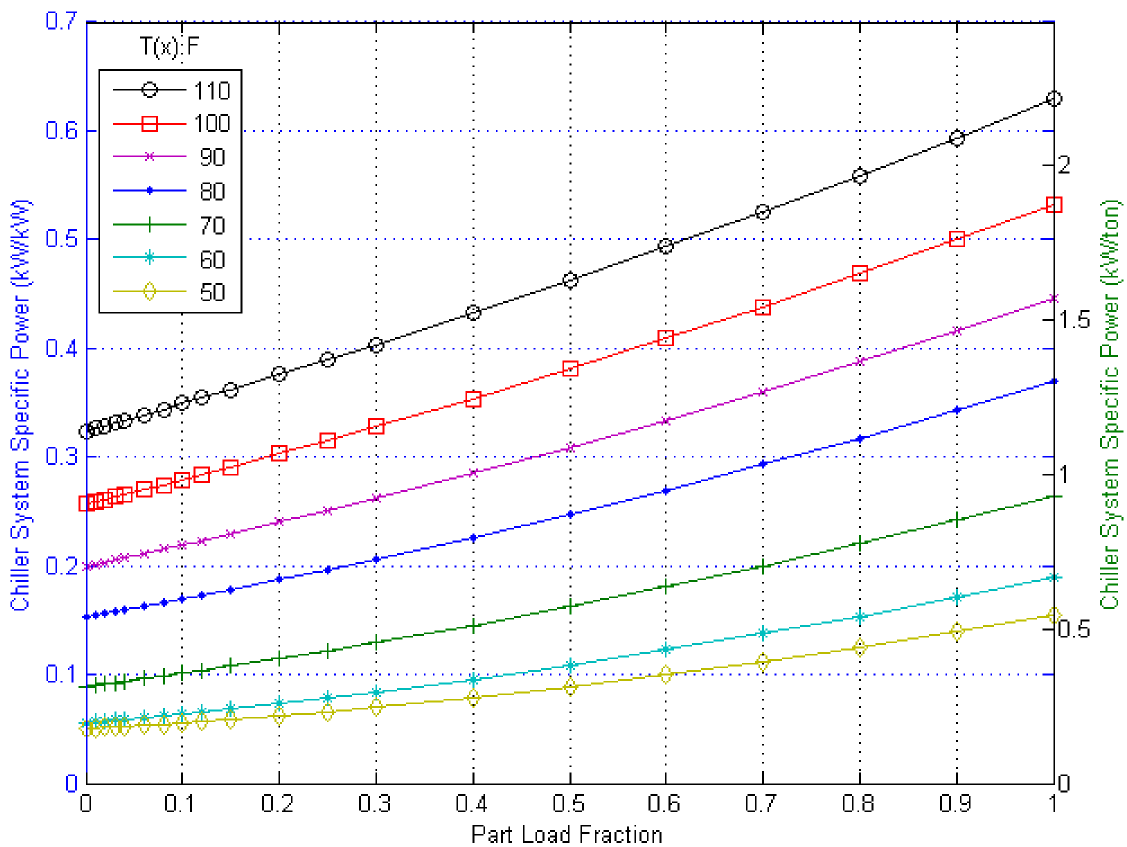

Figure 5 Prototype Low-Lift VAV-Chiller Performance Map with the Chilled Water Reset Schedule Shown in Figure 2

Conventional Chiller Performance Map

Figure 6 shows the performance of a typical conventional single-speed air-cooled chiller. Although at full-load the conventional chiller performance is comparable to prototype low-lift or the ideal low-lift chiller, its performance below 50% part-load is significantly higher that the variable-speed low-lift chiller options.

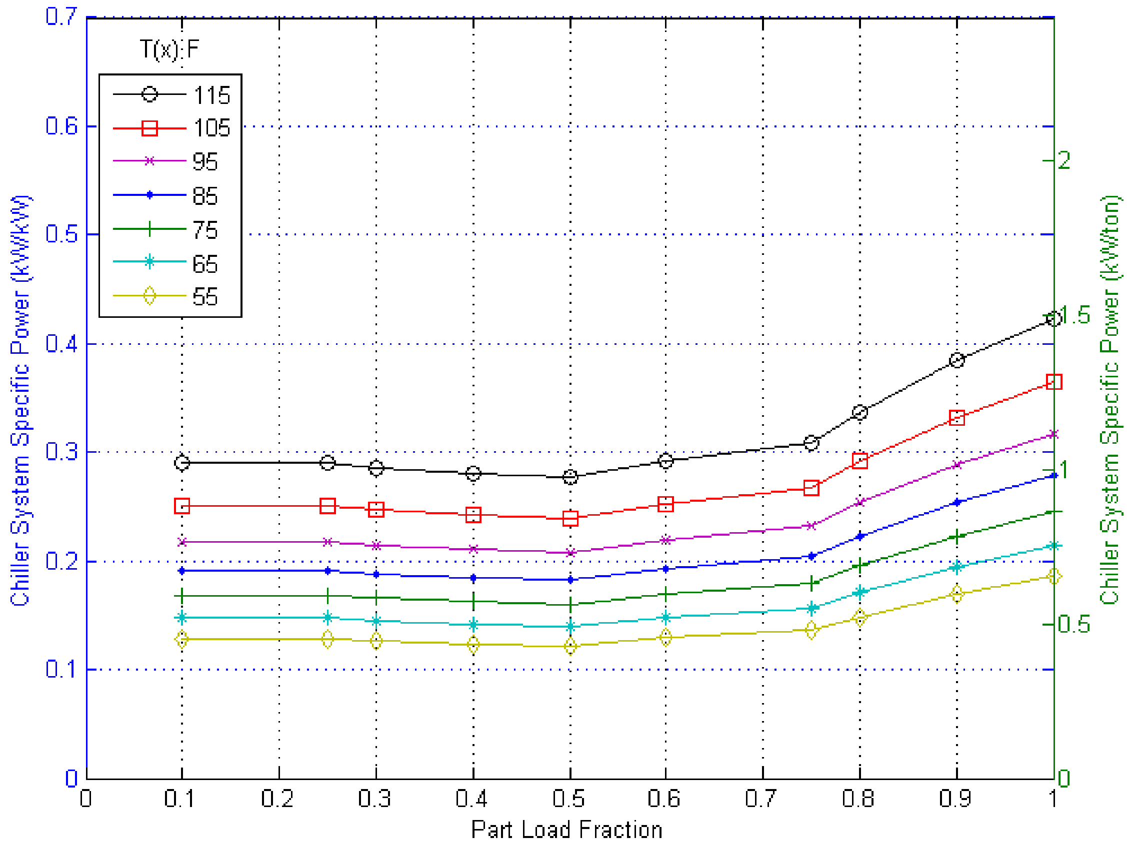

Figure 6 Performance Map of a Typical Conventional Air-Cooled Chiller

Comparison of Prototype Chiller Performance to Ideal Low-Lift Chiller

The RCP-Chiller performance map for the prototype chiller is compared to the ideal low-lift RCP-chiller performance in Figure 7.

Comparison of Prototype Chiller Performance to Conventional Chiller

The RCP-Chiller performance map for the prototype chiller is compared to the ideal low-lift RCP-chiller performance in Figure 8.

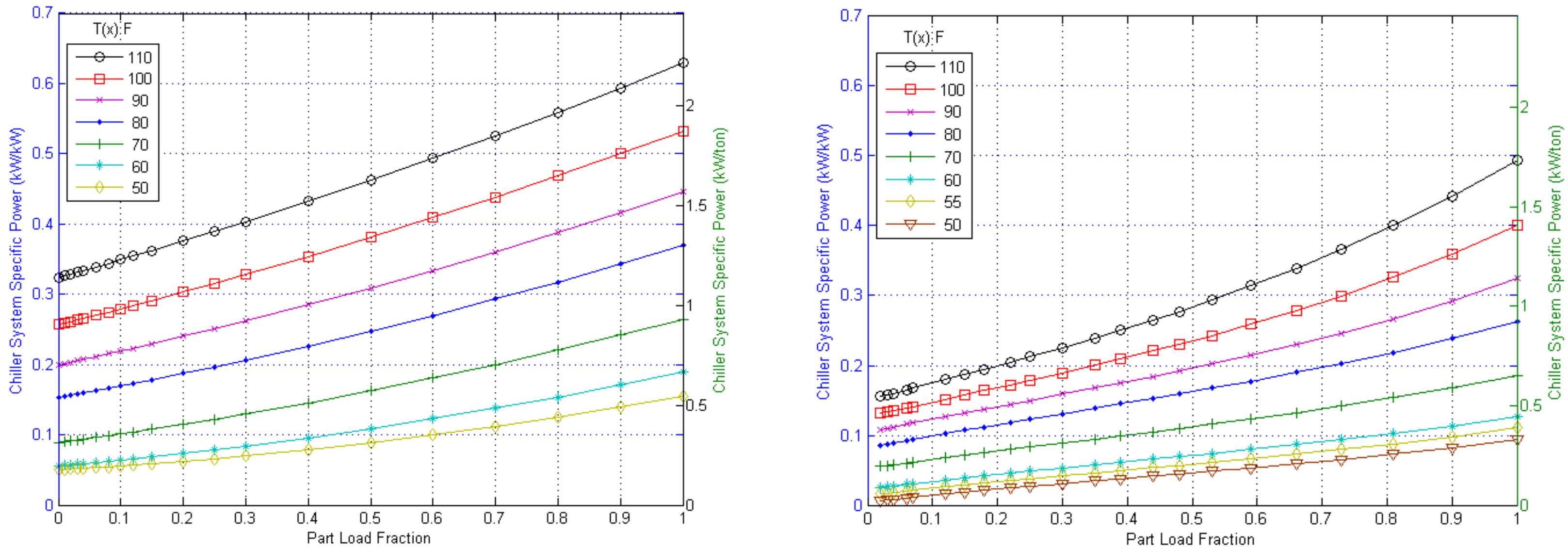

Figure 7 Comparison of Prototype Low-Lift VAV-Chiller System Performance Map (left) at Tz = 72°F with Tx ranging from 110°F (topmost curve) to 50°F in 10 R increments with Ideal Low-Lift VAV-Chiller Performance (right)

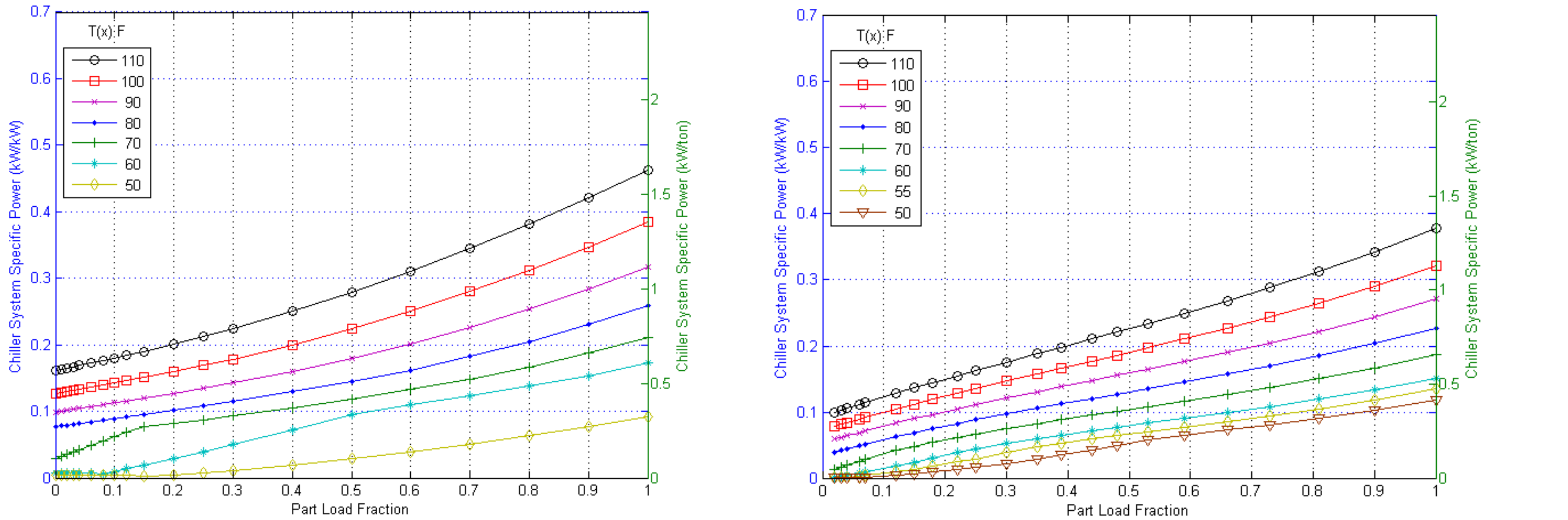

Figure 8 Comparison of Prototype Low-Lift RCP-Chiller System Performance Map (left) at Tz = 72°F with Tx ranging from 110°F (topmost curve) to 50°F in 10 R increments with Ideal Low-Lift RCP-Chiller Performance (right)

Commercial Building Benchmarks

To estimate the Pacific Northwest Regional energy savings potential, energy use for a number of prototypical buildings for which this LLCS applies has to be simulated and scaled to a regional level. The U.S. Department of Energy (DOE) and the American Society of Heating, Refrigeration and Air Condition (ASHRAE) have defined prototypical buildings, also referred to as Commercial Building Benchmarks[11] (Torcellini et al. 2008). The ASHRAE prototypes are derived from the DOE prototypes and reflect minor changes made by the ASHRAE 90.1 committee. In this report, we will refer to these as ASHRAE-Reviewed Benchmarks.

A combination of benchmarks (EnergyPlus input files) from DOE and ASHRAE was used for this work. In this section, the two sets of templates are first introduced and then the sources of the templates used in this study are identified. Although some minor changes were made to EnergyPlus input files, the focus of this study was not to develop the EnergyPlus inputs or to validate the EnergyPlus models. Validation of these models was done as part of other DOE and ASHRAE work.

Commercial Building Benchmarks

The DOE Benchmark building models are comprised of two parts—the building models consisting of the energy modeling descriptions and the regional sector model consisting of the sets of building types and locations, and weighting factors. Because these models are regularly updated, in this report the discussion pertains to version 2.2 of the benchmarks. These cover 15 building types and 21 U.S. locations. Although as part of the DOE benchmark development effort, building weights for each building type were developed, for this study, PNNL developed its own weights from the McGraw-Hill Construction Projects Starts Database because the weights developed for benchmark were for the nation and not for the Pacific Northwest.

Table 5 lists the 15 benchmark building prototypes along with the CBECS (Commercial Buildings End Use Consumption Survey) Principal Building Activity (PBA) and CBECS Specific Building Activity categories represented and used in the development of each benchmark building type. The CBECS Specific Building Activities used in the development of and represented by these 15 benchmark building types represent 3,279 buildings (out of a total of 5,215 CBECS buildings) from the full CBECS data set. The selected set of building types represents 44 billion ft^2 or 62% of the total weighted floor area in the survey. They also represent 65% of the total energy consumption for commercial buildings in the survey.

[11] http://www1.eere.energy.gov/buildings/commercial_initiative/benchmark_models.html

Table 5 Categorization of 2003 CBECS Data for Benchmark Buildings

Number	Name	Floor Area (ft^2)	2003 CBECS Principal Building Activity	2003 CBECS More Specific Building Activity
1	Large Office	460,240	Office	Administrative/professional office; bank/other financial; government office; medical office (non-diagnostic); mixed-use office; other office;
2	Medium Office	53,630	Office	Administrative/professional office; bank/other financial; government office; medical office (non-diagnostic); mixed-use office; other office;
3	Small Office	5,500	Office	Administrative/professional office; bank/other financial; government office; medical office (non-diagnostic); mixed-use office; other office;
4	Warehouse	52,050	Non-refrigerated warehouse	Distribution/shipping center; non-refrigerated; warehouse
5	Stand-alone Retail	41,790	Retail other than mall	Retail store
6	Strip Mall	24,010	Strip shopping mall'	Strip shopping mall
7	Primary School	73,960	Education	Elementary/middle school
8	Secondary School	210,890	Education	High school
9	Supermarket	45,000	Food sales	Grocery store/food market
10	Fast Food	2,500	Food service	Fast food
11	Restaurant	5,500	Food service	Restaurant/cafeteria
12	Hospital	201,250	Public assembly	Hospital/inpatient health
13	Outpatient Healthcare	10,000	Outpatient health care	Medical office (diagnostic); clinic/other outpatient health
14	Small Hotel	21,080	Lodging	Motel or inn
15	Large Hotel	100,820	Lodging	Hotel

Building Prototypes and Climate Locations Used for Low-Lift Energy Savings Analysis

Motel, fast food, and restaurant buildings are not included in this analysis because they are generally not suitable for TES applications, which is one of the components in the LLCS. For motels, this is largely the result of the combination of 24-hour occupancy, which prohibits use of intrinsic building mass in combination with the use of HVAC equipment that is generally not suitable for use in conjunction with discrete TES.

Fast food and restaurants are not suitable for three reasons: high ventilation rates and internal gains relative to building size both of which limit the value of intrinsic building mass; and finally, because the ability to use DOAS equipment with energy recovery is complicated by the high ventilation requirements for kitchen hoods. The public assembly (movie theater/cinema) building type is also not used, primarily because of its variability in occupant and ventilation loads.[12] The remainder of the non-residential building types will be included in the energy savings analysis.

PNNL is developing a set of prototypes in EnergyPlus by modifying the DOE Benchmark, developing additional prototypes and incorporating information from Advanced Energy Design Guide Prototypes[13] to be used for ASHRAE 90.1 work. These prototypes (referred to as ASHRAE-modified prototypes) incorporate the review comments from both PNNL and the ASHRAE 90.1 simulation working group.

For all but three building types, PNNL chose to use the ASHRAE-modified benchmarks for this analysis, in large measure because of the greater review provided by industry members and because these modifications will eventually be incorporated into the next iteration of the DOE benchmarks. For three building types, standalone retail, supermarket and outpatient buildings, PNNL used the original DOE benchmarks because no ASHRAE benchmarks exist at this time. Table 6 highlights additional changes made to the benchmarks by PNNL for this analysis.

Table 7 summarizes the city locations selected for this analysis. The 21 climate locations were selected by mapping each county in the Pacific Northwest to the TMY2 (typical meteorological year version 2) weather location that best approximated the climate in that county.

Table 8 lists the major features of the commercial building benchmark used in the study to estimate the energy savings for the various combinations of the LLCS (referred to as "low-lift" prototypes.)

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[12] We do not rule out that future developments in occupancy forecasting may make some theater applications of LLCS attractive and feasible.

[13] http://www.ashrae.org/technology/page/938

Table 6 Modifications to the DOE and ASHRAE-Modified Benchmarks Made by PNNL for Analysis of Low-Lift Cooling

Building Prototype	Benchmark Model	Changes for Low Lift
Large Office	ASHRAE 30% June 2008 model	Removed latent heat to the occupied space as a result of service hot water consumption.
Medium Office	ASHRAE 30% June 2008 model	Removed latent heat to the occupied space as a result of service hot water consumption.
Small Office	ASHRAE 30% June 2008 model	Removed latent heat to the occupied space as a result of service hot water consumption.
Hospital	ASHRAE 30% June 2008 model	Removed latent heat to the occupied space as a result of service hot water consumption. Removed exhaust fan when ERV[14] is used.
Outpatient Healthcare	DOE benchmark model 3.0	Removed latent heat to the occupied space as a result of service hot water consumption.
Standalone Retail	ASHRAE 30% June 2008 model	No changes made.
Strip Mall	ASHRAE 30% June 2008 model	NA
Primary School	ASHRAE 30% June 2008 model	Removed exhaust fan when ERV[14] is used.
Secondary School	ASHRAE 30% June 2008 model	Removed exhaust fan when ERV[14] is used.
Large Hotel	ASHRAE 30% June 2008 model	Removed latent heat to the occupied space as a result of service hot water consumption. Removed exhaust fan when ERV[14] is used.
Warehouse	ASHRAE 30% June 2008 model	NA
Supermarket	DOE benchmark model 3.0	Removed latent heat to the occupied space as a result of service hot water consumption. Removed exhaust fan when ERV[14] is used.

[14] This is a limitation of EnergyPlus.

Table 7 Selected Commercial Building Benchmark Locations for the Pacific Northwest

Number	Representative City
1	Pendleton, OR
2	Spokane, WA
3	Missoula, MT
4	Boise, ID
5	Pocatello, ID
6	Helena, MT
7	Astoria, OR
8	Salem, OR
9	Eugene, OR
10	North Bend, OR
11	Arcata, CA
12	Medford, OR
13	Redmond, OR
14	Portland, OR
15	Yakima, WA
16	Burns, OR
17	Olympia, WA
18	Quillayuta, WA
19	Seattle, WA
20	Kalispell, MT
21	Cut Bank, MT

Table 8 Low-Lift Building Prototypes

Building Type	Building Prototype	Floor Area (ft^2)	Envelope			HVAC			Model Source
			Roof	Wall	WWR[a]	Heating	Cooling	System	
Office	Small Office	5,500	Attic	Wood Frame	20%	Gas Furnace	Unitary DX[b]	PSZ[c]	ASHRAE-modified benchmark
	Medium Office	53,627	Insulation entirely above deck	Steel Frame	33%	Gas Furnace	Unitary DX	VAV[d] + electric reheat	ASHRAE-modified benchmark
	Large Office	498,588	Insulation entirely above deck	Mass	40%	Gas Boiler	Water Cooled Chiller	VAV + hot water reheat	modified DOE benchmark
Mercantile	Stand-alone Retail	24,692	Insulation entirely above deck	Mass	40%[e]	Gas Furnace	Unitary DX	PSZ[d]	DOE benchmark
	Strip Mall	22,500	Insulation entirely above deck	Steel Frame	45%[f]	Gas Furnace	Unitary DX	PSZ	Modified DOE benchmark
School	Primary school	73,960	Insulation entirely above deck	Steel Frame	35%	Gas Boiler	Unitary DX	VAV + hot water reheat; PSZ (kitchen and gym)	Modified DOE benchmark
	Secondary school	210,886	Insulation entirely above deck	Steel Frame	35%	Gas Boiler	Water Cooled Chiller	VAV + hot water reheat; PSZ (kitchen and gym)	Modified DOE benchmark
Food Sales	Supermarket	45,000	Insulation entirely above deck	Mass	14%	Gas Furnace	Unitary DX	PSZ	DOE benchmark
Health Care	Outpatient health care	10,005	Attic	Steel Frame	15%	Gas Furnace	Unitary DX	PSZ	DOE benchmark
	Hospital	241,501	Insulation entirely above deck	Mass	14%	Gas Boiler	Water Cooled Chiller	VAV + hot water reheat	Modified DOE benchmark
Lodging	Large hotel	100,816	Insulation entirely above deck	Mass	22%	Gas Boiler	Water Cooled Chiller	VAV + hot water reheat	Modified DOE benchmark
Warehouse	Non-refrigerated warehouse	52,045	Insulation entirely above deck	Mass	<10%	Gas Furnace	Unitary DX	PSZ and unit heater	Modified DOE benchmark

a: WWR – window wall ratio; b: DX – direct expansion; c: PSZ – packaged single zone; d: VAV – variable air volume;
e: 40% on primary front wall surface, no fenestration on other walls; f: 45% on primary front wall surface, no fenestration on other walls;

Market Assessment of Low-Lift Cooling System

An assessment of the potential market for LLCS was performed by Navigant Consulting Inc. (NCI) under a subcontract to PNNL. The market assessment, primarily focused to the Pacific Northwest region, consisted of four steps: A review of the proposed technology and models, identification of potential benefits and barriers to market penetration, validation of those benefits and barriers through surveys and discussions with stakeholders, and recommendation of initiatives that BPA/DOE can take to accelerate market adoption of the proposed low-lift solutions.

The following subsection was drafted by NCI and it summarizes the findings from the market assessment.

NCI Summary of Market Assessment

An earlier study was conducted on LLCS that focused on identifying technical and market barriers for the overall new construction market in the U.S. (Katipamula et al. 2010). This study focuses on states in the Pacific Northwest region that fall within BPA's territory, such as Washington, Oregon, Idaho, and Montana. Table 9 compares these Pacific Northwest states to other U.S. states based on relevant LLCS market characteristics. This comparison highlights the low cost of energy, low cooling demand, and low emissions of the Pacific Northwest region relative to other U.S. states and suggests that other U.S. regions may be better suited for LLCS technologies.

Approach

This study assessed the market potential for low-lift base-load cooling technology in the Pacific Northwest new construction market over the next 20 years. As part of this assessment, NCI identified barriers preventing adoption and recommended strategies for overcoming these barriers. After conducting background research to better understand regional characteristics, NCI interviewed 11 stakeholders with a variety of backgrounds and experience working across the Pacific Northwest. Table 10 lists these stakeholders by category and major office location. While most of the office locations only list one state, many of the stakeholders also had extensive experience working on projects in other parts of the Pacific Northwest.

The stakeholders listed in Table 10 were asked a number of questions regarding regional barriers, customer acceptance levels of technology, customer demographic, acceptable paybacks, and technology purchase decisions. A copy of the survey can be found in Appendix A (Appendix: Market Assessment Supporting Material). NCI then synthesized results from these interviews and other research in addition to developing recommendations on how to best increase market adoption in the Pacific Northwest.

Table 9 State Rankings for Key Market Attributes Associated with Low Lift Cooling Applications

State Rankings for Key Market Attributes Associated with Low Lift Cooling Applications				
State	Energy Costs	Energy Efficiency Program Support	Cooling Demand	CO_2 Emissions from Electricity
California	High	High	Medium	Medium
New York	High	High	Medium	Medium
Texas	Medium	Medium	High	High
Oregon	Low	High	Low	Low
Washington	Low	High	Low	Low
Idaho	Low	Medium	Low	Low
Montana	Low	Low	Low	Low
Sources	EIA Retail Price of Electricity	ACEEE 2008 State Energy Efficiency Scorecard	Weather Map	EIA State Energy Profiles

Low ○ Medium ⊙ High ●

Table 10 Stakeholder Interview List

Interviewee List		
Stakeholder	Office Location(s)	Organization, Position
Architect	Montana	CTA Architect, Architect
	Washington	CTA Architect, Architect
Building Owner	Oregon	State of Oregon, DAS Sustainability Coordinator
	Washington (experience in Idaho)	General Services Administration, Regional Energy Manager
Energy Service Provider	Washington	JCI, Service Branch Manager
LEED and HVAC Engineers/Consultants	Oregon	Glumac, Principal Engineer
	Oregon	PAE Consulting, Consultant
	Washington (experience in Idaho)	Coffman Engineers, Mechanical Engineer
	Washington and Oregon	Interface Engineering, Principal Engineer
Utility Representative	Oregon	BPA, Mechanical Engineer
	Oregon	Eugene Water & Electric Board, Staff Engineer

Results and Conclusions

Table 11 summarizes the current customer acceptance level of each technology in the Pacific Northwest region based on feedback obtained during the interviews. Regional climate characteristics explained the low acceptance of enthalpy wheel and radiant cooling technology as the moderate humidity and low cooling demand relative to other regions of the U.S. were not favorable in the Pacific Northwest.

Table 11 Regional Customer Acceptance Level of Each Technology

Low Lift Technology Options – Customer Acceptance Level in the Pacific Northwest Region	
Technology	**Customer Acceptance Level**
Variable Capacity Chillers	High – Industry is moving in this direction and there is a need to migrate designs into large size chillers.
Advanced Controls	Medium/High – Significant opportunity exists in coupling systems to achieve higher efficiencies. Requires better user interfaces and must focus on enabling diagnostics and prognostics of the full HVAC system (supervisory level). Requires better training for operators and other users.
Dedicated Outdoor Air System (DOAS) + Enthalpy Wheel	Medium– Humidity is not a major concern in many parts of the Pacific Northwest, and temperate climate in both winter and summer reduces ERV benefit. More product offerings of this type entering the marketplace but there is limited awareness and regional specific field data on the units.
Thermal energy storage (TES)	Medium – Limited time-of-use rates offered by utilities in the BPA region lengthen paybacks for this technology, but that could change if TOU pricing becomes more widespread. However, with nuclear and hydro resources, TOU pricing may be less critical Also, requires significant technology improvements and implementing this as an integrated solution with radiant cooling and low lift cooling options to further demonstrate benefits is required.
Radiant cooling/heating	Low/Medium – Low cooling demand limits cooling applications. Requires significant improvement in implementer and consumer awareness. Also, initial failures with technology have discouraged adoption.

Low ■ Medium ■ High ■

TOU = Time of Use

Figure 9 summarizes the major regional barriers NCI identified through primary and secondary research and lists corresponding strategies to overcome each barrier. These potential strategies were developed based on both NCI's experience and stakeholder feedback.

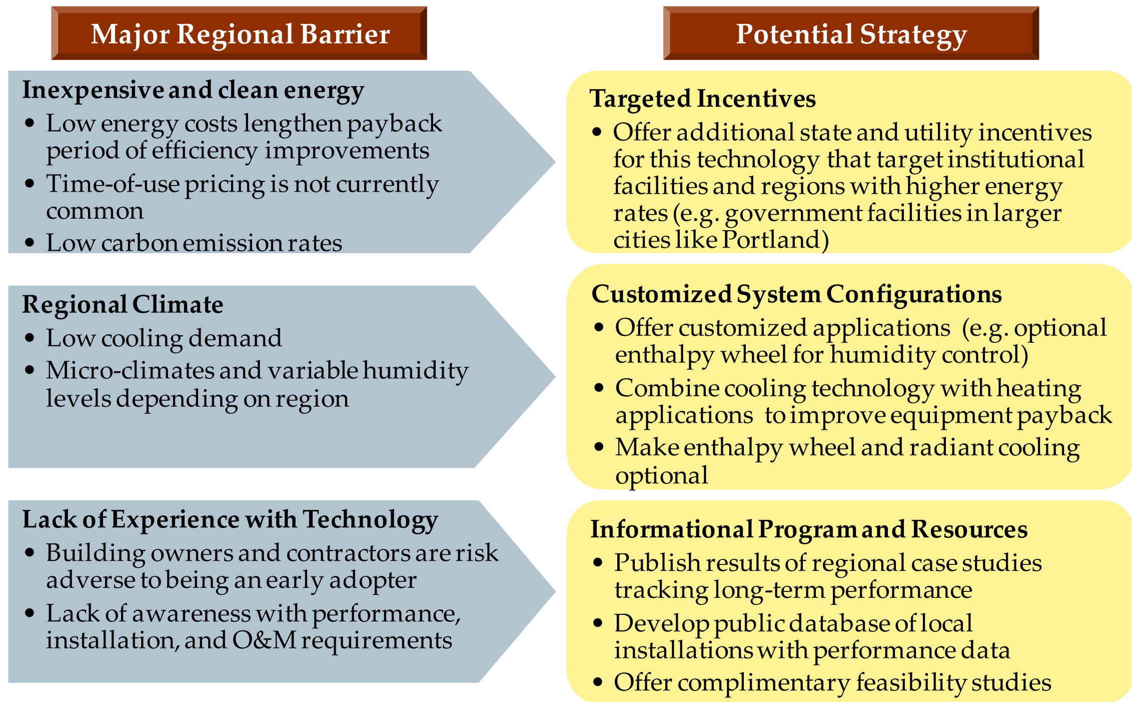

Figure 9 Major Regional Barriers Identified and Potential Strategy to Overcome Barrier

While the acceptance of low-lift cooling technology in the Pacific Northwest could be impeded by low electricity costs and low levels of CO_2 emissions from power generation, the market still has some early adopters and strong support for LEED (Leadership in Energy and Environmental Design) and other green buildings, which increases adoption potential. Furthermore, the increasing electricity demands in the region are likely to be met with additional fossil-fuel-powered plants and if these enter the generation mix, the appeal and case for energy efficiency and LLCS would likely improve. Other key findings from this study include:

- Low energy costs and the low cooling demand in the Pacific Northwest lengthen payback of low-lift cooling technology.
- Institutional customers (e.g., government buildings) are more accepting of longer energy efficiency paybacks (≤ 10 yrs) than private sector facilities (≤ 3 yrs) and therefore are better potential targets for LLCS technology.
- Site constraints and regional climates limit the potential for thermal energy storage and radiant cooling technologies.
- In areas with high acceptance of LEED standards, there is sufficient communication between architects and engineers in the early planning stages of building energy systems.
- There is a general lack of understanding and local experience with the technology.

Recommendations

While other regions of the U.S. are better suited for LLCS technology, the Pacific Northwest market still has some potential for adoption. Additionally, an effective program to promote these technologies would provide educational information on the technology and target customers with the highest value proposition. NCI makes the following recommendations to expedite market adoption in the Pacific Northwest:

- Evaluate and focus on market segments where technology has the highest value proposition such as government and other institutional facilities that are more accepting of technologies with longer paybacks.

- Target regions with higher electricity rates, high cooling demand, and a track-record for support of energy efficiency and green buildings.

- Offer some customization of systems to accommodate micro-climates (e.g., exclude radiant cooling system or provide optional enthalpy wheel to control humidity).

- Develop and publish informational resources with lessons learned from local case-studies to increase understanding of the technology.

- Implement effective training practices and resources for engineers and contractors in target regions and markets.

PNNL Conclusion of Market Assessment

In general PNNL agrees with the findings presented by NCI in this section. Many of the findings are consistent with PNNL's own experience. The recommendation made by NCI should be valuable for BPA, because these recommendations apply to most integrated technology options that are going to be used in high performance and net-zero energy buildings.

PNNL agrees the limitation and barriers noted by NCI for the use of active TES. Although PNNL has investigated the active TES option, PNNL does not think that active TES is essential to realize the savings. A significant fraction of the savings that can be attributed to TES can be achieved by passive TES (using thermal mass). PNNL has not evaluated passive TES as an option because of simulation limitations.

Incremental Cost Estimates for the Low-Lift Cooling System

One of the objectives of this study was to conduct a simple economic analysis of the LLCS. Because of limited resources, PNNL decided to estimate simple payback, rather than conducting a detailed life-cycle cost analysis. To estimate the simple payback, the incremental cost and energy savings estimates are need. The energy savings estimates were estimated through simulations (see next section). Again because of limited resources, the incremental cost was estimated for four buildings types.

Estimating incremental cost of emerging technology is difficult because of limited availability of information that is available in the open literature. To estimate the incremental cost for the components that make up the LLCS, PNNL hired NCI. The following subsection was drafted by NCI and it summarizes the incremental cost estimates.

NCI Summary of Incremental Cost Estimates

As part of this assessment, NCI analyzed the HVAC systems at the component level. After identifying and sizing the essential HVAC components within each building type, NCI developed a spreadsheet to calculate the baseline and low-lift component costs using *RS Means – Mechanical Cost Data 2007* and inputs from various component suppliers. Table 12 lists these components and the inputs used to derive the costs of each component. PNNL provided EnergyPlus building sizing files to list and size the baseline HVAC systems, and also provided parameters for sizing and pricing the low-lift system. For details of the incremental cost estimation process refer to the Appendix B (Appendix: Incremental Cost Supporting Material).

Table 12 HVAC System Components and Cost Sources

Component Cost Sources		
Component	Baseline Costs	Low-Lift Costs
Chiller, Rooftop Units	RS Means 2007	Suppliers, RS Means 2007
Boiler	RS Means 2007	RS Means 2007
Furnaces	RS Means 2007	RS Means 2007
Control System	Assumed no incremental	
Ductwork	Suppliers, RS Means 2007	Suppliers, RS Means 2007
Air-Handlers	RS Means 2007	RS Means 2007
DX HP Coils	-	RS Means 2007
Enthalpy Wheel	-	RS Means 2007
Radiant Cooling	-	Suppliers

HP: Heat Pump

Each system was sized and priced according to the specific system requirements provided by PNNL. NCI calculated the costs based on the national average provided in RS Means, and then applied a cost index for material and labor to calculate each component cost for the other cities in the Pacific Northwest region.

Incremental costs were calculated for each HVAC sub-system, by subtracting the cost of the baseline components to the equivalent low-lift components. Incremental costs were derived for both the national average and 21 cities in the Pacific Northwest.

Incremental costs were divided by sub-system as follows:

1. Low-lift chiller incremental cost

2. Radiant cooling system incremental cost

3. DOAS with DX HP and energy recovery ventilator (ERV) incremental cost

4. Heating system.

Results

The charts in Figure 10 through Figure 13 show the results of the incremental cost study, for each of the four building type: medium office, large office, supermarket and secondary schools. These costs reflect the national average cost. Using the city cost index from RS Means, the national cost can be translated to each of the 21 cities in the Pacific Northwest, as described in the Economic Analysis Section.

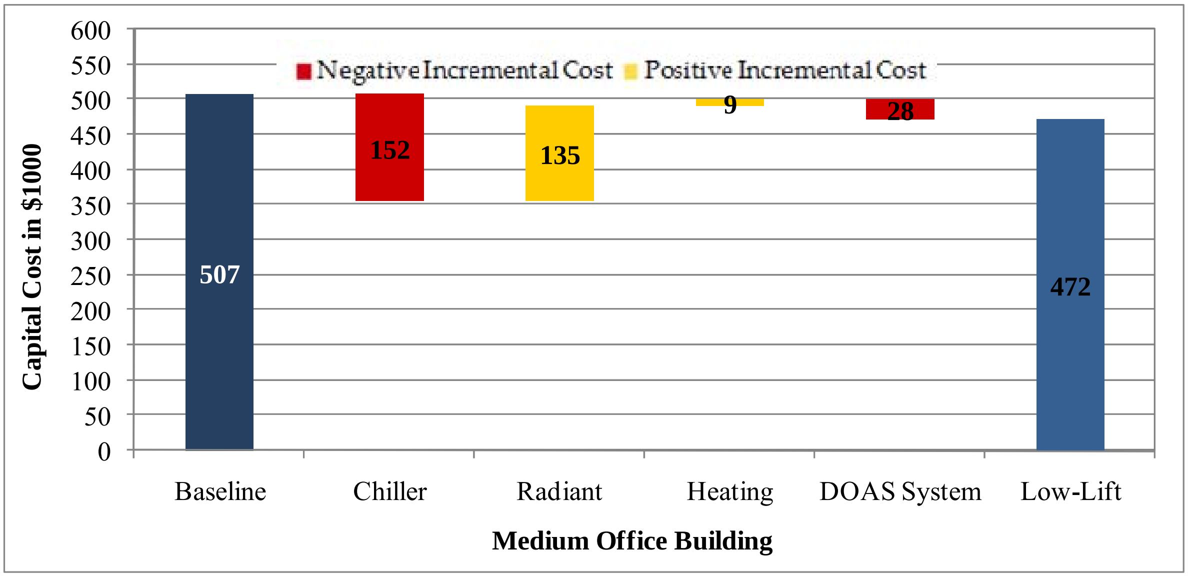

Figure 10 Incremental Cost (National Average) for Medium Office Building Using Low-Lift Cooling

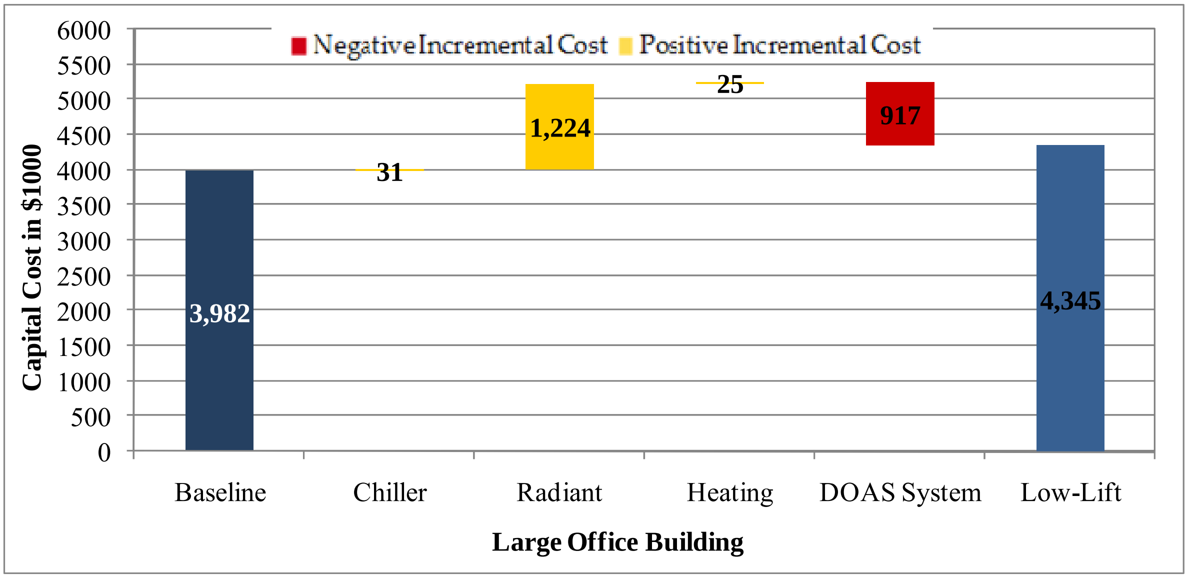

Figure 11 Incremental Cost (National Average) for Large Office Building Using Low-Lift Cooling

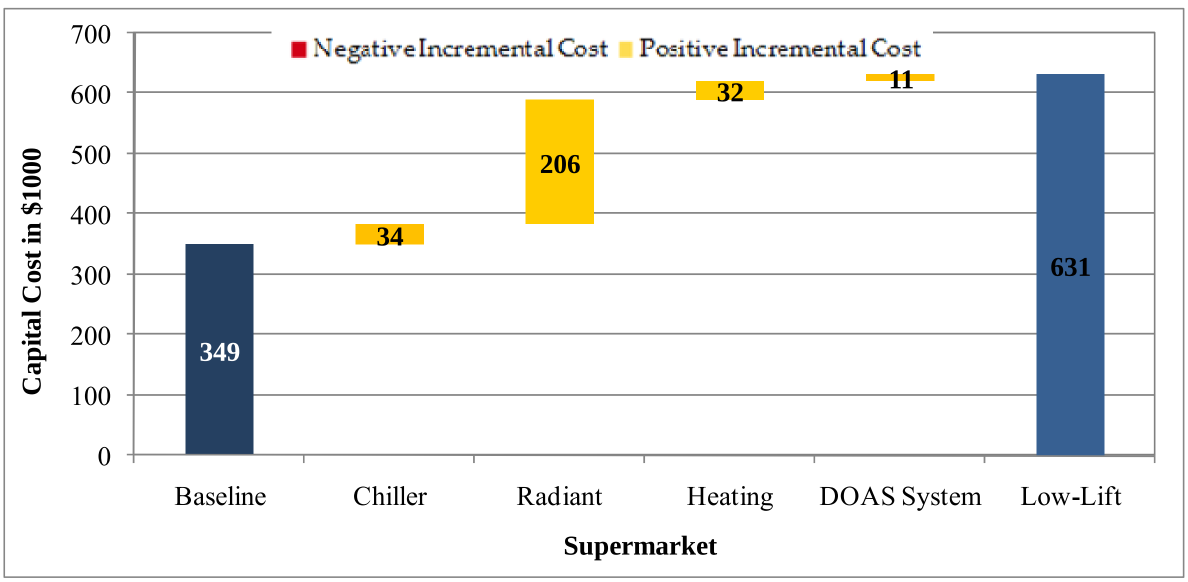

Figure 12 Incremental Cost (National Average) for Supermarket Building Using Low-Lift Cooling

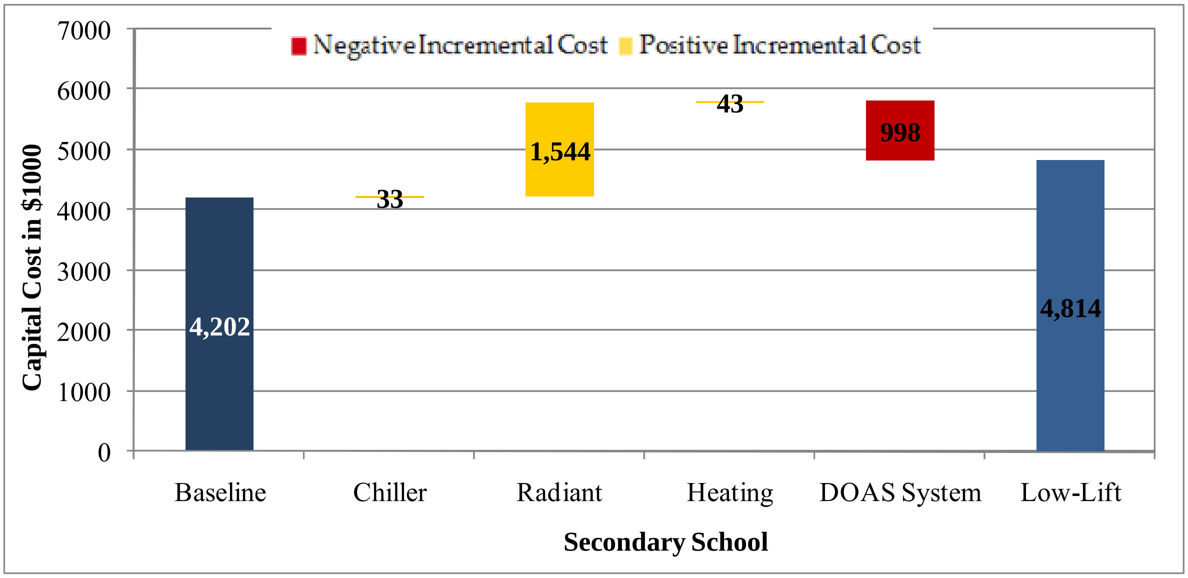

Figure 13 Incremental Cost (National Average) for Secondary School Building Using Low-Lift Cooling

The charts show that the cost of a radiant cooling system drives most of the overall cost incremental. In medium office buildings, the high cost of multi-zone rooftop air-conditioning units compared to a similar-sized chiller results in virtually no incremental cost for the low-lift cooling system. For the large office building and secondary school building, large reductions in the sizing of the ductwork drove negative incremental costs for the ducting systems. The supermarket buildings typically use inexpensive single-zone packaged units; therefore, these building will have difficulty competing with variable speed chillers.

Findings

The key conclusions in the overall analysis of the incremental costs for the low-lift systems are:

- Office buildings may be the most ideal first application for low-lift cooling technologies/systems, particularly those using multi-zone rooftop systems.

- The large cost of the multi-zone rooftop systems (with respect to a similar-sized chiller) allows for a favorable cost comparison for low-lift chiller systems in medium office buildings.

- While inexpensive single-zone packaged units make supermarkets unfavorable cost comparison for low-lift chiller system, large office buildings show a low incremental cost per square foot, because of small increases in chiller costs, and large savings from the smaller ductwork as a result of the DOAS system.

- Radiant cooling drives the cost increment for all of the building types. A large portion of these costs is associated with the labor required for installation.

- The cost advantage resulting from reduction of the ductwork for large buildings is a large factor and needs to be validated further.

In addition, there are additional items to consider:

- Some components of the low-lift system, particularly the radiant cooling system, can be considered emerging technologies. There is often a 10 to 20% premium associated with emerging technologies that may gradually decline as the technology is commoditized.

- Potential additional benefits of the low-lift system include reducing the amount of materials used in construction, particularly the ductwork material.

Recommendations

The component-based cost approach for estimating baseline and advanced system costs is limited in scope, and only covers a portion of the total costs required for incorporation of HVAC systems into buildings. Some of the key recommendations that need to be addressed include:

- The common practice of equipment sizing by cooling load and cubic feet per minute (cfm), and not by square footage. This however can be addressed through the use of a detailed design process to understand costs on a square foot basis (possibly by picking a candidate building that can serve as a future test bed).

- Sizing by cooling load is very effective for calculating the cost of the main components, but not as effective for finding the cost of the distribution systems.

- The design process will also help in assuring that material costs are better estimated (ducts, piping, valves, etc.) that also require further exploration.

As a next step, NCI recommends proceeding through this detailed costing exercise for a candidate building (large office) along with an associated payback/economic analysis for various parts of the country. An economic analysis will help identify whether the cost premium for low-lift systems is justified and help identify candidate regions for pilot projects.

PNNL Conclusions on Incremental Cost Estimates

In general PNNL agrees with NCI findings. As noted by NCI, these are the best estimates given the limited time, resources and the approach that was taken to estimate the costs. PNNL believes that these cost estimates are conservative for a number of reasons:

1. Limited availability of cost information for the emerging technologies.

2. Emerging technologies generally have a premium when introduced but generally the cost go down significantly as the market is transformed (e.g., compact fluorescent lamps).

3. Low-lift chiller size has not been optimized to reflect the lower size needed when used with passive thermal storage option.

4. Redundant heating systems have been added for the building with low-lift system, which may not be needed.

Widespread use of these technologies, and building design and optimization for inclusion of LLCS could potentially lower the cost by between 20 and 30% from the current estimates.

Energy Use Estimation Methodology

To estimate the energy consumption of a prototype building with baseline equipment, a modified prototype with LLCS equipment or some subset of the LLCS, a detailed simulation model is needed. The existing mainstream detailed simulation models (DOE-2[15] and EnergyPlus[16]) currently lack the capability to simulate the full LLCS. Although EnergyPlus can model many the elements of the LLCS, it still lacks a low-lift chiller, thermal storage and advanced controls needed to optimize the operation. Because some of the proposed technologies, such as ERV and economizers directly influence the required heating and cooling loads, the benchmark templates had to first be modified to include these components. In addition, several other minor changes were made. Table 6 lists the changes made to the benchmark templates.

The energy consumption estimates and the savings were computed in two steps: 1) building thermal loads were estimated for 12 different building types (two performance levels) and 21 climate locations using EnergyPlus simulations and 2) using the thermal loads as a basis, the systems were simulated with a set of component models that were previously developed as part of the DOE effort (Jiang et al. 2008; Armstrong et al. 2009a, b).

Performance map models or mathematical models of the key components—chiller, DOAS, and radiant panels—were developed for use with loads simulated by Energy Plus. The modeling and simulation activities (application of the component models) are described below. Details of the component models are presented and reported in Jiang et al. (2008). A semi-empirical compressor performance model was developed based on published performance data for an existing reciprocating compressor designed for operation over a 4:1 speed range. Compressors in the model line have similar performance for machines rated from 10 to 30 hp (7 to 20 ton). Chiller component models were developed to be assembled into a higher level program that models overall chiller performance. The component models include the previously mentioned compressor, an air-cooled condenser and condenser fan, a water-cooled evaporator and chilled water pump, and two types of distribution heat transfer equipment (a radiant cooling panel system and a CAV- or VAV-fan-coil system). The condenser fan and chilled water pump were modeled with variable-speed controls.

A performance-optimized chiller model that includes load-side transport power, as well as compressor and condenser fan power, was developed based on the above component models. The chiller model solves for the saturated condenser and evaporator refrigerant temperatures that minimize input power given cooling load and the external load-side and outdoor thermal conditions. The primary mechanism for reducing chiller input power is the adjustment of fan, pump and compressor speeds to match saturated condenser and evaporator refrigerant temperatures with chiller load and external conditions.

Three versions of the chiller model were developed to produce two chiller performance maps. The first performance map is for the ideal low-lift chiller RCP system (Figure 1), which includes

[15] http://www.doe2.com/
[16] http://apps1.eere.energy.gov/buildings/energyplus/

both compressor and refrigerant-side economizer operation. The chiller model for economizer operation uses the same components as the chiller for compressor operation except that the compressor is replaced by a flow-pressure characteristic of the compressor bypass branch used during economizer operation. At each performance evaluation, the two maps are evaluated and the mode of operation (compressor or economizer) is determined by which map evaluation returns the lower kW/ton number.

The VAV system uses an air-side economizer so only one chiller model is needed to produce a ideal chiller performance map (Figure 3). However, the map has three regions corresponding to a chilled water supply temperature reset schedule, which is a function of outdoor temperature. Two-speed operation of the compressor, condenser fan and chilled water pump is simulated by performance curves derived from the variable-speed performance map. The low- and high-speed specific power curves—functions of outdoor temperature only—are obtained by evaluating the variable-speed performance map at part-load fractions of 0.5 and 1.0.

In addition, to the ideal chiller performance maps, chiller performance maps were also developed using the test data from the prototype low-lift chiller. Like the ideal chiller, two maps where used: 1) prototype RCP-chiller map (Figure 4) and 2) prototype VAV-chiller map (Figure 5) The prototype RCP-chiller map is used with the radiant cooling option and prototype VAV-chiller map is used with the conventional HVAC configuration.

Energy recovery ventilation is modeled in EnergyPlus. The remaining latent load is satisfied by a DX dehumidifier modeled as two subsystems: the wetted evaporator coil and a scaled-down version of the variable-speed chiller with heat rejection to the ventilation supply air. The resulting sensible load is added to the building sensible load and can therefore be treated as peak-"shiftable" load. Air flow and fan power are determined by ventilation demand, while compressor power is determined by the latent load remaining after enthalpy recovery and the evaporator inlet conditions.

The annual energy simulations use EnergyPlus-generated load sequences to which DOAS reheat has been added for the cases that use DOAS. For systems without TES, the appropriate chiller map is applied directly to the baseline load sequence of interest.

For systems with TES, annual energy is evaluated in 365 daily sub-simulations and the 24-hour peak-shifting algorithm applies the appropriate chiller performance map to each 24-hour load sequence plugged into its objective function. The solution to this sub-problem is the 24-hour load sequence that minimizes chiller input energy for the day in question.

Building Performance Levels

The building prototypes used for the low-lift analysis had two permutations, baseline and high-performance. The baseline buildings complied with Standard 90.1-2004 (ASHRAE 2004) requirements. Where the Standard did not have a specification, typical construction practice was used within the benchmark prototype. This is consistent with the current benchmark development process. The baseline building prototypes were modified to create high-performance prototypes, as shown in Table 13. The goal of specifying the high-performance building is to assess the benefits of low-lift when applied to future near-zero energy buildings (near ZEB).

Table 13 Comparison of Key Parameters for the Baseline and High-Performance Buildings

Component Performance Levels to be Analyzed		
Component	Baseline	High Performance
Wall-Roof U-Factor	90.1-2004[a]	4/9th of 90.1-2004
Window U-Factor and SHGC	90.1-2004[a]	4/9th of 90.1-2004
Window-to-Wall-Ratio	40%	20%+Shading[b]
Lighting and Plug Load[c] Power Density (W/sf)	1.3+0.63	0.58+0.21
Fan Power (W/scfm)[d]	0.8	0.356

(a) Because the values vary by climate locations, the values are not listed in this table
(b) Completely shade the solar direct beam
(c) Load density during hours of the highest loads
(d) Total HVAC fan power divided by total HVAC fan flow rate
(e) SHGC: solar heat gain coefficient.

The building designs address the *non-HVAC* aspects of a building's energy performance, including U-factors for the wall and roof, window-to-wall ratio coefficients, and plug loads. Note, for example, that in the "high-performance" design case, the performance assumptions are *much* more aggressive than 90.1-2004. This wide range of non-HVAC energy performance allows us to investigate the LLCS across two distinctly different cases – "high-performance" buildings being well on the way to net-zero energy performance.

Energy Savings Analysis Grid

As noted earlier, the energy savings analysis for this study is based on a combination of simulation runs: EnergyPlus and Matlab component models. The analysis grid is based on the following combination of runs:

1. 12 building types
2. 21 climate locations
3. 2 building performance levels (standard and high performance)
4. 3 base systems combinations (with economizer, without economizer and with energy recovery ventilation)
5. 2 chiller performance curves, and
6. 8 different low-loft combinations.

These combination of simulations resulted in 1,512 EnergyPlus runs and 24,192 Matlab simulation runs. The energy savings estimates are summarized in the next section.

Energy Savings Estimates for the Various LLCS Combinations

The potential energy savings for the LLCS for each of the building prototypes for which the LLCS is applicable, and in each of the 21 climate locations is summarized in this section. First, the general approach to the estimation of energy savings is described, followed by the savings estimates by building type and climate locations with the LLCS. Second, the energy use estimates for the various combinations of HVAC systems are discussed, followed by the percentage savings potential from use of the LLCS compared to the baseline equipment configuration for each building prototype. The default baseline building is an ASHRAE Standard 90.1-2004 compliant version of the building.

To condition the occupied spaces, first, the buildings are modeled using the base HVAC systems (Table 8) with EnergyPlus. This configuration is referred to "Case 0" or baseline in this report. For Case 0, the thermal loads and the HVAC energy consumption estimates are from EnergyPlus simulations. In addition to the base case, energy consumption for each building type in 21 climate locations is calculated with eight different combinations of the LLCS with two different chiller performance curves.

Because the prototype buildings use different HVAC systems, the energy consumption for each building was also estimated with a standard air distribution system (either constant volume or VAV system depending on the building type) fed by a central chiller. This is referred to as Case 1. For Case 1, the modeling of the chiller and distribution system energy is done through post-processing of the building cooling loads generated from the EnergyPlus simulation. The chiller and a simple fan model described in Appendix B of Jiang et al. (2008) are used. The purpose of using specially developed system performance curves is to provide for a comparable evaluation by using identical chiller components for the low-lift baseline as well as all partial and full LLCS configurations. In addition to the base HVAC system (Case 0 below), eight alternative HVAC systems (low-lift baseline, six partial LLCS configurations and the full LLCS configuration) were analyzed. The fan and DOAS consumption is estimated for the entire year (i.e., both cooling and heating seasons). There are additional reheat savings, for some building types (6 out of 12) that use reheat. These savings are also estimated independently and described and presented later in the section.

The nine different sets of simulations are as follows:

1. Case 0: the base case HVAC configuration case (different of each building, see Table 8).
2. Case 1: two-speed chiller with VAV or CAV AHU, depending on building type – this is referred to as low-lift base case HVAC configuration.
3. Case 2: low-lift variable-speed chiller and VAV AHU – this configuration uses VAV AHU from Case 1 but with variable-speed low-lift chiller, pump and fan equipment.
4. Case 3: two-speed chiller with RCP/DOAS – this configuration replaces AHU from Case 1 with a hydronic distribution system serving radiant cooling/heating panels and a DOAS for ventilation.

5. Case 4: low-lift variable-speed chiller with RCP/DOAS – combines the alternatives provided separately in Case 2 and Case 3.
6. Case 5: two-speed chiller with VAV AHU and TES – this case adds TES to Case 1.
7. Case 6: variable-speed chiller, VAV AHU and TES – this case adds TES to Case 2.
8. Case 7: two-speed chiller with RCP/DOAS and TES - this case adds TES to Case 3.
9. Case 8: low-lift variable-speed chiller with RCP/DOAS and TES – this case adds TES to Case 4.

Case 8 noted above is the full LLCS, consisting of: 1) peak-shifting with active or passive thermal storage (implemented here as idealized discrete TES), 2) radiant cooling/heating (implemented using zone radiant cooling panels) with DOAS (implemented as enthalpy heat recovery from exhaust air and a variable-speed DX dehumidifier), and 3) low-lift variable-speed vapor compression chiller (achieved using high turn-down ratio compressor with a refrigerant-side economizer and assuming condenser and evaporator heat exchangers identical in size with the low-lift base case).

Cases 2, 4, 6 and 8 use advanced variable-speed compressor and transport (fan and pump) controls to optimize the instantaneous hourly operation of the chiller and distribution systems. Cases 5, 6, 7 and 8 implement a 24-hour look-ahead algorithm to optimize charging of the TES.

The energy savings from these technologies (RCP/DOAS, TES and low-lift chiller) are assessed individually and in combination, as described previously. This approach not only provides the energy savings potential associated with the LLCS, but also demonstrates the synergisms of the component technologies and thus illustrates the importance of *systems integration* in achieving truly exemplary levels of energy performance.

In addition to the “baseline” (ASHRAE Standard 90.1-2004 compliant) building design, one other higher performance building design was also simulated as described previously (Table 13).

Energy Use Estimates for the Various LLCS and Building Configurations

The energy use estimates for the base case and eight LLCS configurations for selected building types are presented in this section, while the reminder of the results that are included in Appendix C (Appendix: Energy Use Estimate Tables and Figures). Results of annual energy simulations for the nine equipment cases are summarized, in terms of the *annual energy* to operate the chiller, pumps, fan and ventilation. Although the chiller and pump energy consumption only represents cooling, the ventilation and fan energy consumption used to compute the annual energy is for the entire year.

Table 14 and Table 15 show the annual energy consumption (chiller, fan, and pump) for the standard- and high-performance medium office building designs for various HVAC combinations across 21 climate locations. The second column (following the climate location labels) represents the annual energy consumption for the base case HVAC system (for medium office, which is packaged multi-zone VAV system). The third column represents the low-lift base case (for medium office, it is two-speed chiller with a VAV AHU). The reminder of the columns provides the annual energy consumption for the various low-lift combinations, as described previously. The savings for each building type and climate location are computed as the difference between Case 0 and Case 8. In addition to computing the ultimate savings, savings from individual technologies can also be computed.

For example, the difference between Case 0 and Case 1 results in savings from going from a packaged direct expansion system to a two-speed chiller and the difference between Case 1 and Case 2 results in savings from going from two-speed chiller to a variable-speed chiller. Although savings in fan energy can be computed as a difference of Case 1 and Case 5 or Case 2 and Case 6, it is only an approximation because switching from a conventional VAV system to radiant cooling, increases the chilled water temperature, which will reduce the chiller energy consumption. Therefore, the difference can be viewed as net reduction in fan energy consumption.

Similarly, the savings associated with thermal storage can be computed as a difference between Case 1 and Case 3, Case 2 and Case 4, Case 5 and Case 7, and Case 6 and Case 8. Each of these differences will yield slightly different energy savings for the thermal storage because of the other system interactions. The annual consumption of the two designs (standard- and high-performance) for large office, supermarket and secondary schools is shown in Table 15 through Table 21. The tables for the rest of the building types are included in Appendix C (Appendix: Energy Use Estimate Tables and Figures).

Figure 14 through Figure 21 compare the annual energy consumption for 4 selected standard buildings (medium office, large office, supermarket and secondary school) for 9 different combinations of the systems (Case 0 through Case 8) in 21 climate locations. In all cases, the base case is significantly higher than the full LLCS (Case 8).

For standard medium office (Figure 14), the reduction in energy consumption between Case 0 and Case 8 ranges from 57% to 67%, with an average reduction of 62%. In general, the trend across all climate locations is similar. The difference between low-lift base case (Case 1) and the full LLCS (Case 8) ranges from 38% to 61%, with an average reduction of 51%, significantly lower than the difference between Case 0 and Case 8. The reason for the difference between the two base cases, Case 0 and Case 1, is the use of two-speed chiller with a VAV system for Case 1, which is more efficient than the packaged multi-zone VAV system used for Case 0.

Table 14 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Medium Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh)

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	79,175	70,064	66,179	56,766	49,369	45,168	39,988	38,867	31,355
Spokane, WA	64,622	56,247	53,162	47,242	41,628	36,435	32,673	32,022	26,391
Missoula, MT	62,728	52,971	50,231	42,137	37,981	33,347	29,755	29,925	23,448
Boise, ID	77,956	70,203	66,631	55,259	49,383	43,911	39,327	38,411	30,856
Pocatello, ID	68,392	59,713	56,580	46,482	41,972	37,492	33,688	32,555	25,567
Helena, MT	63,531	53,166	50,327	44,719	39,572	34,231	30,464	30,791	24,804
Astoria, OR	44,450	28,672	26,824	27,781	25,054	21,914	18,142	21,137	16,658
Salem, OR	65,589	49,259	46,003	40,537	35,055	32,800	27,934	29,408	22,301
Eugene, OR	66,006	49,098	45,736	40,765	35,120	32,493	27,657	29,494	22,009
North Bend, OR	42,258	27,691	26,126	27,143	24,762	21,594	17,618	20,768	16,283
Arcata, CA	35,808	24,996	23,846	24,514	22,897	19,765	16,319	18,941	15,492
Medford, OR	82,800	72,786	68,988	53,221	47,427	45,606	40,398	37,431	28,675
Redmond, OR	64,342	55,730	52,576	43,543	39,194	36,957	32,657	31,701	24,596
Portland, OR	64,469	46,568	43,095	41,495	35,041	31,816	26,683	29,720	22,693
Yakima, WA	72,383	61,725	58,046	50,266	43,038	39,937	35,264	35,091	27,670
Burns, OR	64,394	55,786	52,628	43,561	39,217	36,998	32,691	31,724	24,579
Olympia, WA	58,097	42,930	40,200	36,127	31,939	28,959	24,860	26,065	20,485
Quillayuta, WA	39,467	27,741	26,074	26,773	24,364	21,238	18,068	20,205	16,604
Seattle, WA	54,336	37,870	35,051	35,334	30,769	27,173	22,703	25,832	20,095
Kalispell, MT	55,169	45,078	42,765	38,620	33,884	29,630	26,419	26,616	21,206
Cut Bank, MT	50,711	41,009	38,689	37,326	33,265	28,008	24,709	25,965	21,127

Table 15 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Medium Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh)

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	30,872	27,034	25,253	21,000	19,153	15,556	13,943	13,799	10,904
Spokane, WA	24,469	21,557	20,280	17,291	15,983	12,802	11,705	11,350	9,368
Missoula, MT	22,944	19,621	18,552	14,959	13,984	11,647	10,757	9,829	8,489
Boise, ID	29,475	26,501	25,009	19,970	18,506	15,419	14,026	13,644	10,858
Pocatello, ID	24,222	21,256	19,994	15,799	14,671	13,200	12,052	10,680	9,113
Helena, MT	22,642	19,036	17,891	15,180	13,955	11,866	10,819	10,371	8,841
Astoria, OR	20,961	14,579	13,755	14,219	13,214	7,113	6,678	7,013	6,465
Salem, OR	26,300	19,716	18,233	15,917	14,439	10,668	9,596	9,513	7,724
Eugene, OR	26,022	19,594	18,096	15,983	14,410	10,526	9,449	9,567	7,713
North Bend, OR	21,089	14,881	14,173	14,696	13,738	6,648	6,269	6,612	6,138
Arcata, CA	19,447	14,405	13,867	14,210	13,563	6,432	6,112	6,341	6,018
Medford, OR	31,958	27,704	25,891	19,541	17,895	15,546	14,069	12,365	9,896
Redmond, OR	24,247	21,161	19,853	16,218	15,133	12,572	11,341	9,605	8,580
Portland, OR	25,928	18,907	17,364	16,165	14,467	10,343	9,190	9,931	7,929
Yakima, WA	27,497	23,062	21,342	17,779	16,193	13,332	11,807	11,549	9,250
Burns, OR	24,222	21,141	19,829	16,185	15,096	12,599	11,364	9,636	8,600
Olympia, WA	23,981	18,023	16,852	15,115	13,897	9,580	8,762	8,640	7,437
Quillayuta, WA	18,617	13,857	13,148	13,350	12,547	7,240	6,842	6,994	6,586
Seattle, WA	22,283	16,136	14,943	14,914	13,423	8,681	7,874	8,513	7,227
Kalispell, MT	20,522	16,912	15,959	13,657	12,775	10,151	9,443	8,429	7,759
Cut Bank, MT	17,761	14,377	13,467	12,572	11,672	9,649	8,845	8,746	7,821

Table 16 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Large Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh)

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	625,525	709,849	680,198	622,919	577,091	466,000	423,626	407,906	348,313
Spokane, WA	535,300	597,716	577,289	526,634	493,144	385,521	359,501	337,375	300,854
Missoula, MT	530,947	580,793	563,338	511,436	480,529	366,507	341,547	318,899	285,125
Boise, ID	655,594	770,135	745,507	673,307	632,489	474,101	440,741	408,687	363,479
Pocatello, ID	708,539	827,382	811,444	744,836	717,250	404,085	382,885	353,318	327,394
Helena, MT	628,500	727,039	712,242	664,208	639,730	374,937	354,539	332,040	305,548
Astoria, OR	337,961	260,779	244,766	251,795	228,418	237,439	195,693	226,731	174,674
Salem, OR	479,758	459,266	431,286	414,395	371,572	342,529	296,089	308,904	248,317
Eugene, OR	479,953	457,731	429,111	413,326	369,628	341,672	295,068	308,088	247,256
North Bend, OR	322,697	252,760	238,106	246,985	225,057	244,702	197,509	231,974	173,363
Arcata, CA	297,758	232,250	222,867	225,639	211,286	221,361	177,249	208,475	160,466
Medford, OR	568,231	729,989	700,050	628,828	577,889	469,047	424,502	402,747	342,412
Redmond, OR	558,967	618,897	599,485	535,407	503,575	403,847	375,935	339,978	305,987
Portland, OR	471,625	435,311	405,932	400,888	355,895	332,260	284,426	308,802	242,340
Yakima, WA	573,644	615,286	586,406	547,111	500,129	413,488	375,706	362,718	310,850
Burns, OR	559,294	619,213	599,798	535,691	503,855	403,944	376,027	340,050	306,052
Olympia, WA	426,075	393,651	370,473	357,271	322,114	300,875	259,599	273,737	222,561
Quillayuta, WA	307,169	253,585	239,029	243,878	225,082	228,604	192,888	214,051	174,060
Seattle, WA	404,817	351,121	327,419	330,388	295,934	287,398	245,305	270,238	212,095
Kalispell, MT	466,128	484,425	468,335	433,766	407,475	323,538	300,923	282,803	254,078
Cut Bank, MT	494,103	564,578	552,444	529,372	506,746	309,418	294,711	276,110	255,455

Table 17 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Large Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh)

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	206,939	227,285	212,605	194,299	168,015	180,065	164,621	161,436	139,812
Spokane, WA	165,517	177,020	167,137	149,233	132,122	151,051	141,226	135,790	121,006
Missoula, MT	159,408	167,093	159,110	141,688	123,221	142,807	134,220	129,888	116,259
Boise, ID	199,594	230,864	219,529	194,321	167,573	185,229	173,145	164,592	146,115
Pocatello, ID	189,386	209,140	202,212	159,605	146,577	164,622	157,708	135,885	126,392
Helena, MT	175,889	183,936	177,411	148,511	136,758	152,016	145,132	131,255	121,354
Astoria, OR	140,856	98,034	90,771	95,879	86,691	82,183	74,415	80,997	72,122
Salem, OR	178,058	160,039	146,887	145,800	124,879	128,091	113,068	120,199	99,997
Eugene, OR	175,872	157,301	144,018	143,704	123,515	125,958	111,550	118,397	98,672
North Bend, OR	133,075	96,512	90,627	95,005	86,891	80,510	72,101	79,298	69,680
Arcata, CA	126,258	90,145	86,130	88,726	83,521	73,412	68,959	72,745	67,798
Medford, OR	217,231	240,640	225,175	200,798	170,575	183,490	166,766	163,321	137,954
Redmond, OR	167,856	175,160	165,757	145,383	124,437	150,900	140,826	133,204	119,865
Portland, OR	174,053	149,909	136,199	139,259	119,497	122,657	107,332	117,531	96,588
Yakima, WA	191,369	194,656	179,870	173,213	149,355	156,644	141,918	144,587	122,810
Burns, OR	167,883	175,183	165,778	145,301	124,434	150,966	140,893	133,246	119,909
Olympia, WA	162,886	139,549	129,074	128,060	111,986	111,152	99,524	105,296	90,256
Quillayuta, WA	124,592	93,802	87,730	91,165	83,769	83,730	77,448	81,880	74,767
Seattle, WA	148,019	119,433	108,912	113,661	99,403	104,631	92,463	101,737	85,789
Kalispell, MT	141,589	137,417	129,956	122,231	107,221	124,306	116,651	115,227	104,058
Cut Bank, MT	139,664	124,299	119,056	108,602	99,412	118,487	113,014	109,483	101,695

Table 18 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Supermarket Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh)

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	202,942	194,761	192,633	185,442	183,065	67,863	65,133	64,938	60,238
Spokane, WA	200,614	193,651	192,245	186,934	185,505	63,979	62,004	61,456	58,204
Missoula, MT	235,408	227,344	226,107	220,170	218,936	63,664	61,825	61,503	57,797
Boise, ID	211,431	202,949	200,963	192,975	190,953	67,840	65,332	65,058	60,172
Pocatello, ID	261,675	253,546	252,029	244,518	242,906	66,185	64,080	63,059	58,741
Helena, MT	269,236	261,224	260,045	255,014	253,616	64,192	62,262	62,304	58,685
Astoria, OR	152,547	146,322	146,131	145,927	145,615	55,104	53,691	54,652	53,007
Salem, OR	175,083	165,623	164,240	160,320	158,727	60,966	58,621	59,418	55,598
Eugene, OR	173,656	164,305	162,891	158,989	157,525	60,724	58,356	59,318	55,408
North Bend, OR	149,531	143,671	143,571	143,498	143,327	54,774	53,622	54,213	52,734
Arcata, CA	148,997	143,740	143,713	143,555	143,480	54,229	53,174	53,563	52,702
Medford, OR	194,706	185,601	183,405	171,154	169,218	70,199	67,368	65,272	59,641
Redmond, OR	202,653	194,933	193,509	188,086	186,976	63,240	61,140	60,238	57,020
Portland, OR	171,717	162,825	161,490	159,419	157,501	60,001	57,609	59,044	55,516
Yakima, WA	197,844	187,985	186,029	179,799	177,787	65,728	63,107	62,974	58,906
Burns, OR	203,028	195,353	193,924	188,463	187,374	63,304	61,195	60,278	57,065
Olympia, WA	174,017	165,526	164,617	161,080	160,092	59,556	57,612	57,859	54,930
Quillayuta, WA	156,289	150,289	150,062	149,802	149,536	54,939	53,711	54,385	53,057
Seattle, WA	162,047	154,388	153,627	152,776	151,628	57,375	55,563	56,611	54,196
Kalispell, MT	232,578	224,794	223,853	220,035	219,005	61,407	59,768	59,109	56,860
Cut Bank, MT	266,031	258,719	257,998	256,047	255,221	60,455	58,860	59,332	57,010

Table 19 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Supermarket Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh)

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	76,131	70,475	69,824	67,112	66,622	35,290	34,748	34,362	32,930
Spokane, WA	76,214	71,218	70,943	68,729	68,453	34,416	34,183	33,107	32,534
Missoula, MT	78,386	72,928	72,678	70,599	70,372	34,146	33,916	32,796	32,460
Boise, ID	79,222	73,796	73,288	70,215	69,760	35,592	35,158	34,171	33,112
Pocatello, ID	80,311	74,906	74,604	72,042	71,767	34,658	34,382	32,998	32,574
Helena, MT	82,817	77,461	77,252	75,555	75,328	34,114	33,909	33,132	32,706
Astoria, OR	60,808	55,814	55,804	55,690	55,669	31,204	31,177	31,117	31,077
Salem, OR	67,164	61,440	61,092	59,638	59,366	32,924	32,603	31,985	31,525
Eugene, OR	66,817	61,067	60,713	59,322	59,023	32,890	32,570	31,992	31,486
North Bend, OR	58,406	53,476	53,476	53,449	53,446	31,091	31,077	31,066	31,052
Arcata, CA	58,503	53,568	53,579	53,517	53,514	31,091	31,091	31,061	31,056
Medford, OR	73,189	67,902	67,188	62,538	62,029	36,682	36,085	34,048	32,944
Redmond, OR	76,628	71,218	70,933	69,019	68,799	33,718	33,464	32,325	32,051
Portland, OR	65,922	60,255	59,956	58,961	58,686	32,543	32,253	32,249	31,493
Yakima, WA	74,417	68,621	68,063	65,697	65,297	34,604	34,129	33,391	32,444
Burns, OR	76,792	71,330	71,043	69,116	68,896	33,744	33,488	32,344	32,064
Olympia, WA	67,125	61,784	61,643	60,232	60,082	32,650	32,491	31,729	31,499
Quillayuta, WA	62,506	57,500	57,482	57,366	57,343	31,237	31,207	31,124	31,093
Seattle, WA	63,847	58,686	58,609	57,991	57,869	31,893	31,814	31,576	31,260
Kalispell, MT	77,472	72,080	71,904	70,588	70,416	33,355	33,185	32,349	32,144
Cut Bank, MT	82,067	76,767	76,665	76,030	75,918	32,960	32,850	32,490	32,319

Table 20 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard Performance Secondary School Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh)

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	802,983	718,847	706,568	631,138	604,540	361,413	349,323	319,593	297,356
Spokane, WA	702,242	632,509	623,734	580,333	561,392	313,571	305,237	289,853	275,185
Missoula, MT	726,628	662,773	654,896	590,316	572,816	323,715	314,923	295,961	281,487
Boise, ID	793,361	730,422	720,057	636,474	609,496	367,576	355,796	327,977	307,505
Pocatello, ID	728,178	669,054	660,832	592,721	572,854	336,206	327,146	302,621	286,992
Helena, MT	732,267	662,788	654,671	602,483	583,202	323,126	314,374	295,094	280,200
Astoria, OR	518,700	433,968	427,526	424,804	413,938	213,421	210,025	210,979	206,342
Salem, OR	669,486	562,168	549,627	522,026	498,522	276,941	266,704	260,955	243,736
Eugene, OR	670,319	560,981	548,342	523,472	500,086	275,868	265,849	260,433	243,042
North Bend, OR	484,289	413,868	409,427	407,765	398,291	201,522	198,872	200,348	196,999
Arcata, CA	467,536	399,340	395,998	394,160	387,924	201,056	199,827	200,364	199,183
Medford, OR	813,169	725,476	711,414	622,720	588,140	368,716	355,404	321,317	296,740
Redmond, OR	711,289	640,032	631,088	564,295	546,173	320,521	310,617	286,426	271,949
Portland, OR	662,236	550,455	537,896	520,155	495,377	271,088	260,398	259,846	241,340
Yakima, WA	744,086	652,407	639,366	596,104	567,091	328,164	314,217	303,670	281,016
Burns, OR	712,003	640,880	631,921	565,221	546,914	320,794	310,861	286,650	272,139
Olympia, WA	625,336	524,151	514,475	486,752	467,352	259,040	251,274	246,521	234,056
Quillayuta, WA	519,483	435,059	429,583	424,338	416,018	216,161	213,090	211,653	207,653
Seattle, WA	585,142	493,033	483,656	474,935	457,306	243,355	236,486	237,211	225,540
Kalispell, MT	659,825	601,206	594,741	549,236	534,802	294,293	287,608	273,730	261,815
Cut Bank, MT	662,458	592,255	585,486	563,240	550,770	288,995	281,552	275,547	264,489

Table 21 Annual Energy Consumption (Chiller, Fan, and Pump) for the High Performance Secondary School Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh)

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	339,264	291,514	285,251	242,258	225,143	171,837	167,046	149,189	138,516
Spokane, WA	280,167	245,089	240,963	212,151	200,806	148,034	145,036	132,338	125,680
Missoula, MT	277,278	242,775	239,202	203,580	192,929	144,085	141,108	129,928	122,491
Boise, ID	333,867	298,523	293,469	241,317	224,343	176,326	172,079	151,765	141,159
Pocatello, ID	288,739	255,768	251,710	212,520	200,657	153,946	150,597	135,965	127,950
Helena, MT	275,933	242,856	239,124	207,686	196,995	148,587	146,089	132,068	124,632
Astoria, OR	220,217	174,617	171,456	169,122	163,612	104,166	103,059	102,829	101,198
Salem, OR	283,981	227,577	221,209	203,257	189,899	131,735	127,786	122,701	115,439
Eugene, OR	282,244	225,448	219,050	203,262	187,918	129,329	125,866	121,577	114,685
North Bend, OR	208,964	172,097	170,422	168,518	164,277	101,100	100,435	100,689	99,898
Arcata, CA	206,736	167,114	166,383	163,201	160,242	102,414	101,739	101,991	101,234
Medford, OR	351,444	307,052	299,865	241,100	222,836	180,527	175,434	152,180	139,589
Redmond, OR	291,486	251,112	246,253	207,469	197,747	150,160	146,354	130,249	123,081
Portland, OR	277,589	219,258	212,760	201,251	188,335	126,639	122,605	121,138	113,797
Yakima, WA	307,633	256,917	250,079	226,058	209,249	147,185	141,860	135,697	125,481
Burns, OR	291,547	251,153	246,288	207,460	197,740	150,236	146,435	130,455	123,142
Olympia, WA	265,439	212,504	207,663	189,376	178,097	124,098	121,196	117,004	111,626
Quillayuta, WA	220,111	173,098	170,324	165,995	161,348	106,600	105,045	103,702	101,565
Seattle, WA	238,639	192,157	187,138	182,237	173,426	114,009	111,266	111,215	106,778
Kalispell, MT	249,097	219,906	216,510	191,948	182,687	131,613	129,185	121,090	115,389
Cut Bank, MT	238,931	203,945	200,502	189,397	182,009	126,262	123,804	121,022	116,737

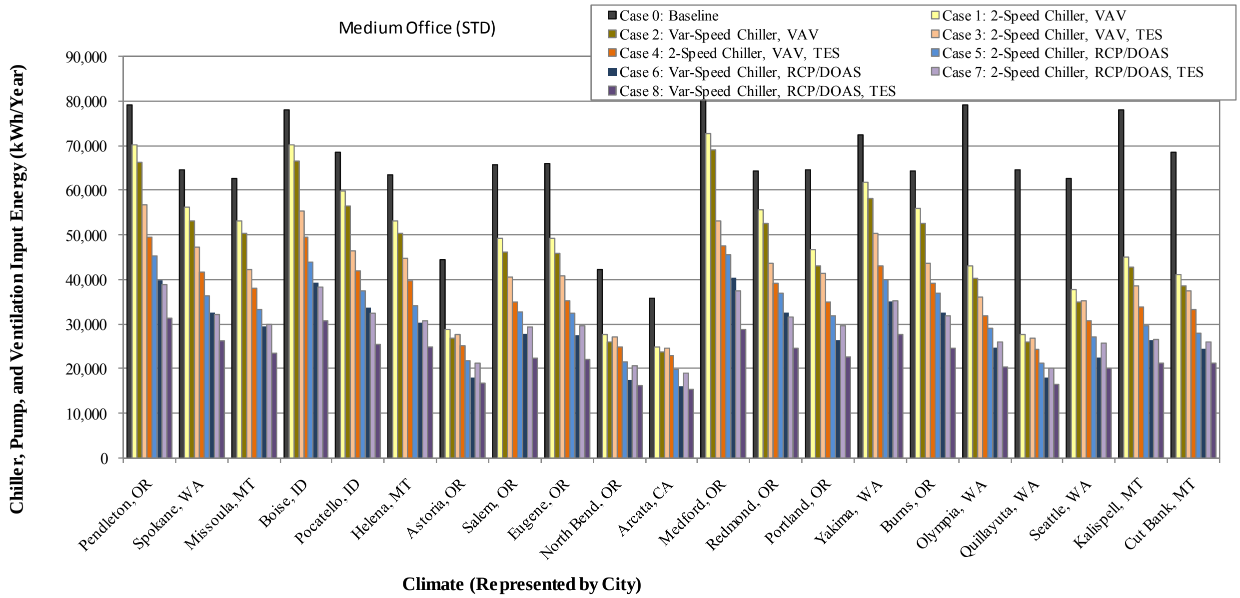

Figure 14 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Medium Office Building for Various System Configurations in 21 Locations

For high-performance medium office (Figure 15), the reduction in energy consumption between Case 0 and Case 8 ranges from 56% to 71% with an average reduction of 66%. In general, the trend across all climate locations is similar. The difference between low-lift base case (Case 1) and the full LLCS (Case 8) ranges from 46% to 64% with an average reduction of 57%, lower than the difference between Case 0 and Case 8.

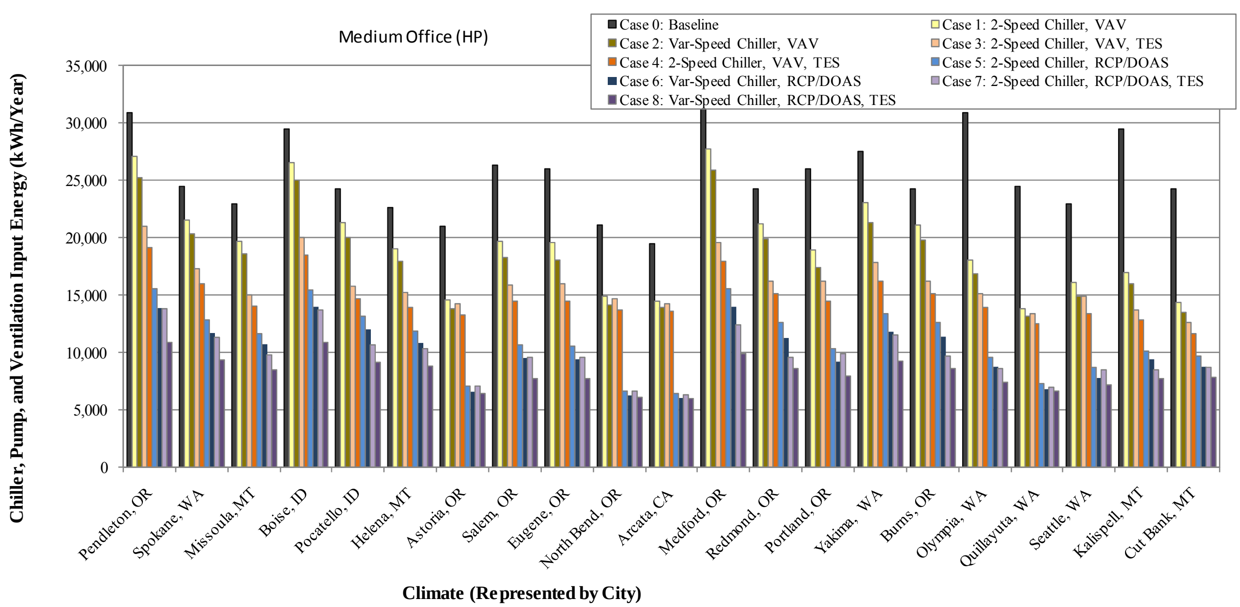

Figure 15 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Medium Office Building for Various System Configurations in 16 Locations

For standard-performance large office building (Figure 16), the reduction in energy consumption between Case 0 and Case 8 ranges from 40% to 54% with an average reduction of 47%. In general, the trend across all climate locations is similar. The difference between low-lift base case (Case 1) and the full LLCS (Case 8) ranges from 18% to 43%, with an average reduction of 32%; this is slightly lower than the difference between Case 0 and Case 8. The large office building uses a water-cooled chiller with VAV system as the base case (Case 0) and 2-speed air-cooled chiller with VAV system as the low-lift base case (Case 1). The water-cooled chiller is generally more efficient than air-cooled chiller in non-humid climates, therefore, in many climate locations, the Case 1 uses more energy than Case 0. In wet-climates (Olympia, Seattle) the air-cooled perform slightly better than the water-cooled, because of high wet-bulb temperatures that limit the water-cooled chiller efficiency.

For high-performance large office building (Figure 17), the reduction in energy consumption between Case 0 and Case 8 ranges from 27% to 49% with an average reduction of 36%. It is worth noting that the difference between the low-lift base case (Case 1) and the full LLCS (Case 8) is lower and ranges from 18% to 43%, with an average reduction of just 32%.

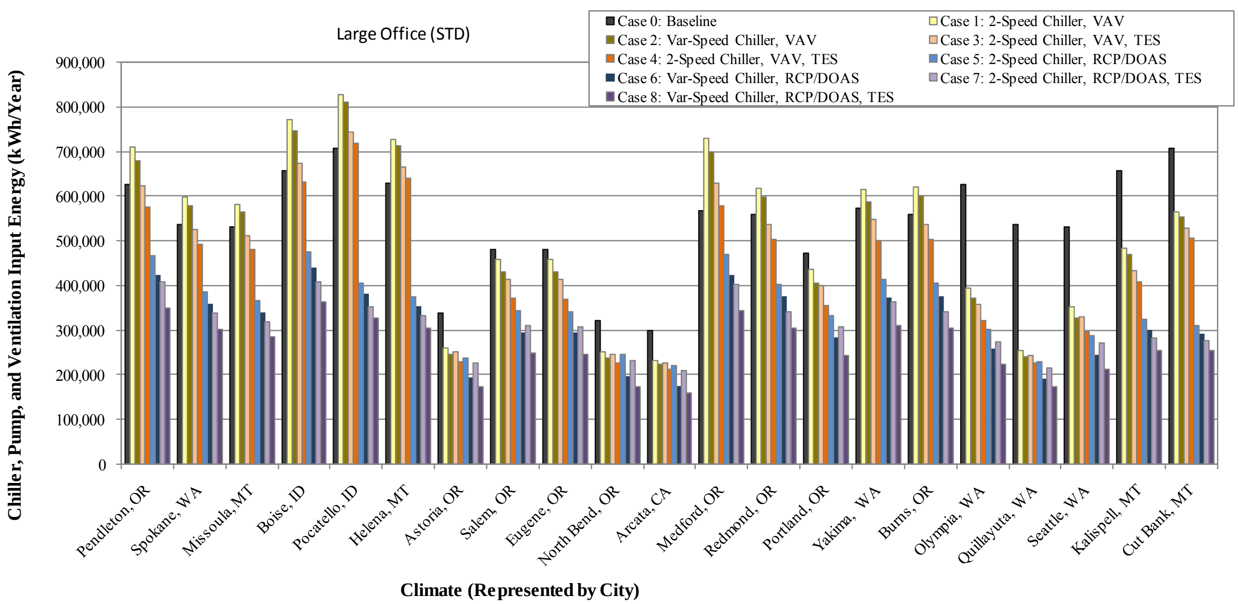

Figure 16 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Large Office Building for Various System Configurations in 21 Locations

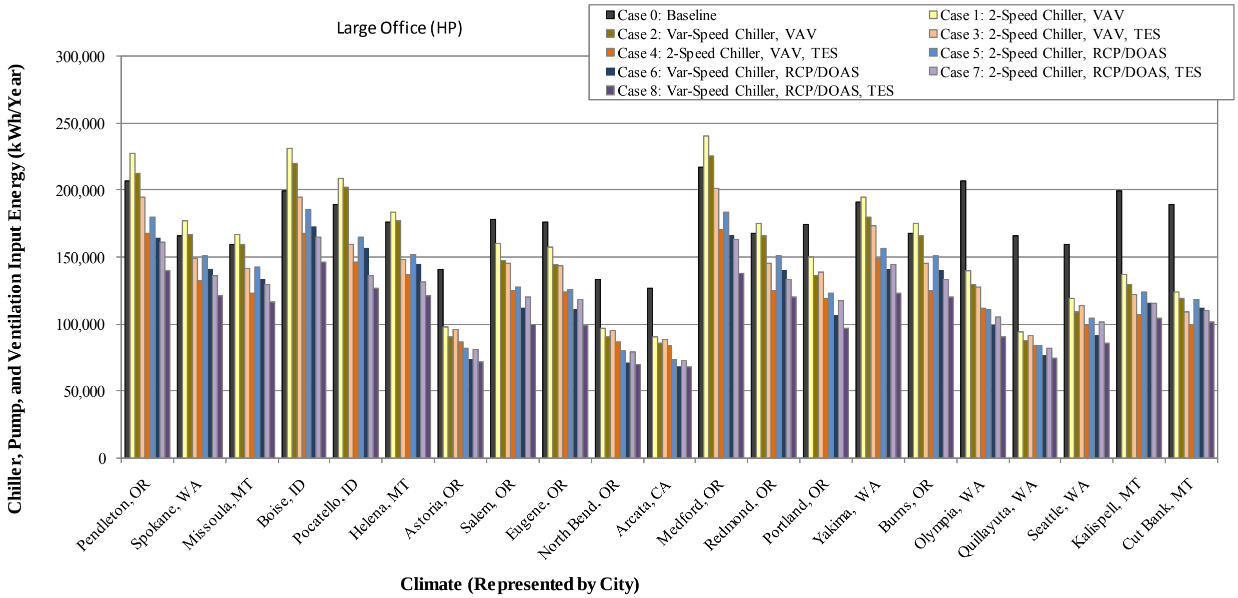

Figure 17 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Large Office Building for Various System Configurations in 21 Locations

For standard-performance supermarket building (Figure 18), the reduction in energy consumption between Case 0 and Case 8 ranges from 65% to 79% with an average reduction of 71%. In general, the trend across all climate locations is similar. The difference between low-lift base case (Case 1) and the full LLCS (Case 8) ranges from 63% to 78% with an average reduction of 69%. The reason for the large difference in both comparisons is that the both base cases, Case 0 and Case 1, use constant speed fans, while all the low-lift options (Case 5 through Case 8) use VAV or RCP.

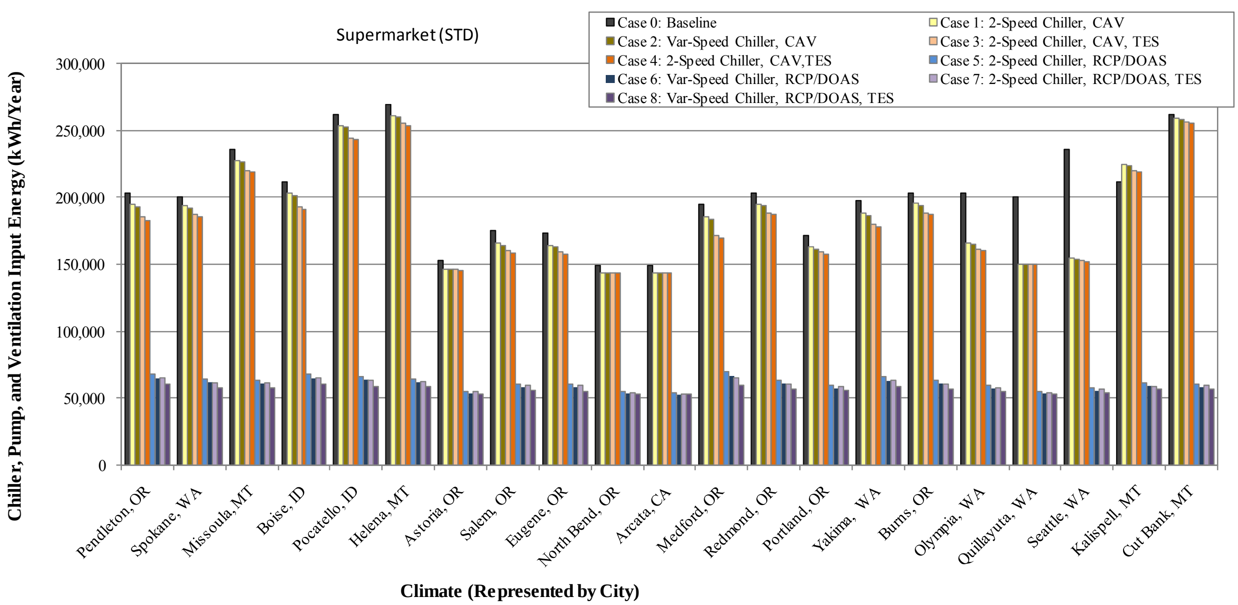

Figure 18 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Perforamance Supermarket Building for Various System Configurations in 21 Locations

For high-performance supermarket (Figure 19), the reduction in energy consumption between Case 0 and Case 8 ranges from 47% to 61% with an average reduction of 55%. In general, the trend across all climate locations is similar. The difference between low-lift base case (Case 1) and the full LLCS (Case 8) ranges from 42% to 58% with an average reduction of 51%, slightly lower than the difference between Case 0 and Case 8.

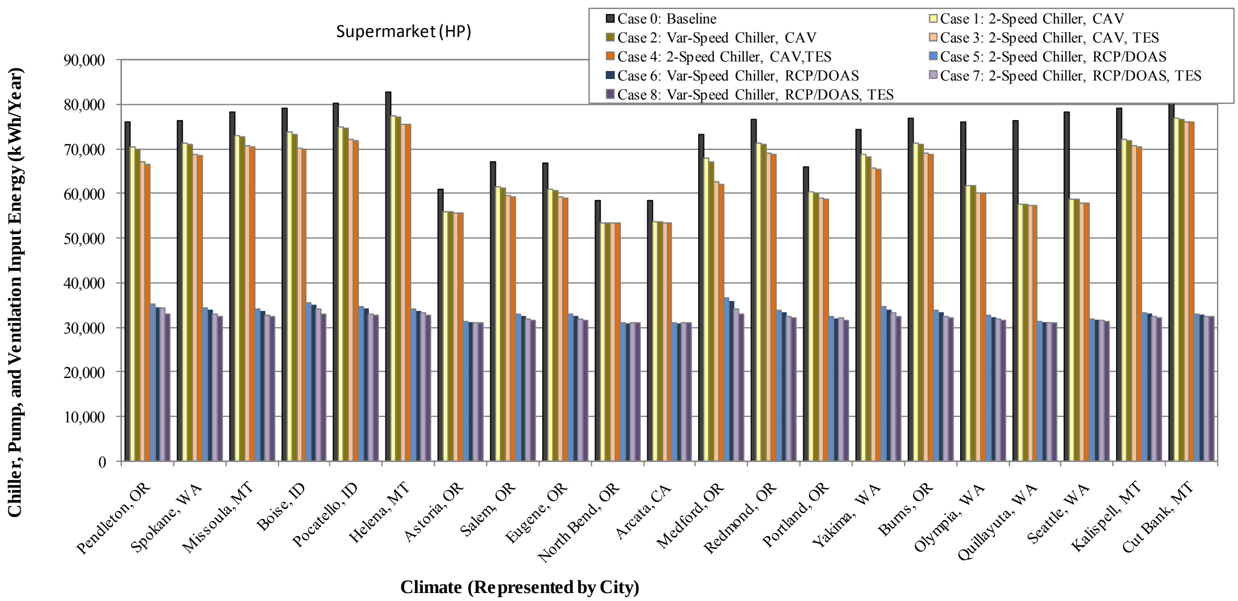

Figure 19 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Supermarket Building for Various System Configurations in 21 Locations

For standard secondary school (Figure 20), the reduction in energy consumption between Case 0 and Case 8 ranges from 57% to 69% with an average reduction of 61%. In general, the trend across all climate locations is similar. The difference between low-lift base case (Case 1) and the full LLCS (Case 8) ranges from 50% to 59%, with an average reduction of 56%; this is slightly lower than the difference between Case 0 and Case 8. The secondary school uses a water-cooled chiller with VAV system as the base case (Case 0) to condition a significant portion of the school area and a packaged constant-speed single-zone DX unit for the kitchen and gymnasium, and two-speed air-cooled chiller with VAV system for Case 1.

For high-performance secondary school (Figure 21), the reduction in energy consumption between Case 0 and Case 8 ranges from 51% to 60% with an average reduction of 56%. It is worth noting that the difference between the low-lift base case (Case 1) and the full LLCS (Case 8) is lower and ranges from 39% to 55%, with an average reduction of just 48%.

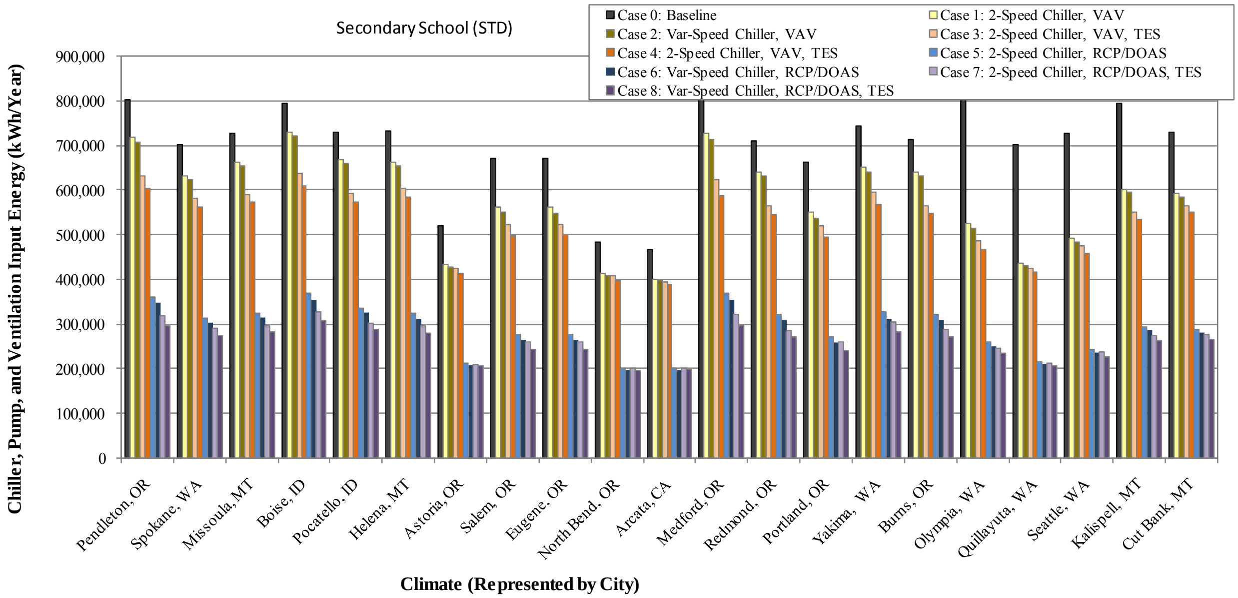

Figure 20 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Secondary School Building for Various System Configurations in 21 Locations

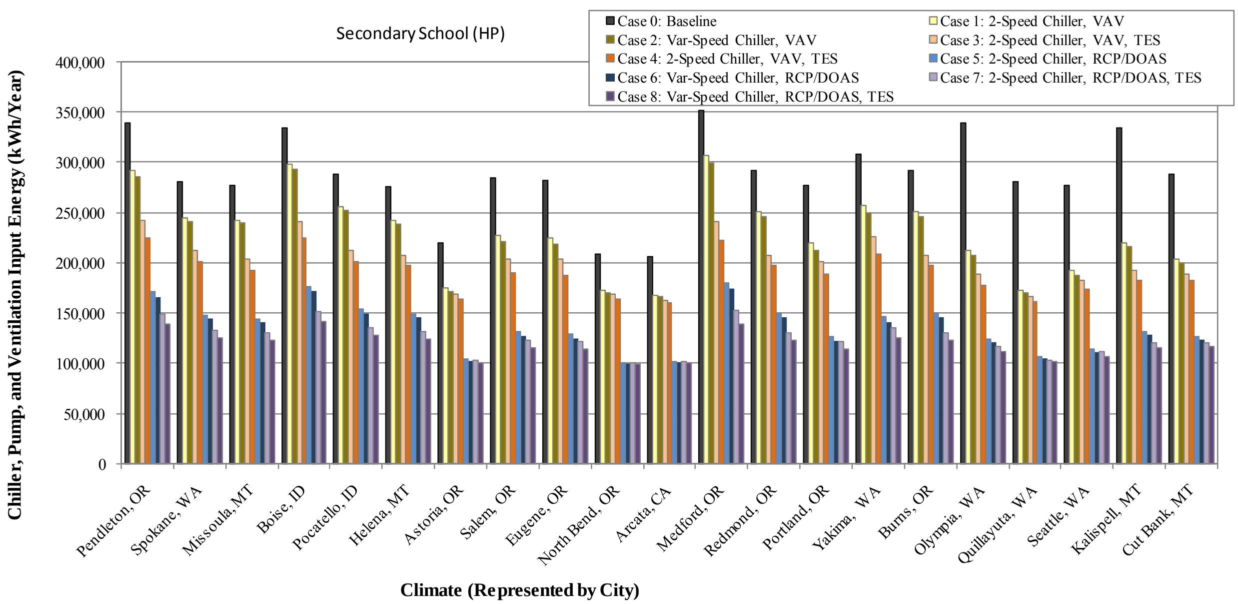

Figure 21 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Secondary School Building for Various System Configurations in 21 Locations

The comparison figures for the rest of the building (similar to Figure 14) are included in Appendix C (Appendix: Energy Use Estimate Tables and Figures). The range of *percent energy savings* across the climate locations for all building types with respect to the base case are shown in Table 22 (Case 0 as reference) and Table 23 (Case 1 as reference). For each row, percent savings are computed with reference to the corresponding Case 0 or Case 1 energy consumption. The general trends are similar to the four building types discussed previously in this section.

Although there are significant percent savings in the large hotel from use of the full LLCS, the saving are only from central HVAC systems used in the common areas and conference rooms and not the individual rooms. Therefore, the percent savings are not computed for Hotels. Note that for the primary and the secondary schools, the percent saving are also high, even considering that these buildings usually have high ventilation requirements. The savings for the warehouses (non-refrigerated) are for the office portion of the warehouse and not the entire warehouse.

Table 22 Range of Energy Reduction (between Case 0 and Case 8) in Annual Chiller and Distribution Energy Consumption for both Standard and High-Performance Buildings in Various Climate Locations

	Standard-Performance Building			High-Performance Building		
Building Type	Minimum	Maximum	Average	Minimum	Maximum	Average
Office Small	77%	82%	81%	14%	54%	44%
Office Medium	57%	67%	62%	56%	71%	66%
Office Large	40%	54%	47%	27%	49%	36%
Retail Standalone	70%	77%	75%	46%	63%	57%
Retail Strip Mall	54%	69%	65%	-8%	47%	30%
Primary School	46%	63%	58%	31%	53%	46%
Secondary School	57%	64%	61%	51%	60%	56%
Hotel Large						
Supermarket	65%	79%	71%	47%	61%	55%
Warehouse	51%	80%	68%	-11%	48%	17%
Outpatient	81%	86%	84%	39%	69%	61%
Hospital	68%	75%	72%	57%	67%	62%

Table 23 Range of Energy Reduction (between Case 1 and Case 8) in Annual Chiller and Distribution Energy Consumption for both Standard- and High-Performance Buildings in Various Climate Locations

	Standard-Performance Building			High-Performance Building		
Building Type	Minimum	Maximum	Average	Minimum	Maximum	Average
Office Small	76%	82%	80%	12%	52%	41%
Office Medium	38%	61%	51%	46%	64%	57%
Office Large	31%	60%	46%	18%	43%	32%
Retail Standalone	70%	77%	74%	46%	61%	55%
Retail Strip Mall	54%	68%	64%	-9%	45%	26%
Primary School	39%	57%	52%	24%	45%	37%
Secondary School	50%	59%	56%	39%	55%	48%
Hotel Large						
Supermarket	63%	78%	69%	42%	58%	51%
Warehouse	50%	79%	67%	-11%	47%	16%
Outpatient	81%	85%	84%	39%	67%	60%
Hospital	64%	75%	70%	47%	57%	53%

Reheat Savings

In the previous section, the cooling and fan (for both cooling and heating) savings were presented. In addition to the cooling and fan savings, there will be reheat savings for some building types. When a multi-zone system is used, there is some reheat that is unavoidable. However, with a radiant cooling system, reheat can be fully avoided. The reheat savings are computed when one or more zones is in the heating mode and the central cooling coil is active (i.e., mechanical cooling is ON). The supply loop for a VAV system is shown graphically in Figure 22. The reheating penalty occurs when both the central cooling (C/C) and the zone heating coils (H/C) are active. This condition occurs when the $T_{z,i} > T_{supply}$. The reheating penalty (E_{reheat}) is estimated using the following equations:

$$E_{reheat} = m_{z,i}\, c_p\, (T_{z,i} - T_{cc}) \quad \text{if } T_{z,i} < T_{mix}$$
$$E_{reheat} = m_{z,i}\, c_p\, (T_{mix} - T_{cc}) \quad \text{if } T_{z,i} \geq T_{mix}$$

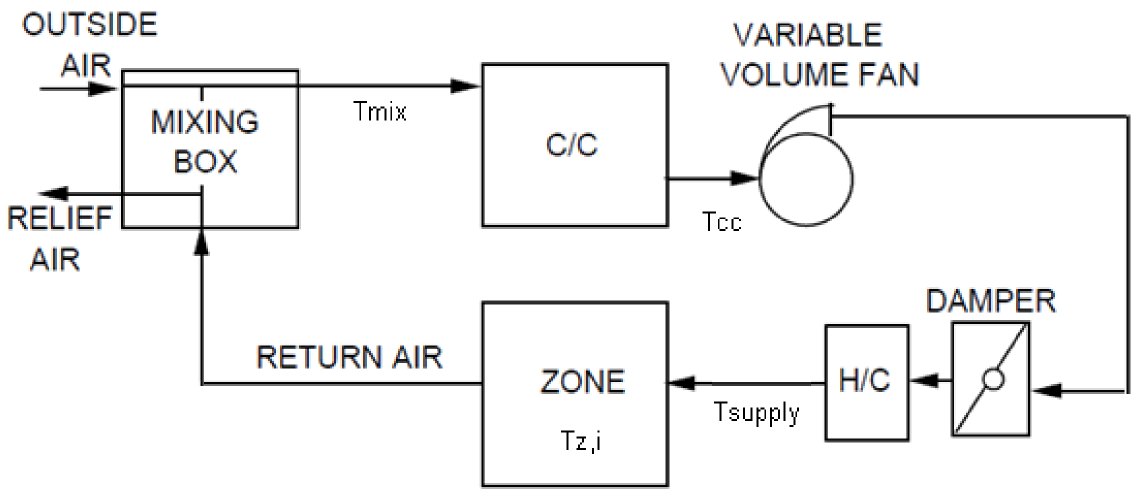

Figure 22 Variable Air Volume System with Terminal Reheat

The reheating penalty is computed for each zone and aggregated in Table 24. Although the absolute energy reheat penalty is significant, it is a very small fraction of the total heating energy use, as shown in Table 25. In reality, the reheating penalty is going to be significantly higher than what the simulation has estimated. Because it is common to have different set point in different zones, which will lead to increased reheat. Also, while simulating buildings, the controls are assumed to perfect, so the controls are idealized.

Table 24 Reheat Savings for Selected Building Types in Different Climate Locations (million Btus)

	Hospital	Hotel Large	Office Large	Office Medium	School Primary	School Secondary
Arcata, CA	1,203.4	136.9	806.6	60.5	21.7	143.5
Astoria, OR	1,363.5	157.9	904.7	65.1	30.1	128.2
Boise, ID	1,480.3	121.5	1,444.5	71.9	50.4	237.3
Burns, OR	1,417.6	95.3	1,315.1	70.5	39.3	231.2
Cut Bank, MT	1,694.5	80.9	1,855.6	74.9	34.0	223.7
Eugene, OR	1,370.1	158.7	1,009.2	76.4	45.1	130.7
Helena, MT	1,160.9	101.9	2,348.4	77.1	39.3	259.6
Kalispell, MT	1,169.1	93.3	1,031.2	65.0	30.6	200.9
Medford, OR	1,383.3	129.0	1,025.8	79.2	50.4	212.9
Missoula, MT	1,379.9	115.2	1,209.7	69.9	35.4	211.1
North Bend, OR	1,215.2	157.0	876.8	62.5	23.2	131.2
Olympia, WA	1,312.2	139.1	956.7	70.2	41.5	127.2
Pendleton, OR	1,277.5	149.9	1,253.6	80.0	52.5	254.0
Pocatello, ID	1,462.6	96.3	2,848.2	72.1	38.3	214.5
Portland, OR	1,445.8	177.5	1,011.5	75.3	46.7	128.9
Quillayuta, WA	1,360.3	124.0	942.4	63.8	26.9	162.2
Redmond, OR	1,414.9	94.9	1,316.4	70.3	39.3	230.2
Salem, OR	1,294.0	151.0	940.3	73.0	43.9	127.6
Seattle, WA	1,427.2	163.8	997.7	73.8	40.7	131.5
Spokane, WA	1,257.3	108.9	1,274.1	70.0	35.8	198.9
Yakima, WA	1,291.4	124.2	941.0	72.0	40.1	174.1

Table 25 Reheating Savings as a Fraction of the Total Heating

	Hospital	Hotel Large	Office Large	Office Medium	School Primary	School Secondary
Arcata, CA	0.025%	0.003%	0.014%	0.006%	0.001%	0.002%
Astoria, OR	0.031%	0.004%	0.016%	0.007%	0.001%	0.002%
Boise, ID	0.021%	0.002%	0.013%	0.004%	0.001%	0.001%
Burns, OR	0.015%	0.001%	0.008%	0.003%	0.000%	0.001%
Cut Bank, MT	0.025%	0.001%	0.019%	0.005%	0.001%	0.001%
Eugene, OR	0.008%	0.001%	0.003%	0.002%	0.000%	0.000%
Helena, MT	0.004%	0.000%	0.005%	0.001%	0.000%	0.000%
Kalispell, MT	0.014%	0.001%	0.006%	0.002%	0.000%	0.001%
Medford, OR	0.028%	0.004%	0.015%	0.010%	0.004%	0.005%
Missoula, MT	0.039%	0.005%	0.045%	0.012%	0.003%	0.007%
North Bend, OR	0.018%	0.003%	0.009%	0.004%	0.000%	0.001%
Olympia, WA	0.008%	0.001%	0.003%	0.002%	0.000%	0.000%
Pendleton, OR	0.004%	0.001%	0.003%	0.001%	0.000%	0.000%
Pocatello, ID	0.017%	0.001%	0.017%	0.003%	0.000%	0.001%
Portland, OR	0.029%	0.006%	0.015%	0.010%	0.003%	0.003%
Quillayuta, WA	0.038%	0.005%	0.035%	0.011%	0.003%	0.006%
Redmond, OR	0.056%	0.007%	0.135%	0.029%	0.009%	0.025%
Salem, OR	0.094%	0.012%	0.150%	0.075%	0.038%	0.046%
Seattle, WA	0.011%	0.002%	0.004%	0.002%	0.000%	0.000%
Spokane, WA	0.028%	0.005%	0.026%	0.011%	0.004%	0.009%
Yakima, WA	0.023%	0.004%	0.016%	0.007%	0.003%	0.004%

Pacific Northwest Regional Energy Savings Estimation Methodology

In the previous section, the potential energy savings for the LLCS for 21 building prototypes in 21 climate locations was summarized. To estimate the regional energy savings potential, however, requires the "translation" from savings per *building* to savings across the commercial buildings' sector in the Pacific Northwest Region. This translation requires a set of factors that weight the results of each building prototype in each climate location proportionately into the national aggregate energy savings estimates. Because the LLCS is more suitable for new construction or major retrofit, the individual building savings estimates have to be scaled to the potential new commercial building stock. The building weights developed by Northwest Power Planning Council[17] (NWPC) were used to calculate the new construction building weights by building type and climate location needed to estimate the energy savings.

The NWPC developed the new construction weights from the McGraw-Hill Construction (MCH) Projects Starts Database. The MHC dataset is drawn from permit data on new commercial building starts in the U.S. and represents an overwhelming sample of over 90% of the new commercial buildings as described in Jarnagin and Bandyopadhyay (2010). This dataset covers construction data for most new buildings as well as additions to existing facilities over a 6 year period (2002-2007).

To estimate the number of equivalent prototype buildings (Table 26), weights, based on square footage, were assigned by 21 climate locations and by building prototype or category of building type (i.e., large office, supermarket). These weights were then converted to number of equivalent prototype buildings by dividing by the area of each representative prototype (Table 26). The number of equivalent buildings built each year for each building type and climate location are shown in Table 27.

[17]The data was provided by Charlie Grist from NW Power Planning Council

Table 26 Benchmark Building Prototype Areas

Building Type	Area (sf)
Supermarket	45,000
Hospital	241,501
Hotel Large	100,816
Office Large	498,588
Office Medium	53,627
Outpatient Health Care	10,005
School Primary	73,960
Retail Stand-Alone	24,692
School Secondary	210,886
Office Small	5,500
Retail Strip Mall	22,500
Warehouse	52,045

Table 27 Annual New Construction Weights (number of buildings per year) by Building Type and Climate Location

	Office Small	Office Medium	Office Large	Retail Stand-Alone	Retail Strip Mall	School Primary	School Secondary	Hospital	Outpatient Health Care	Warehouse	Hotel Large	Supermarket
Spokane, WA	15.97	15.97	15.97	15.97	15.97	15.97	15.97	15.97	15.97	15.97	15.97	15.97
Pendleton, OR	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85
Missoula, MT	2.09	1.38	0.00	1.10	0.83	0.00	0.01	0.01	0.49	0.62	0.09	0.71
Boise, ID	49.03	9.87	0.31	9.64	10.61	4.37	1.51	0.48	13.36	6.13	2.07	1.25
Pocatello, ID	8.07	2.63	0.07	4.57	2.51	0.97	0.44	0.50	4.77	2.92	0.36	0.31
Helena, MT	0.65	0.99	0.00	0.59	0.49	0.17	0.06	0.05	1.25	0.12	0.00	0.00
Astoria, OR	0.73	0.22	0.00	0.46	0.08	0.07	0.09	0.01	0.00	0.29	0.30	0.32
Salem, OR	9.97	3.45	0.95	6.72	3.71	1.00	0.33	0.48	6.31	2.78	0.76	0.99
Eugene, OR	8.67	2.13	0.14	1.51	2.35	0.84	0.29	1.15	8.54	2.68	0.32	0.49
North Bend, OR	1.10	0.34	0.00	0.36	0.02	0.00	0.01	0.00	0.26	0.04	0.00	0.00
Arcata, CA	0.00	0.03	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00
Medford, OR	5.85	2.10	0.00	3.68	0.92	0.84	0.16	0.49	7.09	1.40	0.77	0.20
Redmond, OR	6.32	3.61	0.00	3.87	2.18	0.80	0.14	0.39	6.74	1.64	0.29	0.23
Portland, OR	28.92	15.54	1.10	24.31	17.66	5.30	1.39	1.40	51.61	34.56	0.84	5.89
Yakima, WA	5.71	2.10	0.10	3.12	1.35	0.84	0.39	0.03	3.64	7.42	0.90	0.98
Burns, OR	0.26	0.08	0.00	0.00	0.05	0.00	0.01	0.04	0.09	0.02	0.00	0.00
Olympia, WA	9.63	4.60	0.17	10.42	2.65	1.00	0.30	0.36	6.99	8.85	1.45	0.54
Quillayuta, WA	0.31	0.18	0.00	1.33	0.22	0.01	0.02	0.01	5.91	0.01	0.08	0.05
Seattle, WA	43.54	26.98	4.05	41.13	21.06	8.39	3.93	2.64	64.56	44.21	7.54	7.33
Kalispell, MT	1.48	0.53	0.00	2.45	0.18	0.29	0.20	0.07	0.94	0.34	0.16	0.27
Cut Bank, MT	0.21	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.43	0.00	0.00	0.00

Pacific Northwest Regional Technical Energy Savings Potential

The annual regional energy savings potential (cooling, fan and pump) from widespread use of the LLCS was estimated by applying the previously described methodology to the energy savings estimated for each building performance level and 21 climate locations. Table 28 summarizes the regional energy saving for the *full* LLCS (Case 8), compared to the baseline buildings that are compliant with ASHRAE 90.1-2004 (Case 0). Note that these annual estimates are for new construction and building-types and climate locations for which the full LLCS is applicable (see previous section). Although it is likely that parts of the LLCS are applicable for a large portion of the existing commercial building stock and the full LLCS may be applicable to a substantial fraction of the existing building stock, the savings were *not* estimated for that potential in this study, because the primary market – as with most advanced systems – is new construction. In this sense, the technical potential presented here is conservative.

Table 28 Summary of Regional *Technical Site* Electricity Savings Potential for the Year 2010 for the Low-Lift Cooling Design Option Set – Case 8 (assuming 100% Penetration) in Comparison to Case 0

Building Performance Level	Cooling and Fan and Pump Electricity Savings		
	million kWh/year	Peak Reduction aMW	Percentage Electricity Savings
Standard	**56.8**	6.5	74.1%
High Performance	**15.5**	1.8	63.5%

For baseline buildings that are compliant with ASHRAE 90.1-2004, the full LLCS saves about 57 million kWh of site electricity use *in 1 year of new construction* with the full LLCS. The corresponding average peak reductions are about 6.2 MW. The annual site electricity savings are about 15.5 million kWh for high-performance buildings and the average peak reduction is about 1.8 MW. The energy saving for the *full* LLCS (Case 8) compared to the conventional VAV system with two-speed chiller (Case 1) are shown in Table 29.

Table 29 - Summary of Regional *Technical Site* Electricity Savings Potential for the Year 2010 for the Low-Lift Cooling Design Option Set – Case 8 (assuming 100% Penetration) Compared to Case 1

Building Performance Level	Cooling and Fan and Pump Electricity Savings		
	million kWh/year	Peak Reduction aMW	Percentage Electricity Savings
Standard	**42.1**	4.8	71.1%
High Performance	**11.3**	1.3	61.0%

The annual regional technical energy savings for different system configurations compared to the baseline building (Case 0) are shown in Figure 23. For baseline buildings, the savings range from 15 million kWh/year for conventional system (Case 1) to 57 million kWh/year for the full LLCS.

The annual regional technical energy savings for different system configurations compared to the conventional VAV system with two-speed chiller (Case 1) are shown in Figure 24. For baseline buildings, the savings range from 1.2 million kWh/year to 0.002 trillion Btu/year for variable-speed chiller system configured with conventional VAV distribution to 44 million kWh/year for the full LLCS.

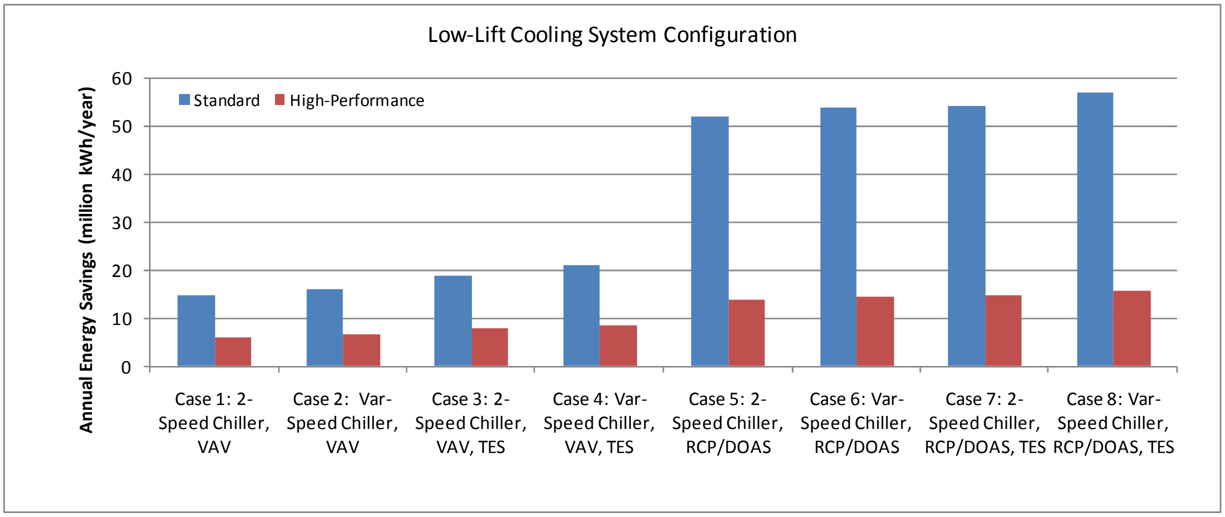

Figure 23 Comparison of Regional Technical Site Electricity Savings Potential for the Year 2010 for Various Low-Lift Cooling Design Option Sets (assuming 100% Penetration) in Comparison to Case 0

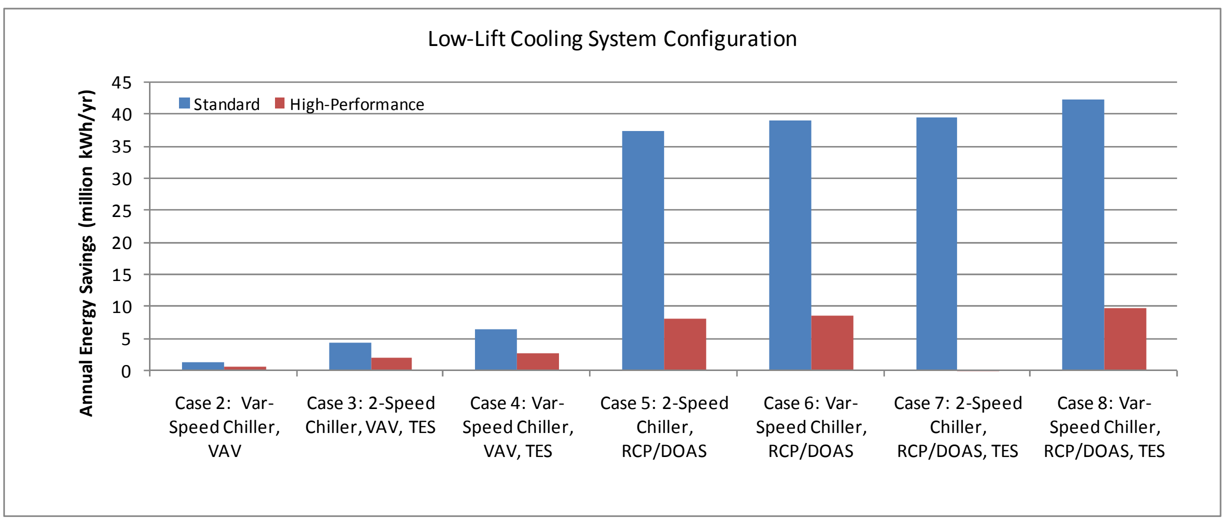

Figure 24 Comparison of Regional Technical Site Electricity Savings Potential for the Year 2010 for Various Low-Lift Cooling Design Option Sets (assuming 100% Penetration) in Comparison to Case 1

Assuming a new construction growth rates (1%) remain the same for the next decade (through the year 2020), the total regional technical site energy savings potential (again assuming 100% penetration) from new construction between 2010 and 2020 for the baseline building would be 625 million kWh/year (Figure 25 and Figure 26). To reiterate, all of these savings are in site energy terms; to calculate source energy savings at the power plant, using average "busbar" savings of 7.25%, the previous estimates should be multiplied by 1.0725. The total savings potential – relative to the baseline building – is therefore 670 million kWh/year.

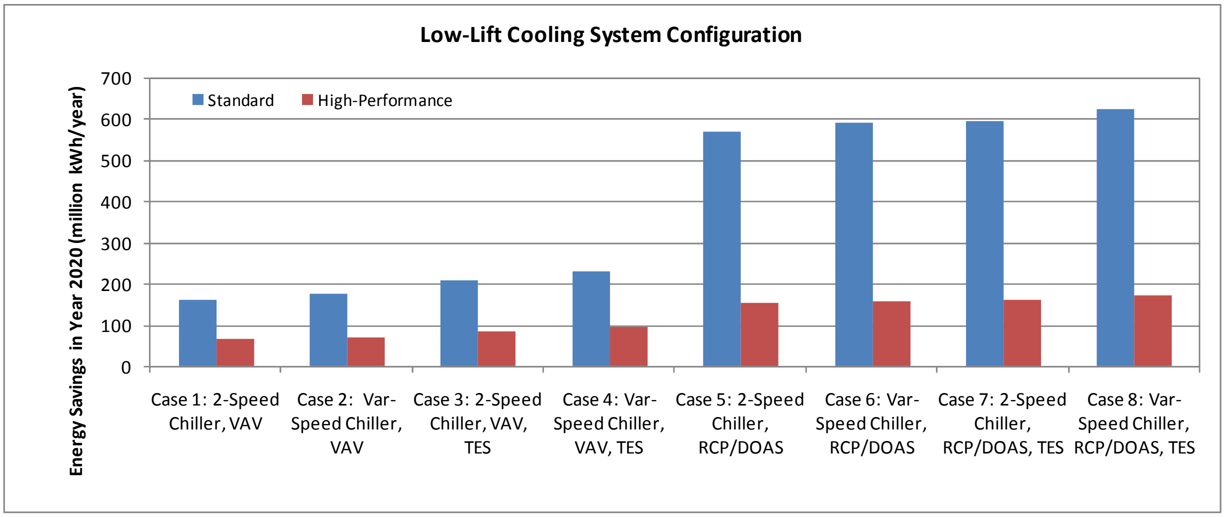

Figure 25 Pacific Northwest Regional Technical Site Electricity Savings in 2020 over the Standard HVAC System (Case 0) for Different System Configurations for 2020 Assuming 100% Penetration

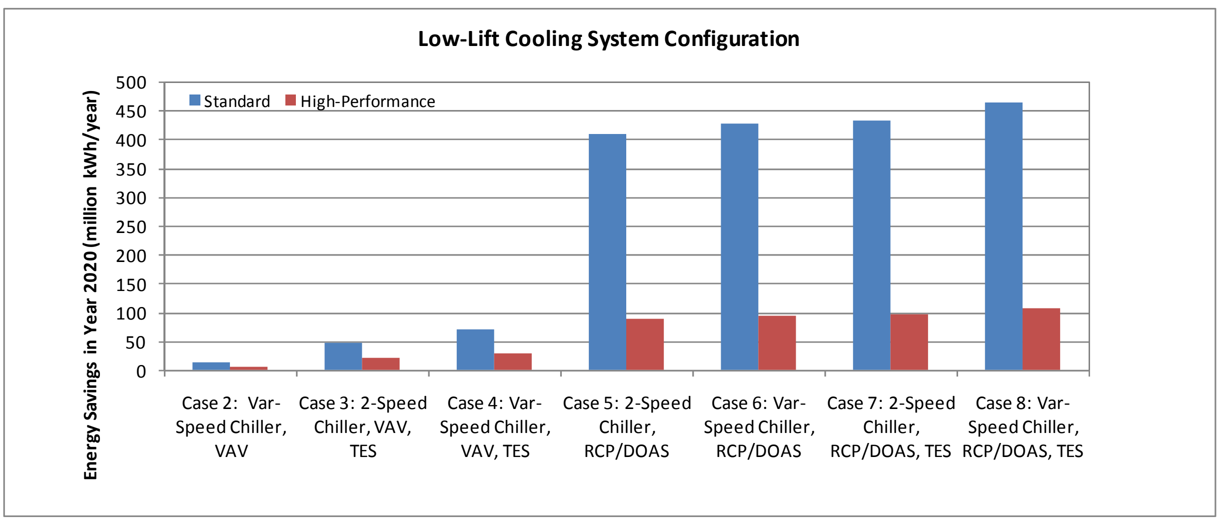

Figure 26 Pacific Northwest Regional Savings Technical Site Electricity Savings in 2020 over Case 1 for Different System Configurations for 2020 Assuming 100% Penetration

Economic Analysis

Unless the benefits (energy cost savings) are significant compared to the incremental cost of the LLCS, it is unlikely that these technologies will find widespread acceptance. Although the incremental cost estimates have some uncertainty, they provide qualitative assessment for the economics of the LLCS. NCI's incremental cost estimates are for Case 7 – variable-speed low-lift chiller, radiant cooling, and dedicated outdoor-air system with energy recovery system. Incremental cost of TES was not estimated because discrete TES is not going to be cost-effective on just energy savings alone. Unless there are significant peak demand savings, TES will not be cost-effective. A significant portion of the discrete TES savings can be captured by using passive (thermal mass of the building). Because this case (passive TES) was not analyzed for this study, the benefits from TES will not be used in studying the economics of the LLCS.

The national average incremental cost for four building types (medium office, large office, supermarket and secondary schools) was estimated to be $0, $383,000, $276,000, $624,000, respectively. Using the incremental cost and the energy savings, simple payback can be estimated. The energy savings was converted into cost savings using the typical electricity[18] (cooling and fan) and gas[19] (heating) cost for each of the regions published by the Energy Information Agency. The energy savings has two components – cooling and fan (Case 0 – Case 7) and the reheat penalty. Although there is also some demand savings, it is not included in the cost savings. Because the incremental cost savings are based on the national average, these costs have to be adjusted for each climate location. RS Means provides the city cost indices for each city, as shown in Table 30. The national cost can be multiplied by the index shown in Table 30 to get an estimate of the incremental cost in each climate location (Table 31).

The energy cost savings for the four building types in the 21 climate location is shown in Table 32. Simple payback is estimated as a ratio of the incremental cost (Table 31) and cost savings (Table 32) and reported in Table 33. Because the incremental cost of the medium office is negative, the LLCS has a zero payback. Large office and secondary school buildings have 8 to 30 year paybacks, which is probably a little bit high even for an emerging technology. Although the technology is applicable to supermarkets, it is difficult to complete with the relatively inexpensive single-zone packaged units. The aggregate payback (weighted by the new construction volume) for large office and secondary schools is reasonable, 17 and 23 years, respectively. The aggregated payback was estimated by weighting the payback periods of each location by their respective new construction volumes (see the next section of more information on new construction volumes). It appears that in the Pacific Northwest, this LLCS may not be favorable, without innovation breakthroughs in technology or provision of other incentives.

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[18]Electricity Prices: Table 5.6.A http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html (December 2009)

[19]Natural Gas Prices: http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm (December 2009)

Table 30 City Cost Index (RS Means 2009[20])

Spokane, WA	0.95
Pendleton, OR	1
Missoula, MT	0.882
Boise, ID	0.898
Pocatello, ID	0.902
Helena, MT	0.899
Astoria, OR	1
Salem, OR	1.002
Eugene, OR	0.997
North Bend, OI	1
Arcata, CA	1.07
Medford, OR	1.001
Redmond, OR	1
Portland, OR	1.01
Yakima, WA	0.98
Burns, OR	1
Olympia, WA	1.02
Quillayuta, WA	1.02
Seattle, WA	1.039
Kalispell, MT	0.882
Cut Bank, MT	0.912

[20] http://rsmeans.reedconstructiondata.com/60020.aspx (December 2009)

Table 31 Incremental Cost of the LLCS by Building Type in each Climate Location

	Medium Office	Large Office	Supermarket	Secondary School
Spokane, WA	$0	$ 363,850	$ 262,200	$ 592,800
Pendleton, OR	$0	$ 383,000	$ 276,000	$ 624,000
Missoula, MT	$0	$ 337,806	$ 243,432	$ 550,368
Boise, ID	$0	$ 343,934	$ 247,848	$ 560,352
Pocatello, ID	$0	$ 345,466	$ 248,952	$ 562,848
Helena, MT	$0	$ 344,317	$ 248,124	$ 560,976
Astoria, OR	$0	$ 383,000	$ 276,000	$ 624,000
Salem, OR	$0	$ 383,766	$ 276,552	$ 625,248
Eugene, OR	$0	$ 381,851	$ 275,172	$ 622,128
North Bend, OR	$0	$ 383,000	$ 276,000	$ 624,000
Arcata, CA	$0	$ 409,810	$ 295,320	$ 667,680
Medford, OR	$0	$ 383,383	$ 276,276	$ 624,624
Redmond, OR	$0	$ 383,000	$ 276,000	$ 624,000
Portland, OR	$0	$ 386,830	$ 278,760	$ 630,240
Yakima, WA	$0	$ 375,340	$ 270,480	$ 611,520
Burns, OR	$0	$ 383,000	$ 276,000	$ 624,000
Olympia, WA	$0	$ 390,660	$ 281,520	$ 636,480
Quillayuta, WA	$0	$ 390,660	$ 281,520	$ 636,480
Seattle, WA	$0	$ 397,937	$ 286,764	$ 648,336
Kalispell, MT	$0	$ 337,806	$ 243,432	$ 550,368
Cut Bank, MT	$0	$ 349,296	$ 251,712	$ 569,088

Table 32 Energy Cost Savings by Building Type in each Climate Location

	Office Medium	Office Large	Supermarket	Secondary School
Spokane, WA	$ 2,727	$ 36,348	$ 9,115	$ 28,773
Pendleton, OR	$ 3,706	$ 28,337	$ 9,909	$ 37,283
Missoula, MT	$ 3,275	$ 27,579	$ 14,225	$ 37,014
Boise, ID	$ 2,623	$ 24,550	$ 7,524	$ 25,869
Pocatello, ID	$ 2,434	$ 41,642	$ 10,209	$ 23,635
Helena, MT	$ 3,330	$ 44,116	$ 16,927	$ 37,957
Astoria, OR	$ 2,334	$ 17,160	$ 7,029	$ 23,394
Salem, OR	$ 3,340	$ 22,385	$ 8,305	$ 30,678
Eugene, OR	$ 3,396	$ 22,573	$ 8,209	$ 30,755
North Bend, OR	$ 2,176	$ 15,405	$ 6,844	$ 21,718
Arcata, CA	$ 2,508	$ 16,054	$ 12,235	$ 35,071
Medford, OR	$ 4,061	$ 22,283	$ 9,293	$ 37,474
Redmond, OR	$ 2,977	$ 24,615	$ 10,225	$ 31,836
Portland, OR	$ 3,259	$ 21,947	$ 8,090	$ 30,199
Yakima, WA	$ 3,207	$ 24,072	$ 8,834	$ 30,154
Burns, OR	$ 3,061	$ 29,077	$ 10,249	$ 32,885
Olympia, WA	$ 2,840	$ 20,096	$ 7,608	$ 26,158
Quillayuta, WA	$ 1,936	$ 16,066	$ 6,675	$ 21,878
Seattle, WA	$ 2,679	$ 21,526	$ 6,906	$ 25,365
Kalispell, MT	$ 2,885	$ 23,719	$ 14,190	$ 33,282
Cut Bank, MT	$ 2,658	$ 33,529	$ 16,908	$ 33,542

Table 33 Simple Payback by Building Type for each Climate Location

	Office Medium	Office Large	Supermarket	Secondary School
Spokane, WA	0	10.0	28.8	20.6
Pendleton, OR	0	13.5	27.9	16.7
Missoula, MT	0	12.2	17.1	14.9
Boise, ID	0	14.0	32.9	21.7
Pocatello, ID	0	8.3	24.4	23.8
Helena, MT	0	7.8	14.7	14.8
Astoria, OR	0	22.3	39.3	26.7
Salem, OR	0	17.1	33.3	20.4
Eugene, OR	0	16.9	33.5	20.2
North Bend, OR	0	24.9	40.3	28.7
Arcata, CA	0	25.5	24.1	19.0
Medford, OR	0	17.2	29.7	16.7
Redmond, OR	0	15.6	27.0	19.6
Portland, OR	0	17.6	34.5	20.9
Yakima, WA	0	15.6	30.6	20.3
Burns, OR	0	13.2	26.9	19.0
Olympia, WA	0	19.4	37.0	24.3
Quillayuta, WA	0	24.3	42.2	29.1
Seattle, WA	0	18.5	41.5	25.6
Kalispell, MT	0	14.2	17.2	16.5
Cut Bank, MT	0	10.4	14.9	17.0
Aggregate Payback	0	17.3	37.5	23.4

Discussion and Recommendations

Electrical power for HVAC, which in most buildings translates to electrical power for cooling (compressors and package equipment) and transport (pumps and fans), may be treated as the quotient of cooling load and cooling system efficiency. The path to *reduced cooling loads* is well understood as a matter of improving window, window-shading, and envelope performance; of recovering ventilation enthalpy and better controlling ventilation rates; of improving lighting efficiencies; and of reducing end-user equipment loads.

This analysis shows that significant *cooling system efficiency gains* can be achieved by integrating *low-lift cooling technologies*: variable-speed compressor and transport motor controls, radiant cooling with dedicated ventilation air transport and dehumidification, and cool storage. The cooling energy savings for a standard-performance building range from 47% to 84% and, for a high-performance building, from 17% to 66%.

For baseline buildings that are compliant with ASHRAE 90.1-2004, the full LLCS saves about 54 million kWh of site electricity use *in 1 year* with the full LLCS being applied to (assuming 100% penetration) a total new construction in 2010 Pacific Northwest new commercial building stock. The corresponding peak reductions are about 6.2 MW. The annual site electricity savings and peak reduction are about 15.5 million kWh and 1.8 MW, respectively for high-performance buildings. Assuming the new construction growth rates remain the same for the next 10 years (through the year 2020), the total regional technical site energy savings potential (again assuming 100% penetration) for all buildings built between 2010 and 2020 for the baseline standard would be 625 million kWh/year in 2020. To reiterate, all of these savings are in site energy terms; to calculate the "busbar" savings, the previous estimates should be multiplied by factor of 1.0725 (using the average transmission loss of 7.625%).[21] The total savings potential – relative to the baseline building – is therefore 670 million kWh in 2020.

Cooling plant savings result from efficient compressor operation at low-pressure ratios and over a wide speed range. So far, compressor and chiller performance in these regions has not been given much attention. The chiller and DX-dehumidifier equipment modeled in the analysis exhibit performance typical of existing package equipment at typical design conditions but represent a significant improvement in performance under part-load and low-lift conditions because compressor and transport motor speeds were independently controlled for optimal performance.

Low-lift operation does not benefit much from two well known, but costly and complex, measures: multi-stage compression and liquid recycle or other forms of inter-cooling. Low discharge temperature is achieved instead by low suction superheat, low internal pressure drops, large heat-transfer capacity per unit refrigerant mass flow and the external design factors—RCP, night pre-cooling, and variable-speed (VS) compressor operation—that result in low pressure ratios.

[21] Personal communication Erik Boyer, BPA.

There are significant savings from use of two-speed or variable-speed (VS) chiller for some building types that use DX systems. When compared to a two-speed chiller case (Case 1), the three low-lift technologies, when combined, result in consistently large savings in spite of wide variations in savings when applied one at a time. For example, the RCP/DOAS element alone results in average savings (for various building types, across 21 climate locations) of between 9 and 57%. A significant portion of savings attributed to RCP/DOAS is from fan energy savings. The VS chiller alone results in savings of only 0.5 to 6%, but when a VS chiller is added to HVAC configurations that already include RCP/DOAS and/or TES, the average incremental savings are slightly higher.

The variable-speed savings, when added after TES, are largest because the load shifting process results in almost all the load being shifted from a high to a low part-load operating range, where a variable-speed reciprocating chiller becomes very efficient. Even the best variable-speed centrifugal chillers start to lose efficiency below about 35% rated capacity (Conry et al. 2002). Although TES is a synergistic technology that enhances the LLCS savings, discrete TES is not a good solution because of its first cost. Use of the passive thermal mass in buildings can provide significant savings associated with discrete TES.

The proper design and integration of low-lift technologies requires careful attention to controls. Controls, in turn, can become a maintenance issue with associated loss, over time, of system efficiency. Integrated delivery of the low-lift system, similar to the approach used for variable-refrigerant-volume (VRV) DX cooling equipment, is one possible way to address both of these issues. However, for broadest market penetration, it would be preferable for manufacturers to supply integrated controls with less of a "black box" approach. A controls package with options that permit flexibility in terms of hydronic distribution—e.g., active-core, ceiling panels, or the two combined—and in the coordination of RCP and DOAS systems would be extremely desirable.

The foregoing analysis is based on the use of vapor-compression equipment for both the sensible and latent cooling loads. Similar low-lift benefits can be expected with absorption cooling plants, thermally-regenerated desiccant dehumidification equipment and direct or indirect evaporative cooling, and a vapor compression system coupled with ground source. The role of TES will generally be diminished in solar-powered cooling applications. It would be interesting, nevertheless, to compare the solar aperture area needed for a state-of-the-art solar-thermal-powered absorption and desiccant cooling system to the apertures needed by state-of-the-art photovoltaic-powered and state-of-the-art solar-thermal-turbine-powered vapor-compression systems for the standard-, mid- and high-performance building prototypes simulated in a few desert and sun-belt climates.

The market assessment indicates that the LLCS package seems to be an attractive option worthy of further research, development and deployment. The stakeholders were generally very receptive, and there did not seem to be any "deal-breakers." Stakeholders all seem to be most interested in packaged solutions, rather than individual technologies. It also appears that the timing is good, because more and more stakeholders are realizing the importance of energy efficiency and are becoming interested in green buildings. One of the most important steps moving forward will be case studies and demonstrations of benefits, including cost and energy savings.

Based on simple payback economic analysis, office buildings appear to be the most ideal first application for LLCS, particularly those using multi-zone rooftop systems medium and small office buildings. The large cost of the multi-zone rooftop systems (with respect to a similar-sized chiller) allows for a favorable cost comparison for LLCS in small/medium office buildings. Large office buildings show a low incremental cost per square foot and also reasonable payback in most climate locations, because small increases in chiller costs, and large savings from the smaller ductwork required as a result of use of the DOAS system. Radiant cooling drives the cost increment for all of the building types. A large portion of these costs is associated with the labor required for installation. Secondary (and probably primary) schools also appear to be a good target building for LLCS. It appears that in mild (Los Angeles, San Francisco and Seattle) and heating-dominated (Chicago, Minneapolis, Duluth and Fairbanks) climates, LLCS may not be favorable, unless other incentives are provided. As more buildings adopt LLCS, over time the incremental cost will decrease.

Although there could be significant cost savings from demand reductions for use of LLCS, those savings were not considered in this analysis. Because the demand rates vary significantly with different utilities, it would take a lot of effort to compute accurate demand savings. Also, the analysis did not consider any carbon tax. Assessing the impact of carbon tax on the relative economics is simple and will be considered in future work.

The analysis also clearly indicates that different (climate) regions need different sets of integrated technology solutions that are optimized for that region. While LLCS with a conventional vapor compression system may be good choice for many of the hot and humid climates, alternate low-lift cooling (evaporative, ground source) may be better suited for mild and heating-dominated climates. The primary focus of this study was cooling needs; there is also a need to look at heating technologies, such as heat pump chillers, which can be integrated with RCP/DOAS. Work for DOE next year (2010 and 2011), will include identifying both alternate low-lift cooling technologies and high-efficiency heating technologies that can be integrated with RCP/DOAS.

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A Appendix: Market Assessment Supporting Material

Questionnaire A: Survey A – Low-Lift Cooling Technologies

Date:
Interviewee:
Title:
Company:
Business Type:
Location:
Type of Buildings:
Phone:

Subject: Low-Lift Cooling Technologies for Buildings

Introduction

Hi, my name is Rakesh Radhakrishnan, calling from Navigant Consulting's Energy group. We're conducting a study on behalf of the Department of Energy Building Technologies Program focused on understanding the market that exists and could evolve for "Low-Lift" cooling technologies. These technologies are intended to help the DOE meet near term objectives of nearly 30% reduced energy consumption for buildings with the ultimate goal of being incorporated into a "net zero energy" building by 2020. Low-lift cooling technologies considered for this study could be incorporated individually or as a combination to offer a more systems type solution. The range of energy benefits for a specific building type for these technologies and technology combinations have been recently evaluated by PNNL through a series of modeling studies, which found energy benefits in the range of 2% to 75% over baseline HVAC systems. The technologies considered in this study included:

1. Peak-load shifting by means of active or passive thermal energy storage (TES)
2. Dedicated outdoor air supply with enthalpy heat recovery from exhaust air
3. Radiant heating and cooling panels or floor system
4. Low-lift vapor compression cooling equipment (variable-speed compressors, refrigerant flows etc.)
5. Advanced controls at the HVAC equipment and HVAC system (supervisory) levels

The objective of this interview is to understand some of the perceived benefits, barriers and enablers that may enhance the adoption of low-lift technologies for buildings in the future. With this focus, there are five main areas that I would like to review today:

1. How are decisions to install new HVAC equipment made?
2. What is the familiarity of the market with low-lift cooling approaches?
3. What are the barriers to market penetration for low-lift technology options?
4. What are the enablers that could enhance market penetration for low-lift and are the stakeholders aware of these drivers?
5. What paybacks are attractive for the market currently for cooling equipment? Are customers willing to pay more for energy efficiency (low-lift technologies) in the current environment?

Specific questions

1. How are decisions to install new HVAC equipment made?

a) Who makes decisions to install new HVAC equipment in a new building/retrofit?
b) What drives their decisions to install new HVAC equipment i.e., what are the key needs (new buildings versus retrofits)?

2. What is the familiarity of the market with low-lift cooling technologies?

a) How familiar are you with active/passive thermal energy storage technologies?
   i) Very familiar – worked on this before
   ii) Somewhat familiar – heard about it
   iii) Not familiar – no knowledge whatsoever

Repeat question for: Dedicated outdoor air systems with enthalpy recovery, radiant heating/cooling panels or floor system, low-lift vapor compression cooling equipment (variable speed compressors, etc.), advanced controls at the HVAC equipment and supervisory controls level.

3. What are the barriers to market penetration for low lift technology options?

Active/passive TES technologies barriers

a) Do you perceive TES as being expensive from a first cost and operating cost perspective (requires more maintenance)?
b) Do you perceive TES as a technology that does not provide sufficient energy savings to warrant adoption?
c) Do you perceive TES as being difficult to design and install in a building (requires a very large footprint)?
d) Do you anticipate any safety concerns with TES solutions?
e) Is there any other barrier that prevents larger scale adoption of TES for buildings?

DOAS+enthalpy wheel technology barriers

a) Do you perceive DOAS with an enthalpy wheel as being expensive from a first cost and operating cost perspective (requires more maintenance)?
b) Do you see zoning costs as a specific issue for DOAS systems?
c) Do you see fouling of enthalpy wheels as a major issue preventing adoption of these technologies?
d) Do you see pressure drop issues as being a major concern for enthalpy wheel based systems?
e) Do you perceive DOAS+enthalpy wheel as a technology that does not provide sufficient energy savings to warrant adoption?
f) Do you anticipate any safety concerns with DOAS+enthalpy wheel solutions?
g) Is there any other barrier that prevents larger scale adoption of DOAS+enthalpy wheels for buildings?

Radiant heating/cooling technologies barriers

a) Do you perceive radiant panels as being expensive from a first cost and operating cost perspective (requires more maintenance)?
b) Do you see the architectural implications of installing radiant heating/cooling as being a significant issue?
c) Do you see condensation issues with radiant panels as being a significant issue preventing technology adoption?
d) Do you perceive radiant panels as a technology that does not provide sufficient energy savings to warrant adoption?
e) Do you anticipate any safety concerns with radiant panel solutions?
f) Is there any other barrier that prevents larger scale adoption of radiant panels for buildings?

Low-lift vapor compression technologies barriers

a) Do you perceive variable-speed chillers as being expensive from a first cost and operating cost perspective (requires more maintenance)?
b) Do you see refrigerant leaks as being a significant issue in variable-speed machines?
c) Do you see the lack of a brand name (e.g., Daikin, Carrier etc.) offering as being a significant market barrier preventing adoption of variable-speed chillers?
d) Do you perceive variable-speed chillers as a technology that does not provide sufficient energy savings to warrant adoption?
e) Do you anticipate any safety concerns with variable-speed chillers?
f) Is there any other barrier that prevents larger scale adoption of variable-speed chillers for buildings?

Advanced controls technology barriers

a) Do you perceive advanced HVAC controls as being expensive from a first cost and operating cost perspective (requires more maintenance)?
b) Do you see a lack of understanding of controls technology and its benefits as being a significant market barrier preventing the adoption of this technology?
c) Do you see complexity in implementing advanced control designs as being a significant market barrier preventing the adoption of this technology?
d) Do you see the lack of trained personnel and complicated troubleshooting protocols as being a major issue preventing adoption of advanced control technologies in HVAC systems?
e) Do you anticipate any safety concerns with advanced control technologies?
f) Is there any other barrier that prevents larger scale adoption of advanced controls for building HVAC systems?

4. What are the enablers that could enhance market penetration for low lift and are the stakeholders aware of these drivers?

i. Energy efficiency and/or LEED awareness
ii. Climate change awareness
iii. U.S. government push towards energy efficiency for federal buildings
iv. Other?

4. What paybacks are attractive for the market currently for cooling equipment? Are customers willing to pay more for energy efficiency (low-lift technologies) in the current environment?

5. Is there any question that you expected me to ask that I did not?

Questionnaire B: Survey A – Low-Lift Cooling Technologies

Date:
Interviewee:
Title:
Company:
Business Type:
Location:
Type of Buildings:
Phone:

Subject: Low Lift Cooling Technologies for Buildings

(INTRO SECTION BELOW CAN BE SOMETHING THAT IS DISCUSSED WITH AN AUDIENCE IN PRESENTATION FORMAT BEFORE HANDING OFF THE SURVEY)

Introduction

We're conducting a study on behalf of the Department of Energy Building Technologies Program focused on understanding the market that exists and could evolve for "Low-Lift" cooling technologies. These technologies are intended to help the DOE meet near term objectives of nearly 30% reduced energy consumption for buildings with the ultimate goal of being incorporated into a "net zero energy" building by 2020. Low-lift cooling technologies considered for this study could be incorporated individually or as a combination to offer a more systems type solution. The range of energy benefits for a specific building type for these technologies and technology combinations have been recently evaluated by PNNL through a series of modeling studies, which found energy benefits in the range of 2% to 75% over baseline HVAC systems. The technologies considered in this study included:

1. Peak-load shifting by means of active or passive thermal energy storage (TES)
2. Dedicated outdoor air supply with enthalpy heat recovery from exhaust air
3. Radiant heating and cooling panels or floor system
4. Low-lift vapor compression cooling equipment (variable-speed compressors, refrigerant flows etc.)
5. Advanced controls at the HVAC equipment and HVAC system (supervisory) levels

The objective of this interview is to understand some of the perceived benefits, barriers and enablers that may enhance the adoption of low-lift technologies for buildings in the future. With this focus, there are five main areas that I would like to review today:

6. How are decisions to install new HVAC equipment made?
7. What is the familiarity of the market with low-lift cooling approaches?
8. What are the barriers to market penetration for low-lift technology options?
9. What are the enablers that could enhance market penetration for low lift and are the stakeholders aware of these drivers?
10. What paybacks are attractive for the market currently for cooling equipment? Are customers willing to pay more for energy efficiency (low-lift technologies) in the current environment?

LOW-LIFT COOLING TECHNOLOGIES SURVEY

1) **Please assign your relative familiarity to each of the technologies presented based on the scale shown below.**

Familiar – Some of our facilities currently use this technology or are considering using it.
Somewhat Familiar – We've heard of this type of technology being applied elsewhere.
Not familiar – First time we are hearing about this technology.

Technology	Familiar	Somewhat Familiar	Not familiar
Low-Lift Cooling			
Radiant Cooling/Heating			
Thermal Energy Storage (Passive – Building materials)			
Thermal Energy Storage (Active – Tank)			
Dedicated Outdoor Air Supply with Enthalpy Wheels			
Variable-Speed / Capacity Chillers			
Advanced Controls			

2) Please check boxes that apply as potential benefits when adopting these technologies.

Energy Efficiency – Technology provides net energy savings.
First Cost Savings – Technology could provide first cost savings from downsizing other equipment in the building (e.g., smaller HVAC).
Operational Cost Savings – Technology is easy to maintain or provides features that enable monitoring health of equipment to extend life before critical failures emerge.

Technology	Energy Efficiency	First Cost Savings	Operational Costs Savings	Other (please comment below)
Low-Lift Cooling				
Radiant Cooling/Heating				
Thermal Energy Storage (Passive – Building materials)				
Thermal Energy Storage (Active – Tank)				
Dedicated Outdoor Air Supply with Enthalpy Wheels				
Variable-Speed / Capacity Chillers				
Advanced Controls				

(Please include technology name and a brief sentence on other benefits in space provided below)

3) Please check boxes that apply as potential barriers to adopting these technologies.

High First Cost – Technology is too expensive to implement currently in new construction.
Complexity – Technology is too complex to implement in new construction today.
Inadequate Energy Savings – Technology does not or may not provide sufficient energy savings to warrant adoption.

Technology	**High First Cost**	**Complexity**	**Inadequate energy savings**	**Other issues (please comment below)**
Low-Lift Cooling				
Radiant Cooling/Heating				
Thermal Energy Storage (Passive – Building material)				
Thermal Energy Storage (Active – Tank)				
Dedicated Outdoor Air Supply with Enthalpy Wheels				
Variable-Speed / Capacity Chillers				
Advanced Controls				

(Please include technology name and a brief sentence on other benefits in space provided below)

4) **Please check boxes that apply as potential enablers that will facilitate adoption of these technologies over the next 15 years.**

LEED/ASHRAE standards – Emerging green building standards will enhance adoption of the technology.
Climate change – Awareness of climate change issues will enhance the adoption of the technology.
Technology maturation – Technology improvements will drive down costs and increase market penetration for the technology.
Government legislation – Government legislation and/or subsidies will enable adoption of the technology

Technology	LEED ASHRAE	Climate change	Technology maturation	Government legislation	Other issues (please comment below)
Low-Lift Cooling					
Radiant Cooling/Heating					
Thermal Energy Storage (Passive – Building material)					
Thermal Energy Storage (Active – Tank)					
Dedicated Outdoor Air Supply with Enthalpy Wheels					
Variable-Speed / Capacity Chillers					
Advanced Controls					

(Please include technology name and a brief sentence on other benefits in space provided below)

Efficient Low Lift Base-Load Cooling Equipment

Evaluation of Regional Market Barriers and Recommendations for Increasing Market Acceptance in the Pacific Northwest

Final Presentation to:

Pacific Northwest National Laboratory and Bonneville Power Administration

October 20, 2009

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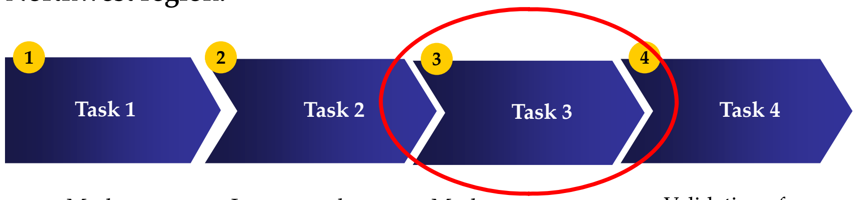
Overview » Introduction

NCI has reviewed the market potential and incremental cost of low lift base-load cooling (LLC) technology nationally and in the Pacific Northwest region.



Task 1	Task 2	Task 3	Task 4
Market assessment of cost effective integration of low lift cooling technologies in the US	Incremental cost estimate for implementing low lift cooling systems in buildings	Market assessment of attractiveness, barriers and issues for low lift cooling in the new construction market in the Pacific Northwest	Validation of incremental costs through discussions with HVAC component manufacturers

This report focuses on Task 3 of the market assessment for LLC equipment.

2

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Overview » Low-Lift System Description

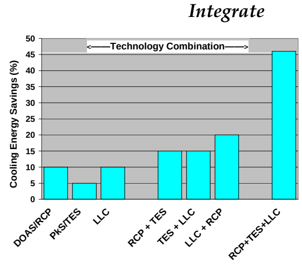
Start with

Peak-Shifting (PS) by Cooling at Night
- Proven demand savings technology
- Use Building Mass or Thermal Energy Storage (TES)
- Improves chiller load factor; milder conditions

Add

Radiant Cooling Panels (RCP) and Dedicated Outside Air Supply (DOAS)
- Emerging Technology - Popular in Europe
- 60°F Panels provide "cool" instead of 50°F air
- DOAS with enthalpy recovery for fresh air
- Eliminates wasteful reheat; reduces fan power

Integrate



Low-Lift Vapor Compression Cooling Equipment (LLC)
- Technology to be developed for small/medium buildings
- Designed for efficient part-load and low-lift operation due to variable speed compressors
- Converts the favorable *Exergy* properties of DOAS/RCP and Peak-Shifting/TES into *Energy* savings

Objective Sum of Energy Savings Greater than its Parts …Plus Comfort and Control Benefits

3

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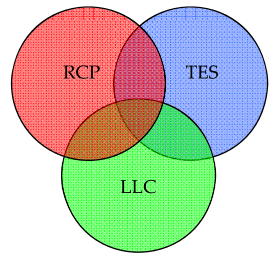
These three technologies achieve higher efficiency when used in combination and are best suited for new building applications.

- **Radiant Cooling Panels (RCP)**
  - Zone control without wasteful reheat
  - 55-60°F chilled water temperature
  - Eliminate 80% of fan transport energy
  - Increase water-side free-cooling capacity & hrs/yr
- **Peak-Shifting/TES**
  - Reduce condensing temperature 10-20F
  - Reduce peak and median load on chiller
  - Increase annual free-cooling load fraction
- **Low-Lift Cooling Equipment (LCC)**
  - Design for efficient part-load, low-lift operation
  - Good match for RCP
  - Good match for TES
  - Can be packaged for small-medium buildings



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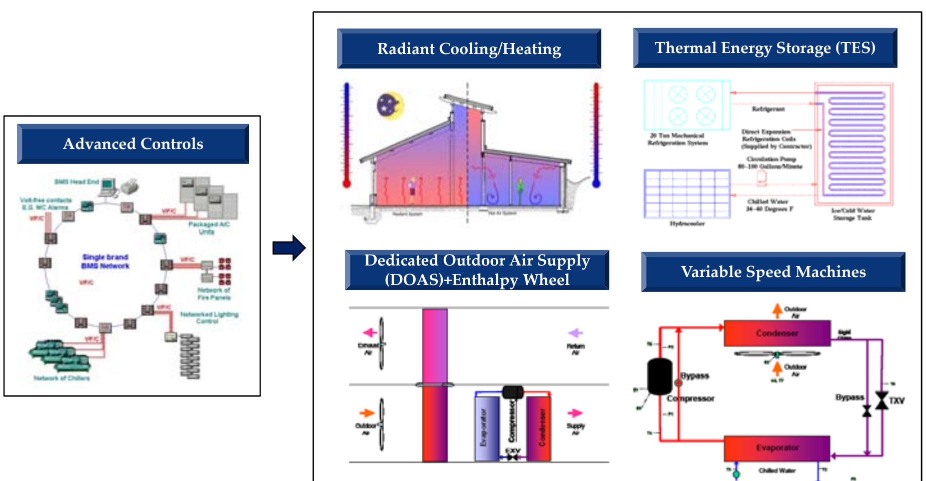
Low lift cooling requires a customized building design and reduces energy by combining HVAC technologies and advanced controls.



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For task 3, NCI assessed market potential and barriers on low lift cooling technology in the Pacific Northwest region.

Low Lift Base-Load Cooling Technology in the Pacific Northwest Market over the next 20 years.

Assess Potential and Identify Market Barriers for Technology

- Conduct research
- Interview stakeholders

Recommendations for Increasing Market Acceptance

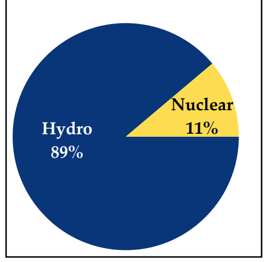
- Synthesize stakeholder feedback
- Summarize recommendations

Bonneville Power Administration (BPA) is a federal agency that generates and sells wholesale electricity in the Pacific Northwest .

BPA Territory in the Pacific Northwest

- As part of its responsibilities, BPA promotes energy efficiency, renewable resources, and new technologies
- While BPA's energy rates tend to be low and fairly constant across its territory, regional utilities that purchase BPA electricity vary rates depending on local taxes and measures

BPA 2008 Average Resource Mix (8,549 MW)

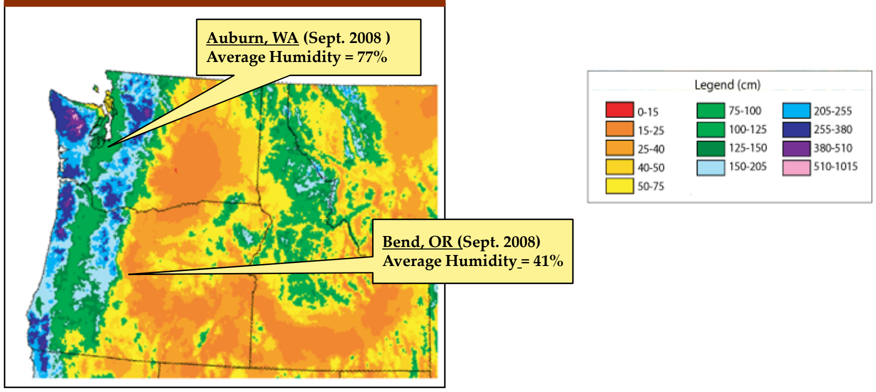


- BPA markets wholesale electric power from hydro and nuclear facilities to publicly and investor-owned utilities
- Due to its resource mix, efficiency measures in BPA territory have a smaller impact on greenhouse gas emissions relative to other parts of the US with higher emission rates

Sources: 2008 BPA Fact Sheet; BPA Website

Climate variation such as fluctuations in humidity across regions in the Pacific Northwest make the impact of the LLC concept variable.

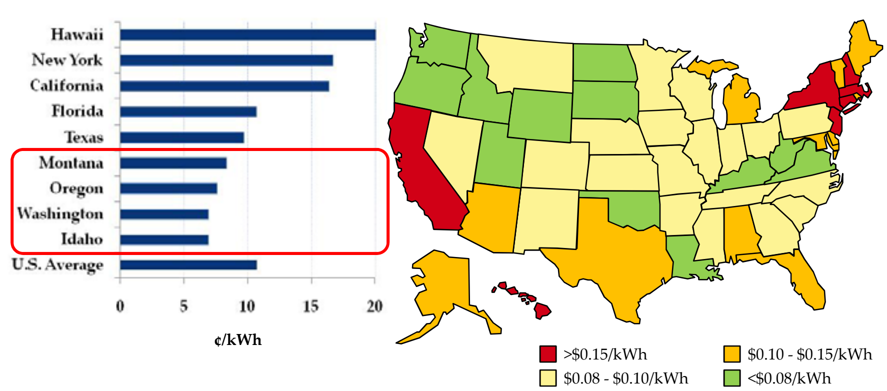
Pacific Northwest Average Annual Precipitation (1961-1990)



Sources: Oregon Climate Service (Oregon State University); Bend, OR and Auburn WA Weather Stations

The Pacific Northwest has significantly lower average electricity costs relative to other regions of the US.

State-Average Commercial Electricity Rates in the United States, July 2009



Source: EIA Retail Price of Electricity

Oregon and Washington are likely the best markets in the Pacific Northwest for Low Lift Cooling but these lag behind others in the US.

State Rankings for Key Market Attributes Associated with Low Lift Cooling Applications				
State	**Energy Costs**	**Energy Efficiency Program Support**	**Cooling Demand**	**CO_2 Emissions from Electricity**
California	●	●	⊙	⊙
Idaho	○	⊙	○	○
Montana	○	○	○	○
New York	●	●	⊙	⊙
Oregon	○	●	○	○
Texas	⊙	⊙	●	●
Washington	○	●	○	○
Sources	EIA Retail Price of Electricity	ACEEE 2008 State Energy Efficiency Scorecard	Weather Map	EIA State Energy Profiles

Low ○ Medium ⊙ High ●

The technology options under consideration improve energy efficiency and offer various market and technical benefits.

Low Lift Technology Options Benefits		
Technology	**Market Benefit**	**Technical Benefit**
Advanced Controls	Allows for occupancy based optimization of energy consumption in building which results in savings and also helps in diagnostics and prognostics to help defer major O&M costs.	Ability to monitor health of the equipment and performance of the building HVAC system critical in avoiding future technical problems in the building, e.g., maintenance and comfort issues.
Variable Capacity Chillers	Allows for actively managing building energy consumption that results in energy and cost savings for customer.	System is managed at low lift conditions with chilled water temperatures at ~60 °F.
Dedicated Outdoor Air System (DOAS) + Enthalpy Wheel	Allows for better humidity control, comfort and IEQ for building occupants.	Active humidity control can help in separating sensible load and latent load handling which reduces "high lift" operation of other HVAC equipment.
Thermal energy storage (TES)	Facilitating load shifting from off peak to peak hours in places with large differences between day time and night time rates can result in energy cost savings.	Ability to actively manage loads with other HVAC systems in the building based on demand changes that are driven by occupancy and weather conditions.
Radiant cooling/heating	Ability to downsize HVAC equipment and defer first costs in new construction.	Integration possibilities with existing water/steam lines.

Various barriers have prevented low lift technologies from achieving higher market penetrations to date.

Low Lift Technology Options Barriers		
Technology	**Market Barriers**	**Technical Barriers**
Variable Speed Chillers	Expensive equipment and limited familiarity among operators and contractors because few major HVAC suppliers provide variable speed compressors and their product range is limited.	Requires sophisticated programming and variable speed equipment that has limited availability.
Advanced Controls	Lack of trained, computer savvy operators. User resistance to advanced controls, no manager wants to deal with complex operation.	Complexity in implementation.
Dedicated Outdoor Air System (DOAS) + Enthalpy Wheel	Not suited for retrofits (outside of roof top units) in most cases because it requires additional ducting. Need co-located supply and exhaust.	Ductwork needs to be modified to take advantage of energy recovery configuration.
Thermal energy storage (TES)	Space constraints exist in many applications. Similar issues as radiant cooling/heating for large tank storage systems. Unproven technologies such as paraffins that could be incorporated into insulating materials may have fire code compliance issues. Historical reliability issues. Economics dependent on night/day differential electricity rates.	Space constraint and need for additional controls.
Radiant cooling/heating	Requires early engagement between architect and engineer for new construction due to footprint and/or construction requirements. Difficult and costly for retrofits. Must be combined with other systems. May be difficult to implement in high humidity climates. Not hearing HVAC equipment may cause some occupants to wonder if it is operating properly. Also, initial failures have discouraged adoption.	Condensation problems often reported with radiant cooling panels in humid climates, so careful engineering is necessary. Lack of forced convective mixing may be a problem in achieving optimal temperatures. Requires additional controls to ensure that building envelope is appropriately controlled.

NCI interviewed 11 stakeholders with a variety of backgrounds and experience working in the Pacific Northwest.

Interviewee List		
Stakeholder	**Office Location(s)**	**Organization, Position**
Architect	Montana	CTA Architect, Architect
	Washington	CTA Architect, Architect
Building Owner	Oregon	State of Oregon, DAS Sustainability Coordinator
	Washington	General Services Administration, Regional Energy Manager
Energy Service Provider	Washington	JCI, Service Branch Manager
LEED and HVAC Engineers/Consultants	Oregon	Glumac, Principal Engineer
	Oregon	PAE Consulting, Consultant
	Washington	Coffman Engineers, Mechanical Engineer
	Washington and Oregon	Interface Engineering, Principal Engineer
Utility Representative	Oregon	BPA, Mechanical Engineer
	Oregon	Eugene Water & Electric Board, Staff Engineer

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The impact of various low lift cooling elements will vary due to regional micro-climates local customer acceptance.

Low Lift Technology Options – Customer Acceptance Level in the Pacific Northwest Region	
Technology	**Customer Acceptance Level**
Variable Capacity Chillers	High – Industry is moving in this direction and there is a need to migrate designs into large size chillers.
Advanced Controls	Medium/High – Significant opportunity exists in coupling systems to achieve higher efficiencies. Requires better user interfaces and must focus on enabling diagnostics and prognostics of the full HVAC system (supervisory level). Requires better training for operators and other users.
Dedicated Outdoor Air System (DOAS) + Enthalpy Wheel	Medium– Humidity is not a major concern in many parts of the Pacific Northwest, and temperate climate in both winter and summer reduces ERV benefit. More product offerings of this type entering the marketplace but there is limited awareness and regional specific field data on the units.
Thermal energy storage (TES)	Medium – Limited time-of-use rates offered by utilities in the BPA region lengthen paybacks for this technology, but that could change if TOU pricing becomes more widespread. However, with nuclear and hydro resources, TOU pricing may be less critical Also, requires significant technology improvements and implementing this as an integrated solution with radiant cooling and low lift cooling options to further demonstrate benefits is required.
Radiant cooling/heating	Low/Medium – Short cooling season limits cooling applications. Requires significant improvement in implementer and consumer awareness. Also, initial failures with technology have discouraged adoption.

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Validate Barriers » Interview Results –Major Barriers by Stakeholder

Stakeholders consistently identified three general barriers preventing higher adoption of low lift cooling technology.

Major Barriers Identified by Stakeholder Type			
Stakeholder	Low Energy Costs in the Pacific Northwest	Regional Climate	Lack of Experience with Technology
Architects	✓		✓
Building Owners	✓		✓
Energy Service Provider	✓	✓	✓
LEED and HVAC Engineers/Consultants	✓	✓	✓
Utility Representatives	✓	✓	✓

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Validate Barriers » Interview Results – Potential Solutions

Significant regional barriers to low lift equipment exist, but can potentially be overcome with properly designed measures.

Major Regional Barrier	Potential Solutions
Inexpensive and clean energy • Low energy costs lengthen payback period of efficiency improvements • Time-of-use pricing is not currently common • Low carbon emission rates	**Targeted Incentives** • Offer additional state and utility incentives for this technology that target institutional facilities and regions with higher energy rates (e.g. government facilities in larger cities like Portland)
Regional Climate • Short cooling season • Micro-climates and variable humidity levels depending on region	**Customized System Configurations** • Offer customized applications (e.g. optional enthalpy wheel for humidity control) • Combine cooling technology with heating applications to improve equipment payback • Make enthalpy wheel and radiant cooling optional
Lack of Experience with Technology • Building owners and contractors are risk adverse to being an early adopter • Lack of awareness with performance, installation, and O&M requirements	**Informational Program and Resources** • Publish results of regional case studies tracking long-term performance • Develop public database of local installations with performance data • Offer complimentary feasibility studies

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The acceptance of low lift cooling technology in the Pacific Northwest could be impeded by low electricity costs and CO_2 emissions, but the market has some early adopters and is a strong market for LEED and other green buildings, which could enhance the adoption potential.

Conclusions
• Low energy costs and the short cooling season in the Pacific Northwest lengthen payback of low lift cooling technology. • Institutional customers (e.g. government buildings) are more accepting of longer energy efficiency paybacks (≤ 10 yrs) than private sector facilities (≤ 3 yrs). • Site constraints and regional climates limit the potential for thermal energy storage and radiant cooling technologies. • In areas with high acceptance of LEED standards, there is sufficient communication between architects and engineers in the early planning stages of building energy systems • There is generally a lack of understanding and local experience with the technology.

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An effective program administered by BPA would provide educational information on the technology and target customers with the highest value proposition.

Recommendations
• Evaluate and focus on market segments where technology has the highest value proposition such as government and other institutional facilities that are more accepting of technologies with longer paybacks. • Target regions with higher electricity rates, high cooling demand, and a track-record for support of energy efficiency and green buildings. • Offer some customization of systems to accommodate micro-climates (e.g. exclude radiant cooling system or provide optional enthalpy wheel to control humidity). • Develop and publish informational resources with lessons learned from local case-studies to increase understanding of the technology. • Implement effective training practices and resources for engineers and contractors in target regions and markets.

While low lift cooling technology is new to most utilities, a variety of energy efficiency programs for HVAC equipment exist.

Utility/ Agency	Program Type	Program Description
Avista, Pacific Gas & Electric, and Southern California Edison	HVAC Efficiency Program	• Administered by Portland Energy Conservation, Inc. (PECI) to offer a comprehensive HVAC efficiency program designed to small and medium-sized commercial customers. • Program targets contractors with training, tools, quality control and incentives for new and existing rooftop units.
Portland General Electric (PGE)	Building Performance Incentives and HVAC Equipment Rebates	• Partners with the Energy Trust of Oregon to offer energy efficiency informational classes to the public and rebates for efficient AC systems (based on SEER rating), chillers, and demand control ventilation. • Offers up to $500,000 per project for newly constructed buildings based on commissioning results ($0.10 per kilowatt hour and $0.80 per therm for the project's first year annual savings)
Bonneville Power Administration (BPA)	Energy Smart and Performance Tested Comfort System (PTCS)	• The EnergySmart Program cofunded by BPA and local utilities provides customers with energy audits and information about efficient technology, operations, and management that illuminate the possibilities and impacts of increasing efficiency. • BPA partnered with Ecos Consulting to administer the PTCS to ensure new HVAC equipment is properly sized, installed and charged.

Sources: http://www.aircare-plus.com/ ; http://www.aircare-plus.com/ ; http://www.bpa.gov/energy/n/projects/

Once the technology matures, an effective incentive program would target customers with highest value proposition.

Program Design	Expected Impact
Evaluate and focus on market segments where technology has highest value proposition	• **Provide tailored efficiency and economic analysis of technology for specific market sectors (e.g. institutional facilities or office buildings)**
Assign appropriate program point of contact or 3rd party that can interface with customers and answer broad scope of policy, technical, and economic questions	• **Avoid confusion and waiting time associated with main customer service hotline**
Establish clear , well-documented, and simple incentive application procedures	• **Facilitate and streamlines adoption by interested customers**
Implement effective training practices and resources for engineers and contractors that target specified market segments	• **Increase understanding and awareness in specific market sectors**

Appendix » Sources

Sources:

1. EIA State Energy Profiles--http://tonto.eia.doe.gov/state/index.cfm
2. ACEEE 2008 State Energy Efficiency Scorecard--http://www.aceee.org/pubs/e086_es.pdf
3. EIA Retail Price of Electricity--
   http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html
4. Oregon Climate Service (Oregon State University)--
   http://cses.washington.edu/cig/pnwc/pnwc.shtml
5. Bend, Oregon Weather Station:
   http://www.wunderground.com/weatherstation/WXDailyHistory.asp?ID=KORBEND33
6. Auburn, Washington Weather Station:
   http://www.wunderground.com/weatherstation/WXDailyHistory.asp?ID=KWALAKET1
7. Weather Map: Wunderground.com

Sources: Oregon Climate Service (Oregon State University); Wunderground.com

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B Appendix: Incremental Cost Supporting Material

Efficient Low Lift Base-Load Cooling Equipment

Task 2, 4 – Incremental Cost Estimation and Validation

Final Presentation to:

Pacific Northwest National Laboratory

October 30, 2009

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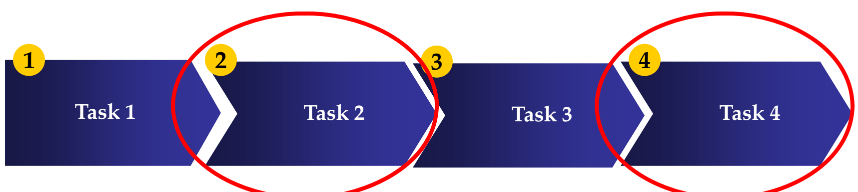
NCI has completed the incremental cost (LLC) technology nationally and in the Houston region.



Task 1	Task 2	Task 3	Task 4
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This report focuses on Task 2 of the market assessment for LLC equipment.

Low Lift Cooling Cost Estimation » Low-Lift System Description

Start with

Peak-Shifting (PS) by Cooling at Night

- Proven demand savings technology
- Use Building Mass or Thermal Energy Storage (TES)
- Improves chiller load factor; milder conditions

Add

Radiant Cooling Panels (RCP) and Dedicated Outside Air Supply (DOAS)

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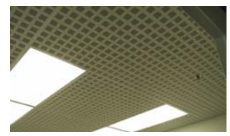
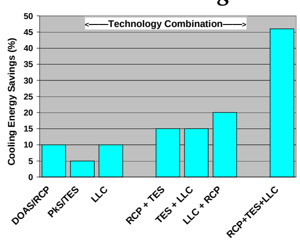


Integrate



Low-Lift Vapor Compression Cooling Equipment (LLC)

- Technology to be developed for small/medium buildings
- Designed for efficient part-load and low-lift operation due to variable speed compressors
- Converts the favorable *Exergy* properties of DOAS/RCP and Peak-Shifting/TES into *Energy* savings

Objective Sum of Energy Savings Greater than its Parts …Plus Comfort and Control Benefits

4

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Low Lift Cooling Cost Estimation » Low-Lift System Benefits

Benefits of combining three technologies are greater than its parts, and approach is ideally suited for new construction of energy efficient buildings.

- **Radiant Cooling Panels (RCP)**
  - Zone control without wasteful reheat
  - 55-60°F chilled water temperature
  - Eliminate 80% of fan transport energy
  - Increase water-side free-cooling capacity & hrs/yr
- **Peak-Shifting/TES**
  - Reduce condensing temperature 10-20F
  - Reduce peak and median load on chiller
  - Increase annual free-cooling load fraction
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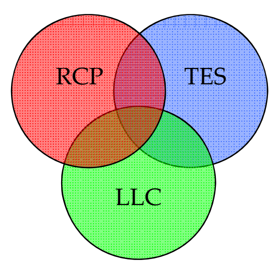
  - Good match for TES
  - Can be packaged for small-medium buildings



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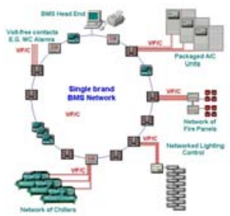
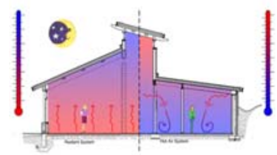
Low lift cooling uses a combination of HVAC technologies and advanced controls to reduce the energy consumption of building HVAC systems in buildings designed specifically for low-lift cooling.

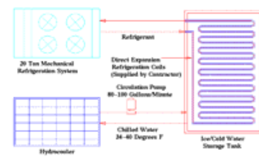
Advanced Controls



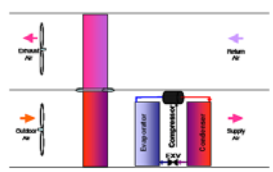
Radiant Cooling/Heating



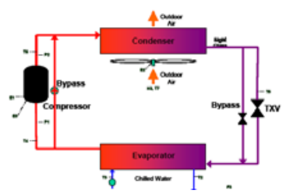
Thermal Energy Storage (TES)



Dedicated Outdoor Air Supply (DOAS)+Enthalpy Wheel



Variable Speed Machines



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As part of Task 2, NCI was tasked with calculating incremental costs for installing low-lift cooling technologies in commercial buildings.

PNNL provided:	• Energy Plus outputs with equipment sizing information for baseline cooling systems • Low-lift cooling system configurations • Low-lift cooling system sizing estimates • U.S. region to analyze

NCI product:	• Incremental costs for a set of low-lift cooling technologies • Based on commercial buildings and costs in Houston, TX

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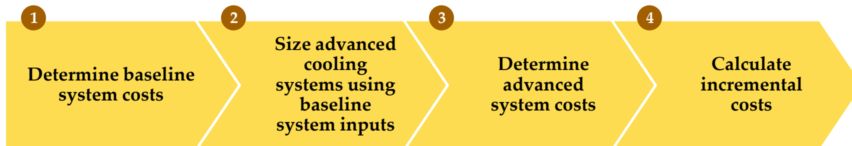
The overall methodology used by NCI to estimate incremental costs is summarized below.



Incremental low-lift cooling costs were calculated for commercial buildings specific to the city of Houston.

- HOUSTON

- Hot humid region
- 2700 CDD in 2003

** CDD data is from : http://www.climate-zone.com/climate/united-states/texas/houston/*

PNNL selected four representative commercial building types to develop incremental costs for.

Prototypical Commercial Buildings

Medium Office

Large Office

School

Supermarket

- PNNL developed baseline system specifications for each building type, specific to the Houston region.
- Each building had a different set of equipment needs and sizes.

EnergyPlus files were used to size the baseline and advanced systems for each building.

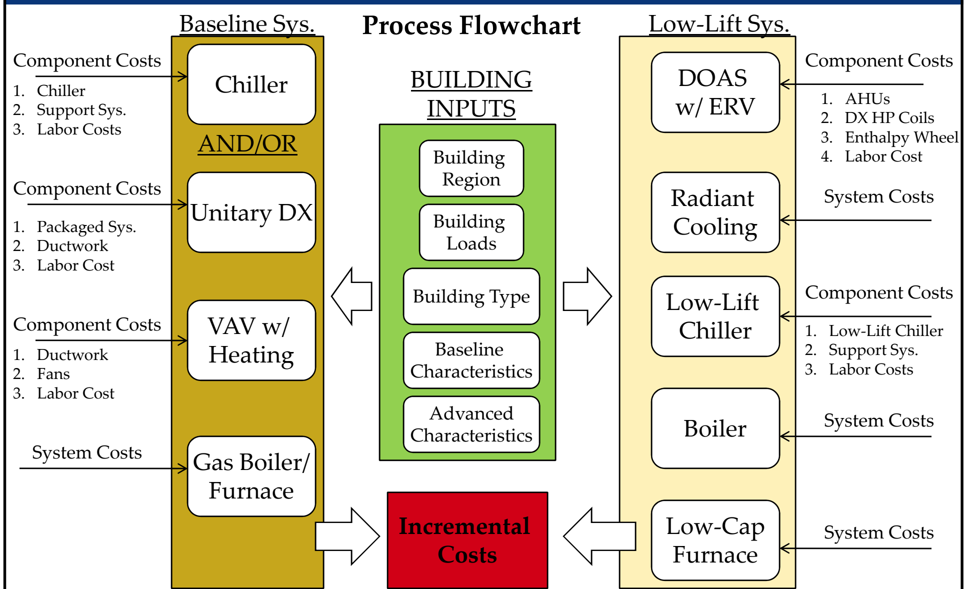
Energy Plus Output Files

→ **Equipment Types** ★
→ **Equipment Sizes** ★
→ **Component Efficiencies**
→ **Monthly Thermal Loads**
→ **Monthly Ventilation Loads**

PNNL provided Energy Plus Files for each building Type.

- NCI relied on the equipment sizes provided for each building to size the baseline system and advanced system components.

Low Lift Cooling Cost Estimation » Cost Flowchart



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Low Lift Cooling Cost Estimation » Proposed Sources for Costs

Costs for the low-lift technologies were developed from a variety of sources.

Component Cost Sources		
Component	Baseline Costs	Low-Lift Costs
Chiller, Rooftop Units	RS Means 2007	Suppliers, RS Means 2007
Boiler	RS Means 2007	RS Means 2007
Furnaces	RS Means 2007	RS Means 2007
Control System	Assumed no incremental	
Ductwork	Suppliers, RS Means 2007	Suppliers, RS Means 2007
Air-Handlers	RS Means 2007	RS Means 2007
DX HP Coils	-	RS Means 2007
Enthalpy Wheel	-	RS Means 2007
Radiant Cooling	-	Suppliers

- For the low-lift chiller costs, the cost premiums for advanced chillers were provided through suppliers, while the component costs for the chiller sizes were taken from RS Means.

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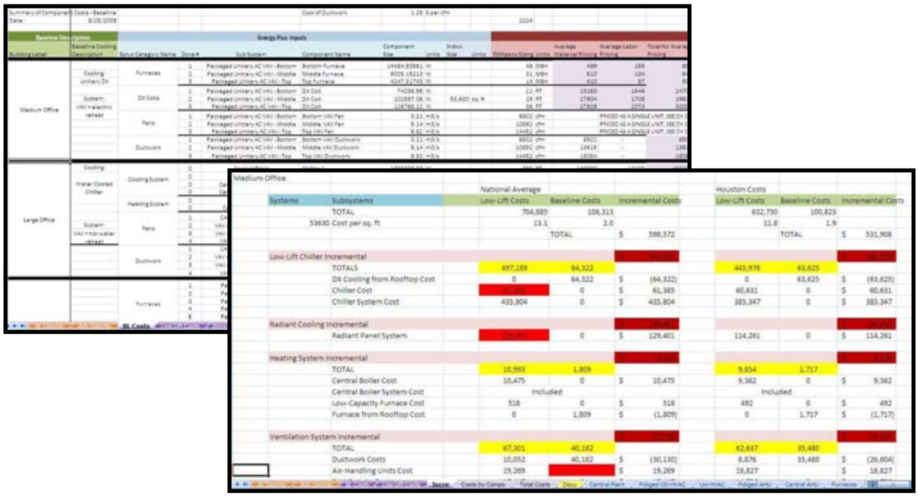
NCI developed a spreadsheet to track individual components costs and calculate incremental costs and metrics.



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The baseline system costs were calculated from RS Means using the baseline inputs provided by PNNL.

1. **Determine baseline system costs**
2. Size advanced cooling systems using baseline system inputs
3. Determine advanced system costs
4. Calculate incremental costs

1

Baseline System Costs	• Used the baseline component sizes provided in the EnergyPlus data from PNNL to determine baseline component costs. • Pulled material and labor costs from 2007 RS Means – Mechanical Cost Data book. • Ductwork material costs were calculated at $1.25 per CFM, with multipliers of 4 (single-zone) and 5 (multi-zone) to include labor costs. • Adjusted RS Means costs using regional cost indexes for the Houston area.

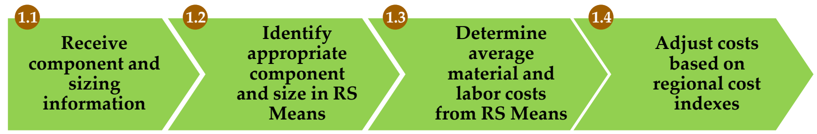
The baseline system configurations provided by PNNL are listed below.

	Baseline System Assumptions of each Building Type for the Houston Region				
	Square Footage (ft2)	HVAC Heating	HVAC Cooling	Ventilation System	Envelope – Wall
Medium Office	53,630	Gas Furnace	Unitary DX	VAV + Elec. Reheat	Steel Frame
Large Office	460,240	Gas Boiler	Water Chilled Cooler	VAV + Hot Water Reheat	Mass
Supermarket	45,000	Gas Furnace	Unitary DX	PSZ*	Mass
Secondary School	210,890	Gas Boiler	Water Chilled Cooler	VAV + Hot Water Reheat; PSZ**	Steel Frame

*PSZ – Packaged Single Zone
**PSZ in the school is used for the kitchen and gym

NCI used RS Means to determine the material and labor costs of the baseline systems.

Steps for calculating baseline costs using RS Means:



Reference - 2007 RSMeans Mechanical Cost Data

23 52	**Heating Boilers**			
23 52 23 -	Cast-Iron Boilers	…..	2007 Bare Costs	
23 52 23.20	Gas-Fired Boilers	……	Material	Labor
0010	**Gas-Fired Boilers,** Natural or propane, standard controls			
1000	Cast iron, with insulated jacket			
3000	Hot Water, gross output, 80 MBH		$1,575	$945
3020	100 MBH		$1,800	$1,025
3040	122 MBH		$1,925	$1,250
3060	163 MBH		$2,350	$1,375

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PNNL provided sizing and description of components from the EnergyPlus package.

	Equipment Specifications– EnergyPlus Baseline Information			
	Medium Office	Large Office	Supermarket	School
Building Size	53,630 sq. ft	460,240 sq. ft	45,000 sq. ft	210,890 sq. ft
Total Cooling Load	86 RT	780 RT	131 RT	985 RT
Ventilation Type	Packaged AC Unitary	VAV	Packaged Single Zone	VAV + Packaged Single Zone
Central Plant	No	Yes	No	Yes

- RT – Refrigeration Tons
- VAV – Variable Air Volume

- Notice that the size of the building is not a good predictor of the required cooling load supplied by the building's equipment.
- More information can be found in the Appendix.

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NCI selected components in RS Means based on the system descriptions provided by the files.

1.2 Identify appropriate component and size in RS Means

Medium Office

HVAC System Description

- Unitary DX Cooling
- Gas Furnace Heating
- VAV + electric reheat Ventilation

Energy Plus Description

- Packaged Air Conditioner Unitary (PACU)
- One PACU for each zone

RS Means Components

- Multizone Rooftop A/C with electric cooling, gas heating, and economizer
- Gas Fired Furnace

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NCI selected the following components in RS Means for pricing components in the baseline HVAC systems

1.2 Identify appropriate component and size in RS Means

Medium Office

RS Means Components

3 Zones – Each with:

1 Multi zone Rooftop Air Conditioner

1 Gas-fired Furnace

Large Office

RS Means Components

1 Central Plant with:

2 Centrifugal Chillers

1 Gas/Oil Fired Boiler

3 Zones – Each with:

1 Central-Station AHU with VAV

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Low Lift Cooling Cost Estimation » Identification of Components

NCI selected the following components in RS Means for the pricing of components listed in the baseline systems

1.2 Identify appropriate component and size in RS Means

Supermarket

RS Means Components

6 Zones – Each with:

1 Single Zone Rooftop Air Conditioner

School

RS Means Components

1 Central Plant:

1 Centrifugal Chillers

1 Gas/Oil Fired Boiler

3 VAV Pods – Each with:

1 Central-Station AHU

5 PSZ Zones – Each with:

1 Single Zone Rooftop Air Conditioner

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Low Lift Cooling Cost Estimation » Using RSMeans for Pricing

NCI used RS Means to determine the material and labor costs of the baseline components.

1.3 Determine average material and labor costs from RS Means

2007 RSMeans Mechanical Cost Data

23 52	**Heating Boilers**			
23 52 23 -	Cast-Iron Boilers	…..	2007 Bare Costs	
23 52 23.20	Gas-Fired Boilers	……	Material	Labor
0010	1.2 **Gas-Fired Boilers,** Natural or propane, standard controls			
1000	Cast iron, with insulated jacket			
3000	Hot Water, gross output, 80 MBH		1.3 $1,575	$945
3020	1.1 100 MBH		$1,800	$1,025
3040	122 MBH		$1,925	$1,250
3060	163 MBH		$2,350	$1,375

- After each component was properly sized and identified, RS Means was used to find the material and labor costs.
- When a component's size fell between two listed sizes, NCI interpolated based on size to find the appropriate material and labor costs.
- When a component's size was larger than the sizes provided in RS Means, NCI split the load among several smaller components, as appropriate.

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To account for regional costs, NCI used the city cost indexes found in RS Means to adjust the labor costs.

1.4 **Adjust costs based on regional cost differences**

RSMeans City Cost = RSMeans National Average Cost × City Cost Index / 100

RS Means City Cost Index Values - Houston			
Division	Materials Cost Index	Labor Cost Index	Total Cost Index
Weighted Average	101.4	71.4	88.5

- The RS Means National Average Cost is based on the 30 City Average from 2007 RS Means – Mechanical Cost Data. The 30 City Average is the average of 30 major U.S. cities. Please see 2007 RS Means – Mechanical Cost Data to view the 30 major U.S. cities used.
- NOTE: Houston is one of the cities listed.

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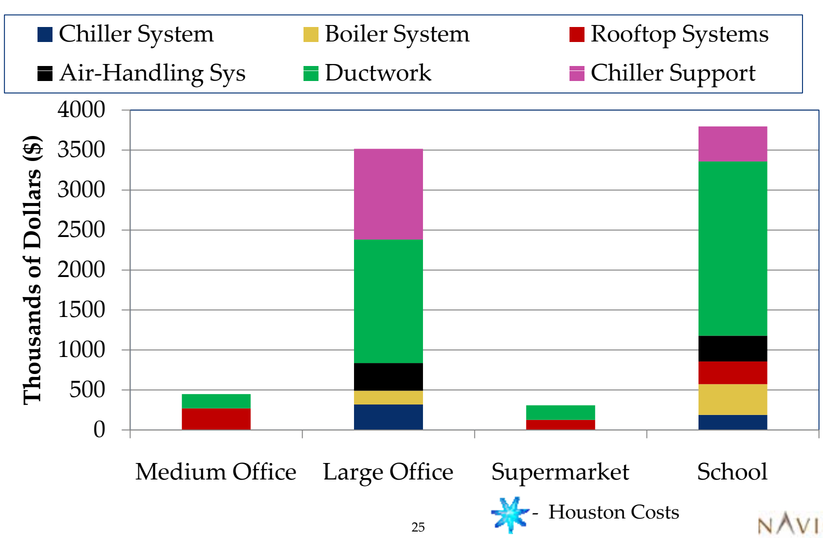
The baseline component costs show that larger buildings are significantly more expensive, because of supporting costs.



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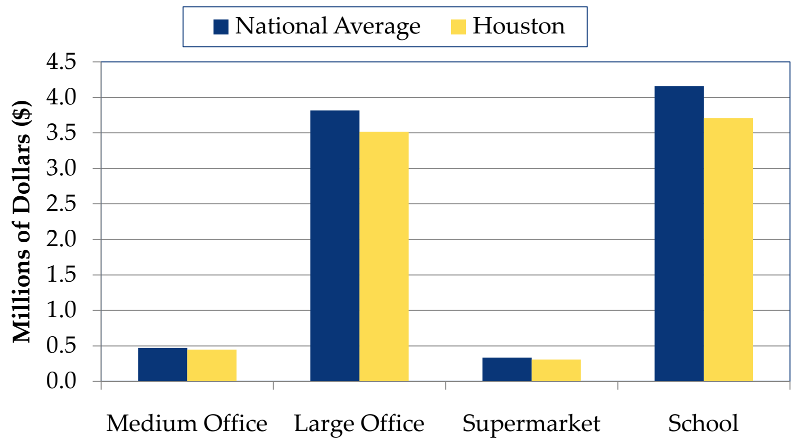
Low Lift Cooling Cost Estimation » Baseline Costs – National vs. Houston

The Houston costs were slightly lower than the national average, with savings in labor costs driving the difference.



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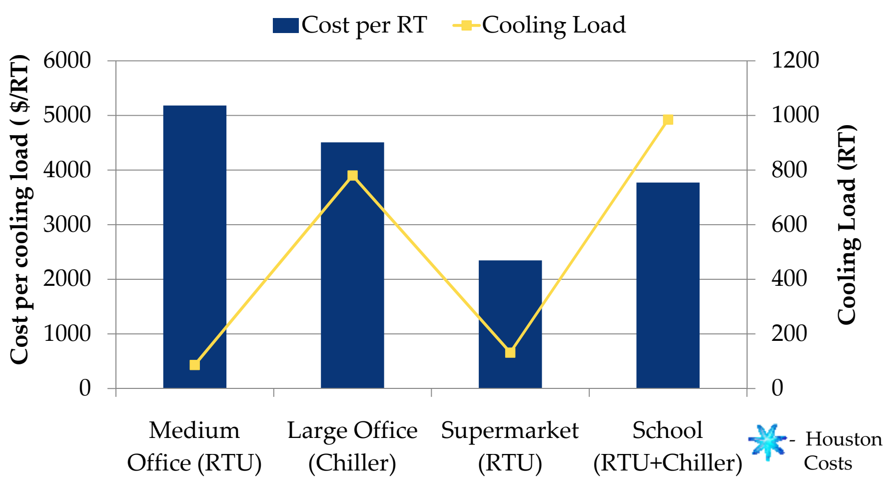
Low Lift Cooling Cost Estimation » Baseline Costs – Cost per sq. ft.

Calculating the cost per refrigeration ton allows for comparison of the cost of each system normalized by the cooling size of the building.



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The low-lift cooling systems were designed to meet the same building requirements as the baseline systems.

	Advanced System Assumptions of each Building Type for the Houston Region			
	Square Footage (ft2)	HVAC Heating	HVAC Cooling	Radiant Panel Distribution
Medium Office	53,630	Gas Boiler	Low-Lift Chiller Air Cooled DOAS w/ DX HP coil and Gas Furnace	Radiant Slab in Ceiling for Cooling
Large Office	460,240	Gas Boiler	Low-Lift Chiller Water Cooled DOAS w/ DX HP coil and Gas Furnace	Radiant Slab in Concrete for Both Heating and Cooling
Supermarket	45,000	Gas Boiler	Low-Lift Chiller Air Cooled DOAS w/ DX HP coil and Gas Furnace	Radiant Slab in Concrete for Both Heating and Cooling
Secondary School	210,890	Gas Boiler	Low-Lift Chiller Water Cooled DOAS w/ DX HP coil and Gas Furnace	Radiant Panel for Both Heating and Cooling

- Based on the requirements for each U.S. region, the low-capacity furnace used for the transitional season may not be required for every region.

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The low-lift system costs were calculated from RS Means and supplier information using the baseline inputs provided by PNNL.

1. Determine baseline system costs
2. Size advanced cooling systems using baseline system inputs
3. Determine advanced system costs
4. Calculate incremental costs

2

Low-lift cooling system sizing	• NCI used the component sizing and ventilation load information provided by PNNL for the baseline systems to size the advanced systems. • NCI sized each advanced system component separately, using the files from EnergyPlus for sizing information. • NCI relied on input from PNNL on appropriate sizing on the low-lift chiller, low-capacity furnace and the radiant cooling systems.

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NCI sized the low-lift system components using the baseline equipment sizing and EnergyPlus data.

Low-lift Cooling System – Sizing Methods

Component	Sizing Method	Pricing Source
Advanced Chiller	Sensible Cooling Load (72% of total cooling)	Suppliers
Advanced Boiler	(1) Baseline Boiler Capacity OR (2) Sum of Baseline Furnace Capacities	RS Means
Low-capacity Furnace	20% of Low-Lift Boiler Capacity	RS Means
Radiant Cooling	Sensible Cooling Load (72% of total cooling)	Suppliers
DOAS Size	Average Outdoor Air Supply Requirements	Suppliers, RS Means
DX HP Size	Baseline Latent Cooling Load (by Zone)	RS Means
Enthalpy Wheel	Low-Lift DOAS Size (by Zone)	RS Means
Concrete	Square Footage of the Radiant System	RS Means

- Information for the advanced component sizing was taken from the Energy Plus files. NCI also relied on inputs from PNNL and suppliers to size and cost the systems.
- Cost estimates derived from RS Means used the same procedure as was used for the baseline cost estimates.

NAVIGANT CONSULTING

The low-lift system costs were calculated using RS Means and inputs from suppliers, using the sizing information provided by PNNL.

1. **Determine baseline system costs**
2. **Size advanced cooling systems using baseline system inputs**
3. **Determine advanced system costs**
4. **Calculate incremental costs**

3

Low-lift cooling system costs	• Using the sizing information calculated for each advanced component, NCI determined the cost of each component.
	• NCI relied on RS Means and component vendors for cost data
	  • Assorted chiller manufacturers provided advanced chiller costs.
	  • Radiant Panel manufacturers and contractors provided cost and sizing information for radiant cooling panels.

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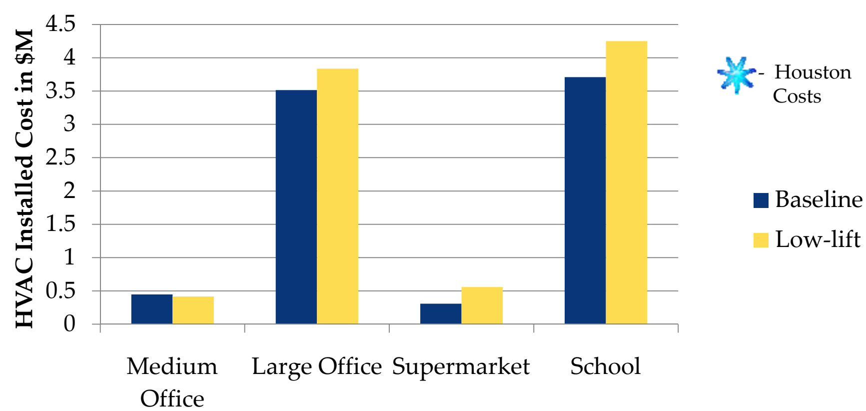
The two larger buildings experienced the largest increases in costs. The cost incremental from single-zone RTUs to a chiller system was significant (supermarket), while the cost incremental from multi-zone RTUs was very small (medium office).



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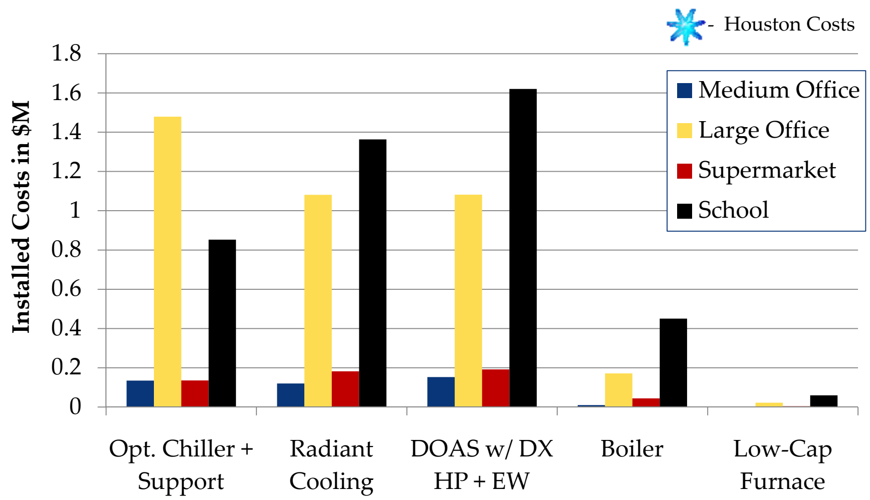
The installed costs for each component show that the chiller, radiant panel and DOAS costs account for most of the overall cost.



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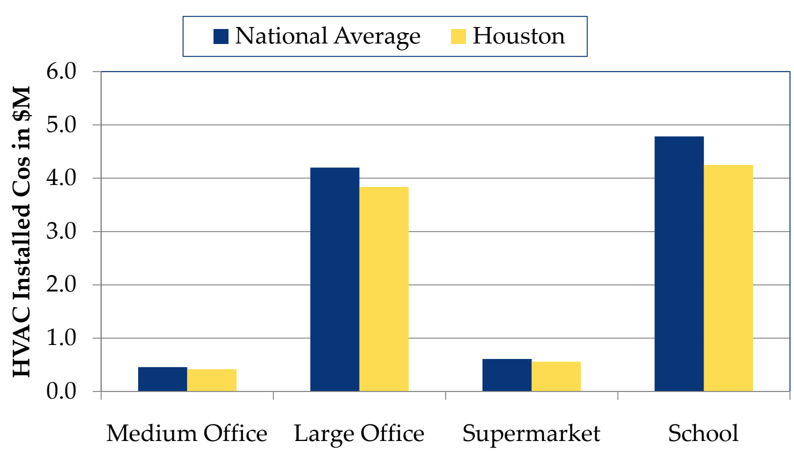
The Houston costs were slightly lower than the national average, with savings in labor costs driving the difference.



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The cost of each chiller system represents the cost of the individual chiller and the supporting system.

	Low-Lift Chiller Costs by Components for each building		
	Chiller Installed Cost	Chiller Supporting System	TOTAL Installed costs
Medium Office	$54,564	$80,071	$134,635
Large Office	$344,829	$1,134,858	$1,479,687
Supermarket	$75,447	$60,045	$135,493
Secondary School	$301,007	$551,859	$852,866

- Chiller costs include a low-lift cost premium: 15% for air-cooled, 16% for water-cooled
- Chiller supporting system costs include:
  - *For air-cooled*: Fan Coil AC unit and Chilled Water Coil Connections (D3030 110)
  - *For water-cooled:* Cooling Tower, Cooling Tower pumps and piping, chilled water unit coil connections, and Fan Coil AC unit. (D3030 115)
- More information can be found in the Appendix.

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NCI made some assumptions about the treatment of certain systems.

System	Assumption
Chiller and Boiler for the School	• The baseline system for the school used both a chiller and boiler system, and rooftop units. • For the low-lift system, NCI grew the size of the chiller and boiler systems and eliminated the rooftop units.
DOAS Systems with DX HP and EW	• The final cost of the DOAS system includes the ductwork, the DX Heat Pump Coils, and the enthalpy wheels.
Radiant Cooling Systems	• The cost for radiant cooling was assumed to be $10 per square foot, minus the cost of concrete slab installation ($2.74/S.F) requested by PNNL • Cooling capacity of the radiant system was established at 40 Btu/hr/S.F., and sized to meet the full sensible cooling load. • Suppliers did not indicate a cost difference between panel and slab methods, so no distinction was made between the two.

NAVIGANT CONSULTING

NCI made some assumptions about the treatment of certain systems.

System	Assumption
Ventilation Sizing of Low-Lift Systems	• NCI took the average of the maximum and minimum CFM requirements specified for each building through EnergyPlus, and found the cost of the low-lift DOAS system based on this average
Chiller and Boiler Plants	• NCI calculated the cost of the chiller and boiler components using the equipment sizes found in RS Means • Low-lift chillers were sized to meet the sensible cooling load of the building. • The supporting system was calculated using square foot costs calculated from RS Means data • The piping distribution system is not included in the cost, it was assumed to be included in the radiant system costs.

Low Lift Cooling Cost Estimation » Incremental Cost Summary

The baseline system costs were calculated from RS Means using the baseline inputs provided by PNNL.

1. Determine baseline system costs
2. Size advanced cooling systems using baseline system inputs
3. Determine advanced system costs
4. Calculate incremental costs

4

Incremental Costs	• Subtracting the baseline system costs from the advanced cooling costs, NCI calculated the incremental costs of each low-lift technology

Incremental Costs = Low-Lift System Component Costs - Baseline System Component Costs

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Low Lift Cooling Cost Estimation » Incremental Cost Component Separation

To compare the right set of components, systems were separated by their respective functions.

Low-Lift System

Low Lift Chiller + Support System | Radiant Cooling | DOAS: DX HP + EW + Ducts | Boiler System + Low-Cap Furnace

COMPARE TO:

Rooftop Cooling System | No Comparison | Fans + Ducts | Gas-Fired Furnace

Rooftop Air Conditioner

Rooftop Baseline System

Illustration from: http://www.aireserv.com/images/ill/PackagedUnitGas.jpg

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To compare the right set of components, systems were separated by their respective functions.

Low-Lift System

Low Lift Chiller + Support System	Radiant Cooling	DOAS: DX HP + EW + Ducts	Boiler System + Low-Cap Furnace

COMPARE TO:

Centrif. Chiller + Support System	No Comparison	Air Handling Unit + Fans + Ducts	Gas-Fired Boiler

Central Plant VAV System

Central Plant Baseline System

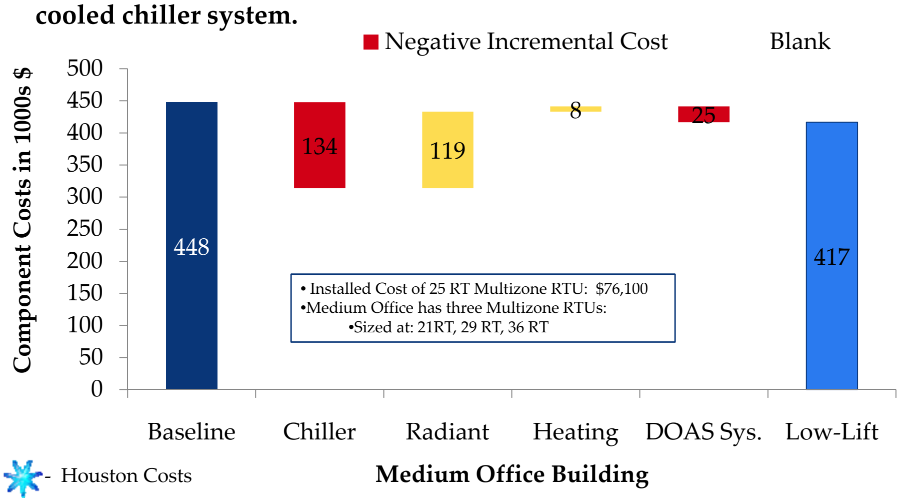
Illustration from: http://www.aireserv.com/images/ill/PackagedUnitGas.jpg

The incremental costs were calculated by comparing similar components within the baseline and low-lift systems.

	Low-Lift System	Baseline System
Low Lift Chiller Incremental	Low-Lift Chiller + Support Sys.	1. Baseline Chiller + Support System 2. Rooftop Air Conditioner - Cooling
DOAS + DX HP Incremental	DX Heat Pump + Enthalpy Wheel + Low-Lift Ductwork	Baseline Ductwork (+ any air-handling units)
Radiant Cooling Incremental	Radiant Cooling System (minus the cost of concrete)	No system for comparison
Heating System Incremental	Boiler for Low-Lift System + Low-Capacity Furnace	1. Baseline Gas Boiler 2. Rooftop Air Conditioner - Furnace

Low Lift Cooling Cost Estimation » Incremental Costs - Medium Office in Houston

The medium office building had a negative incremental cost, because of the large cost of the multi-zone rooftop units compared to the air-cooled chiller system.



- Houston Costs

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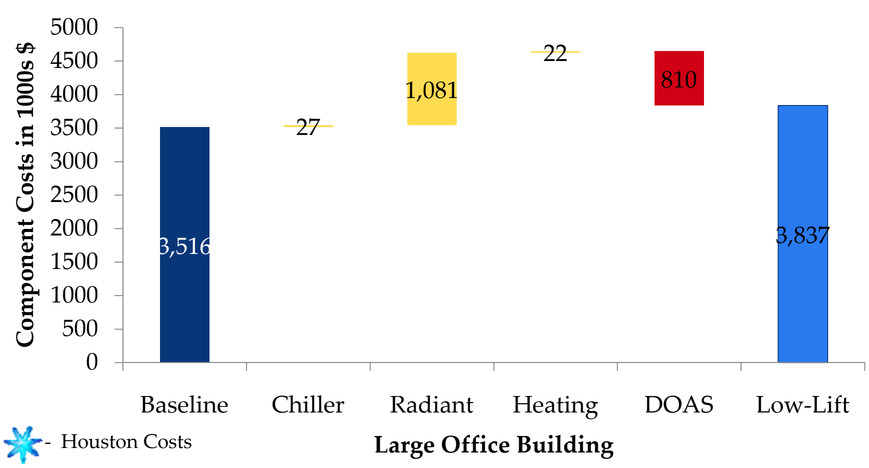
Low Lift Cooling Cost Estimation » Incremental Costs – Large Office in Houston

The large office chiller was resized to meet the sensible cooling load, offsetting the additional cost of the advanced chiller system. The radiant cooling and ductwork resizing drove the incremental costs.



- Houston Costs

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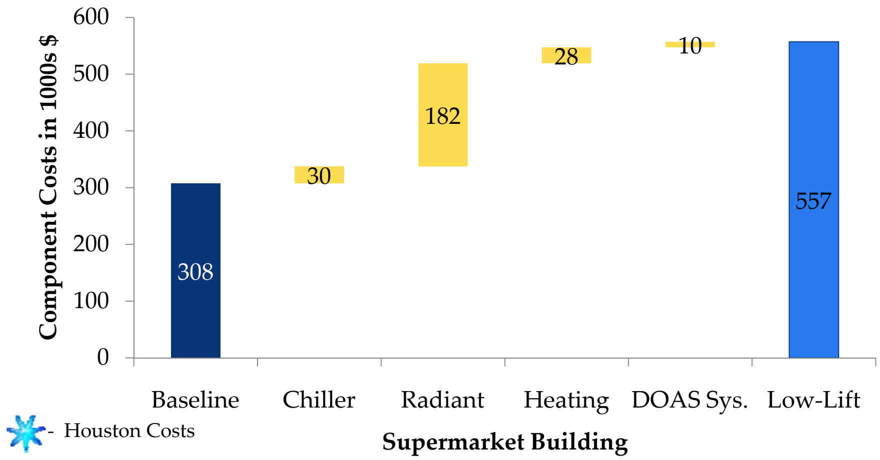
The supermarket system incremental costs are driven by the radiant cooling system. The low cost of single zone vs. multi-zone rooftops differentiates the supermarket from the medium office.



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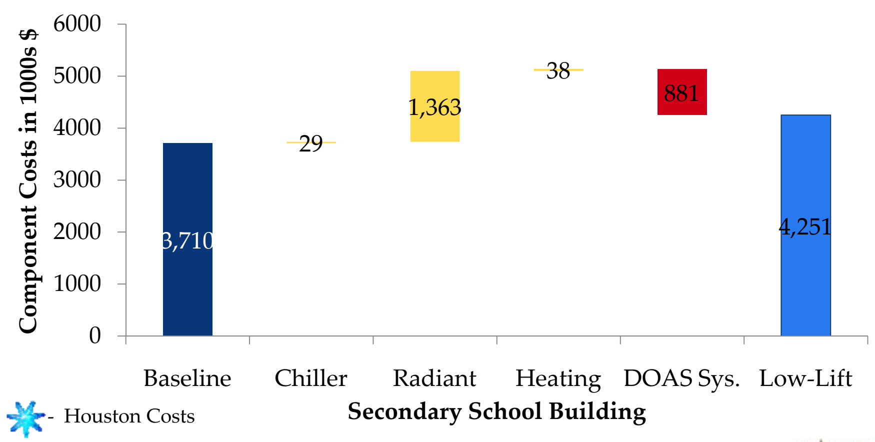
The chiller system increased in size by replacing a number of rooftop units, but was also downsized to meet the sensible cooling load only. The large radiant cooling system and the ductwork resizing drove the incremental costs.



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Incremental cost differences between Houston and national average costs are primarily driven by labor differences.

	Incremental Cost Comparisons Houston vs. National Average		
	Houston	National Average	% Difference
Medium Office	-$31,000	-$15,000	~52%
Large Office	$321,000	$383,000	~19%
Supermarket	$250,000	$276,000	~11%
Secondary School	$550,000	$624,000	~14%

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Calculating the incremental cost per square foot allows for a rough comparison between the buildings. The office buildings appear most favorable in this comparison of national average costs.

	Cost Increments per Square Foot by Building Type (HoustonCosts)		
	Total Incremental Cost	Square Feet	Incremental Cost per S.F.
Medium Office	-$31,000	53,630	-0.58
Large Office	$321,000	460,240	0.70
Supermarket	$250,000	45,000	5.55
Secondary School	$550,000	210,890	2.61

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When compared to other systems, multi-zone rooftop units are the most expensive option.

	Component Installed Cost Comparison– National Average 80 Cooling Ton Unit (RS Means)		
	RS Means Material Costs	RS Means Labor Costs	RS Means Total Installed Cost
Single Zone Rooftop	$57,500	$6,900	$64,400
Multi Zone Rooftop	$173,000	$9,850	$182,850
Reciprocating Chiller – Air-Cooled	$53,500	$5,300	$58,800

- Multizone rooftop units are significantly more expensive than single zone rooftop units or chillers sized for the same load (based on RS Means costs).
- The medium office building used multi-zone rooftop units, while the supermarket used single zone rooftop units. The result was that the medium office had very low incremental costs, while the supermarket experienced much higher incremental costs.
- The chiller costs do not including the cost of the supporting system, which includes connective piping and the fan coil air conditioning unit. NCI did not consider the cost of distributive piping in this analysis.

For the large office and secondary school, the smaller ductwork size provided a large cost reduction when moving from VAV to DOAS.

- The large office and secondary school have large airflow requirements, particularly the secondary school. Ductwork costs are therefore substantial contributors to the baseline cost of the buildings.
- The use of a DOAS system reduces the size of the ductwork, since the system is now sized by the average airflow requirements, not the maximum airflow requirements. This results in a large cost reduction.
- For the large office and the secondary school, the large size of these buildings meant that the cost of the ductwork would dominate the cost incremental for the air delivery systems. For the medium office and supermarket, the reductions in ductwork were balanced by the cost increases associated with the enthalpy wheels and the DX HP systems.

Office buildings may be the most ideal first applications for low lift cooling technologies/systems, including those using multi-zone rooftop systems or chillers.

Conclusions

- The high cost of multi-zone rooftop systems compared to chillers allows for a favorable cost comparison for low-lift chiller systems in medium office buildings.
- Large office buildings show a low incremental cost per square foot, due to a small increase in chiller costs, and large savings from the DOAS system
- Radiant cooling drives the cost incrementals for all of the building types.
- The cost advantage resulting from reduction of the ductwork for large building systems needs to be validated further, to confirm that ductwork costs dominate this comparison.
- Some components of the low-lift system may be considered emerging technologies . There is often a 10-20% cost premium associated with emerging technologies, which may decrease as the technology becomes more common.
- Other potential benefits of the low lift system include reducing the amount of materials used in construction, for example in ductwork material.

A more detailed costing exercise and associated payback/economic analysis is warranted.

Recommendations

• The component costs based approach for estimating baseline and advanced system costs is limited in scope, and only covers a portion of the total costs required for incorporation of HVAC systems into buildings. Some of the key limitations that need to be addressed include:

- Use a detailed design process to understand costs on a square footage basis (possibly by picking a candidate building that could also serve as a future test bed). This will address the current limitation where the equipment was sized by cooling load and CFMs, and not by square footage.
- The detailed design process will also help in better sizing of system components and the balance of plant equipment. This helps address the current limitation where sizing by cooling load is very effective for calculating the cost of the main components, but not as effective for finding the cost of distribution systems.
- The design process will also help in assuring that material costs are estimated more precisely (e.g. ducts, piping, valves, etc.)

• As a next step, NCI recommends proceeding through this detailed costing exercise for a candidate building, along with an associated payback/economic analysis using energy savings and electricity rate structures in various regions to assess financial attractiveness of the concept.

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The sizing of the building loads from Energy Plus is different than what is cited in RS Means.

Sizing of the Building Loads

- **NCI compared the cost per square foot of each building's baseline HVAC system to the square foot costs provided by RS Means for a number of comparable buildings. The calculated costs did not entirely match the expected costs.**
- **NCI believes that there may be some differences in the way EnergyPlus calculates the cooling loads and equipment sizes for each building, compared to the standard used in RS Means. This difference may be significant in the case of multi-zone ductwork systems.**
- **In particular, the medium office building appears to be undersized (in terms of cooling load) given its footprint. In an example office building in RS Means, a building with a footprint of 25,000 sq. ft had equipment sized to provided 80 RT. In comparison, the medium office described by EnergyPlus had a footprint of 53,000 sq. ft, and equipment sized to provided 86 RT.**

A closer analysis of the equipment sizing provided by EnergyPlus may illustrate why there are differences between the calculated square foot costs and the expected square foot costs.

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The sizing of the DOAS system is an important input for determining proper incremental costs.

Sizing of the DOAS systems

- The sizing of the DOAS system determines the cost of the ductwork and the air-handlers in the low-lift system, and this incremental cost can have a large impact on the overall incremental cost.
- NCI looked at the incremental cost of the DOAS system using the minimum outdoor airflow provided by EnergyPlus, the maximum outdoor airflow provided by EnergyPlus, and an average of the minimum and maximum.
- The DOAS system consisted of the air-handling units, the ductwork, the DX HP systems, and the enthalpy wheels. The air-handling systems, the ductwork, and the enthalpy wheels were all sized using the CFM requirements of the building, while the DX systems were sized using the latent heat requirements of the building.
- There may be savings that are not captured for buildings that use less ductwork than typical buildings, such as the supermarket.

A closer inspection of both the sizing of the DOAS system as well as the cost of ductwork within each building would improve the DOAS cost incremental.

The costs of the distribution systems for chillers were calculated using square foot costs specific to each building type.

Cost of the distribution systems

- The distribution systems for the chilled water systems were calculated using square foot costs from RS Means. They do not include distributive piping.
- While these costs are distinct for each building type and chiller type, there may be additional costs or savings that are not captured within this broad treatment.
- For example, NCI did not consider any savings associated with combining chiller, radiant cooling, and boiler piping systems.
- This issue is especially important for calculating the incremental cost of moving from a rooftop system to a chiller-based system.

A closer analysis of the distribution systems that accompany the chiller systems would enhance our understanding of the incremental costs associated with chiller cooling systems.

An economic analysis of the cost premium and associated payback for systems in large office buildings in several regions is warranted.

Systems Economic Modeling

- **Complete an analysis of large office building and associated energy consumptions for several different parts of the US for both baseline and low lift cooling systems with split done by climate zones using a single platform.**
- **Leverage work on detailed costing exercise for the candidate large office building to estimate cost premium for the different regions/cities of interest.**
- **Use hour electricity, and natural gas consumption data and local utility rates to estimate the economic value of energy savings and calculate the associated payback period.**

An economic analysis will help identify if the cost premium for low lift systems are justified and help identify candidate regions for pilot projects.

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The reference numbers for the components taken from RS Means are displayed in the table below.

2007 RS Means Reference Numbers – Cooling and Heating Components		
Component	RS Means Reference	RS Means Descriptors
Rooftop Units	23.74.33.10	1000 – Single Zone, Elec. Cool, Gas Heat 2000 – Multi Zone, Elec. Cool , GH, econ.
Chillers	23 64 16.10 23 64 19.10	0274 – Centrifugal, pckd unit, water cooled, ni tower 0494 – Water chillers, integral air cooled condenser
Boilers	D3020 136 D3020 130	Boiler, Cast Iron, Gas & Oil, Hot Water Boiler, Cast Iron, Gas, Hot Water
Furnaces	23 54 6.13	3000 – Gas, AGA certified, upflow, direct drive
Chiller System – Water-Cooled	D3030 115	Chilled Water, Cooling Tower Systems
Chiller System – Air-Cooled	D3030 110	Chilled Water, Air Cooled Condenser
In-place Concrete	03 30 53.40	4820 – 6” Slab on grade, reinforcing

The reference numbers for the components taken from RS Means are displayed in the table below. (continued)

2007 RS Means Reference Numbers – Ventilation Components		
Component	RS Means Reference	RS Means Descriptors
Air-Handling Units	23 74 13.10 23 73 13.10	3010 – Constant volume 3200 – Variable air volume 2300 – Variable air volume, also incl. heating coil
DX HP Coils	D3040 124	1010 – Fan coil A/C system, horiz. w/ housing, cntrls
Enthalpy Wheel	23 72 13.10	4000 – Enthalpy Recovery Wheel
Rooftop System - Multi Zone	D3050 155	Rooftop Multizone Unit Systems
Rooftop System - Single Zone	D3050 150	Rooftop Single Zone Unit Systems

The chiller system costs included some of the following component costs from RS Means model systems.

Reference - 2007 RSMeans Mechanical Cost Data

System D3030 110 1200 (Used in the Medium Office and the Supermarket)

Packaged Chiller, Air Cooled, with Fan Coil Unit

Fan coil air conditioning unit, cabinet mounted & filters chilled water
Water chiller, air conditioning unit, reciprocating, air cooled
Chilled water unit coil connections
Chilled water distribution piping

System D3030 115 1320 (Used in the Large Office and Secondary School)

Packaged Chiller, Water Cooled with Fan Coil Unit

Fan coil air conditioning unit, cabinet mounted & filters, chilled water
Water chiller, water cooled, 1 compressor, hermetic scroll
Cooling tower, draw thru single flow, belt drive
Cooling tower pumps & piping
Chilled water unit coil connections
Chilled water distribution piping

Some of the assumptions associated with the overall costs are listed below.

Central Plant Assumptions

- **Chillers and Boiler costs include chiller/boiler component costs and some distribution system costs**
- *From D3030 110 (air cooled)*: used the 'Fan coil AC unit' and 'Chilled water unit coil connections' costs
- *From D3030 115 (water):* used 'Cooling tower', 'Cooling tower pumps and piping', 'Chilled water unit coil connection', and 'Fan coil AC unit' costs.

- **The rooftop-cooled buildings were converted to air-cooled chillers**
- **The central plant buildings used water-cooled chillers**
- **Chillers and Boilers were considered as completely separate systems**

- **The baseline supporting system for the school was sized at a percentage of the full school, based on the part of the cooling that the system provides.**

For the Low-Lift Chiller:

- **NCI first calculated the cost of a conventional chiller and distribution system using RS Means. It was sized to meet the sensible cooling load.**
- **NCI then used cost premiums for costing out advanced chillers: 15% for an air-cooled chiller, 16% for a water-cooled chiller.**

Some of the assumptions associated with the overall costs are listed below.

Radiant Cooling Assumptions

- **NCI calculated the cost of radiant panels using a fixed cost of $10 per square foot of slab or paneling. To calculate the pure incremental cost, NCI subtracted a cost of $2.74 per square foot for work related to the concrete foundation. PNNL requested that the cost of concrete was subtracted from the overall cost.**

- **The radiant systems were sized to meet the sensible cooling load of the building (72% of the total cooling load). NCI used an assumption of 40 Btu/hr per square foot to size the system (by square feet) appropriately.**

Rooftop Systems

- **NCI calculated the rooftop air-conditioners in RS Means using the cooling size of each device. Ductwork costs were calculated separately.**

- **NCI determined rooftop costs as a whole package, and then divided the full cost of the unit into furnace and cooling parts to calculated the incremental costs.**

Low Lift Cooling Cost Estimation » HVAC System Assumptions

Some of the assumptions associated with the overall costs are listed below.

Ventilation System

- **NCI calculated the cost of ductwork using a fixed cost of $5.00 per CFM for single zone systems or $6.25 per CFM for multi-zone systems. These costs account for the both a standard cost per CFM, and the expected cost of ductwork per square foot of building in RS Means (using the system costs incorporating ductwork).**
- **This allowed for a simple calculation of the incremental cost of ductwork.**

- **PNNL provided the maximum and minimum airflows handled by the outdoor air controllers**
  - **The conventional VAV and PSZ systems were sized according to the EnergyPlus equipment sizing information (maximum system CFM).**
  - **The low-lift DOAS systems were sized according to the average of the minimum and maximum system CFM requirements.**

For the Direct-Expansion Heat Pump Coils:

- **DX HP was sized using the latent loads of the building provided by PNNL.**

For the Enthalpy Wheels:

- **The enthalpy wheels were sized in RS Means using the DOAS system CFM size.**

PNNL provided sizing and description of components from the EnergyPlus package.

1.1 Receive component and sizing information

	Equipment Specifications– EnergyPlus Baseline Information			
	Large Office	Medium Office	Supermarket	School
Building Size	460,240 sq. ft	53,630 sq. ft	45,000 sq. ft	210,890 sq. ft
Chillers	780 RT	-	-	509 RT
Boilers	12,577 MBH	-	-	28,398 MBH
DX Coils	-	86 RT	131 RT	476 RT
Furnaces	-	94 MBH	2224 MBH	-
Ventilation Size	279,856 CFM	32,145 CFM	43,736 CFM	433,653 CFM
Ventilation Type	VAV	Packaged AC Unitary	Packaged Single Zone	VAV + Packaged Single Zone
# of Cooling Systems	3	3	6	10
Central Plant	Yes	No	No	Yes

- RT – Refrigeration Tons
- VAV – Variable Air Volume

NCI compared the component based approach to a square foot approach in RS Means, by comparing the cooling systems.

	Cost Analysis – Rooftop System Cost per Square Foot (National Average)		
	System	Component based $ per sq. ft	Square foot based $ per sq. ft
Medium Office	Rooftop	8.8	16.0
Large Office	Chiller	8.3	15.7
Supermarket	Rooftop	7.4	4.5
School	Chiller + Rooftop	19.7	18.1

- The square footage examination was used to confirm the validity of the RS Means Costs independently.
- The results show that the system based approach does not cover the entire expected cost of the cooling system, especially for rooftop systems. Some costs are intentionally not included, such as the cost of the chiller distribution systems.
- There is variation due to the sizing of the systems, which in many of the cases dominates the comparison.

Comparison of PNNL Buildings to RS Means Square Foot Costs

	Cost Analysis – Cost per square foot (PNNL Buildings)			
	Floorspace	Baseline Cost	$ per sq. ft	HVAC Type
Medium Office	53,630 sq. ft	$470,598	8.8	Rooftop Multizone
Large Office	460,240 sq. ft	$3,815,896	8.3	Central Plant
Supermarket	45,000 sq. ft	$334,295	7.4	Rooftop Single Zone
School	210,890 sq. ft	$4,160,202	19.7	Central Plant + PSZ

	Cost Analysis – Cost per square foot (RS Means Sq. Foot Baselines)				
	Floorspace	Total Cost per sq. ft	% of Cost for HVAC	HVAC $ per sq. ft	HVAC Type
Office (2-4 Stories)	20,000 sq. ft	114.31	14.0%	16.0	Rooftop Multizone
Office (11-20 stories)	260,000 sq. ft	100.05	15.7%	15.7	Central Plant
Supermarket	44,000 sq. ft	65.80	6.8%	4.5	Rooftop Single Zone
High School, 2-3 Flrs.	130,000 sq. ft	109.71	16.5%	18.1	Central Plant

Reference - 2008 RS Means Square Foot Costs (29^{th} Annual Edition)

The incremental costs were made up of the costs of the various components for the baseline and low-lift systems.

	Incremental Cost – Low-Lift Chiller (Houston Costs, Medium Office)			
	DX Coils from Rooftop	Chiller Cost	Chiller Distribution System	TOTAL
Low-Lift Costs	-	$54,564	$80,071	$134,635
Baseline Costs	$268,710	-	-	$268,710
Difference				-$134,075

	Incremental Cost – Heating System (Houston Costs, Medium Office)			
	Central Boiler System	Low-Capacity Furnace	Furnace from Rooftop	TOTAL
Low-Lift Costs	$9,362	$492	-	$9,854
Baseline Costs	-	-	$1,717	$1,717
Difference				$8,136

The incremental costs were made up of the costs of the various components for the baseline and low-lift systems.

	Incremental Cost – Ventilation System (Houston Costs, Medium Office)				
	Ductwork	Air-Handling Units Cost	DX HP Units Cost	Enthalpy Wheel Cost	TOTAL
Low-Lift Costs	$110,891	-	$14,726	$27,037	$152,653
Baseline Costs	$177,401	-	-	-	$177,401
Difference					-$24,748

	Incremental Cost – Radiant System (Houston Costs, Medium Office)
	TOTAL
Low-Lift Costs	$119,453
Baseline Costs	-
Difference	$119,453

NAVIGANT CONSULTING

The large office did not change cooling systems, it just acquired a more efficient chiller.

	Incremental Cost – Low-Lift Chiller (Houston Costs, Large Office)			
	DX Coils from Rooftop	Chiller Cost	Chiller Support	TOTAL
Low-Lift Costs	-	$344,828	$1,134,858	$1,452,423
Baseline Costs	-	$317,566	$1,134,858	$1,479,687
Difference				$27,263

	Incremental Cost – Heating System (Houston Costs, Large Office)			
	Central Boiler System	Low-Capacity Furnace	Furnace from Rooftop	TOTAL
Low-Lift Costs	$171,734	$21,819	-	$193,553
Baseline Costs	$171,734	-	-	$171,734
Difference				$21,819

NAVIGANT CONSULTING

The large office did not change cooling systems, it just acquired a more efficient chiller.

	Incremental Cost – Ventilation System (Houston Costs, Large Office)				
	Ductwork	Air-Handling Units Cost	DX HP Units Cost	Enthalpy Wheel Cost	TOTAL
Low-Lift Costs	$909,636	-	$23,961	$148,331	$1,081,927
Baseline Costs	$1,544,457	$347,215	-	-	$1,891,672
Difference					-$809,745

	Incremental Cost – Radiant System (Houston Costs, Large Office)
	TOTAL
Low-Lift Costs	$1,081,432
Baseline Costs	-
Difference	$1,081,432

NAVIGANT CONSULTING

The supermarket used single-zone rooftop units, but the cooling equipment size was larger than the medium office.

	Incremental Cost – Low-Lift Chiller (Houston Costs, Supermarket)			
	DX Coils from Rooftop	Chiller Cost	Chiller Distribution System	TOTAL
Low-Lift Costs	-	$75,447	$60,045	$135,493
Baseline Costs	$105,623	-	-	$105,623
Difference				$29,870

	Incremental Cost – Heating System (Houston Costs, Supermarket)			
	Central Boiler System	Low-Capacity Furnace	Furnace from Rooftop	TOTAL
Low-Lift Costs	$44,281	$3,830	-	$48,111
Baseline Costs	-	-	$19,945	$19,945
Difference				$28,167

NAVIGANT CONSULTING

The supermarket used single-zone rooftop units, but the cooling equipment size was larger than the medium office.

	Incremental Cost – Ventilation System (Houston Costs, Supermarket)				
	Ductwork	Air-Handling Units Cost	DX HP Units Cost	Enthalpy Wheel Cost	TOTAL
Low-Lift Costs	$123,813	-	$20,289	$47,881	$191,983
Baseline Costs	$182,056	-	-	-	$182,056
Difference					$9,927

	Incremental Cost – Radiant System (Houston Costs, Supermarket)
	TOTAL
Low-Lift Costs	$181,654
Baseline Costs	-
Difference	$181,654

NAVIGANT CONSULTING

The secondary school was a mix of rooftop and central plant cooling, which was integrated into one large chiller system.

	Incremental Cost – Low-Lift Chiller (Houston Costs, Secondary School)			
	DX Coils from Rooftop	Chiller Cost	Chiller Support	TOTAL
Low-Lift Costs	-	$301,007	$551,859	$852,866
Baseline Costs	$197,341	$187,603	$438,762	$823,706
Difference				$29,160

	Incremental Cost – Heating System (Houston Costs, Secondary School)			
	Central Boiler System	Low-Capacity Furnace	Furnace from Rooftop	TOTAL
Low-Lift Costs	$450,120	$59,877	-	$414,246
Baseline Costs	$384,101	-	$87,673	$384,583
Difference				$38,223

NAVIGANT CONSULTING

The secondary school was a mix of rooftop and central plant cooling, which was integrated into one large chiller system.

	Incremental Cost – Ventilation System (Houston Costs, Secondary School)				
	Ductwork	Air-Handling Units Cost	DX HP Units Cost	Enthalpy Wheel Cost	TOTAL
Low-Lift Costs	$1,250,769	-	$121,871	$247,604	$1,620,244
Baseline Costs	$2,180,366	$320,971	-	-	$2,501,337
Difference					-$881,093

	Incremental Cost – Radiant System (Houston Costs, Secondary School)
	TOTAL
Low-Lift Costs	$1,363,355
Baseline Costs	-
Difference	$1,363,355

The incremental cost for each low-lift technology was determined as the cost difference between the baseline cooling system and low-lift cooling system.

	Cost Increments for Each Low-Lift Technology by Building Type (Houston Costs)					
	Optimized Chiller	Radiant Cooling	Heating System	Sub-total	DOAS System with HP and EW	TOTAL
Medium Office	-$134,000	$119,000	$8,000	-$6,000	-$25,000	-$31,000
Large Office	$27,000	$1,081,000	$22,000	$1,131,000	-$810,000	$321,000
Supermarket	$30,000	$182,000	$28,000	$240,000	$10,000	$250,000
Secondary School	$29,000	$1,363,000	$38,000	$1,431,000	-$881,000	$550,000

- The reduction in CFM requirements for the ventilation system can have a large impact on the incremental costs. The incremental costs will vary depending on the final CFM requirements chosen. Current DOAS sizing uses the average of the maximum and minimum CFM requirements provided by EnergyPlus.

The national incremental costs differ from the Houston costs in a few areas, notably in the chiller and DOAS increments, because of the large labor savings taken in the Houston costs.

Cost Increments for Each Low-Lift Technology by Building Type (National Average)						
	Optimized Chiller	Radiant Cooling	Heating System	Sub-total	DOAS System with HP and EW	TOTAL
Medium Office	-$129,000	$135,000	$9,000	$15,000	-$30,000	-$15,000
Large Office	$28,000	$1,225,000	$22,000	$1,274,000	-$891,000	$383,000
Supermarket	$31,000	$206,000	$33,000	$270,000	$6,000	$276,000
Secondary School	$32,000	$1,544,000	$41,000	$1,616,000	-$992,000	$624,000

- The reduction in CFM requirements for the ventilation system can have a large impact on the incremental costs. The incremental costs will vary depending on the final CFM requirements chosen. Current DOAS sizing uses the average of the maximum and minimum CFM requirements provided by EnergyPlus.

The incremental cost associated with the DOAS System varied depending on the CFM sizing of the low-lift system, dependent on the costs of the ductwork, additional air-handlers, and enthalpy wheels.

Variation of DOAS System Incremental Costs (Houston Costs)						
	Low-Lift Sized for: Minimum CFM		Low-Lift Sized for: Average CFM		Low-Lift Sized for: Maximum CFM	
	CFM	DOAS Incre. Cost	CFM	DOAS Incre. Cost	CFM	DOAS Incre. Cost
Medium Office	8,042	-$98,000	20,093	-$25,000	32,145	$51,000
Large Office	49,797	-1,535,000	164,826	-$810,000	279,856	-$120,000
Supermarket	14,851	-$58,000	28,044	$10,000	41,236	$78,000
Secondary School	123,255	-1,684,000	274,862	-$881,000	426,470	-$103,000

- The reduction in CFM requirements for the ventilation system can have a large impact on the incremental costs. The incremental costs will vary depending on the final CFM requirements chosen. Current DOAS sizing uses the average of the maximum and minimum CFM requirements provided by EnergyPlus.

C Appendix: Energy Use Estimate Tables and Figures

Table: C-1 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Small Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	8,231	7,107	7,058	6,315	6,167	2,378	2,265	1,877	1,507
Spokane, WA	7,636	6,807	6,772	6,181	6,083	2,077	1,988	1,662	1,393
Missoula, MT	7,250	6,449	6,423	5,850	5,776	1,882	1,803	1,518	1,297
Boise, ID	8,181	7,150	7,106	6,362	6,228	2,301	2,194	1,797	1,472
Pocatello, ID	7,914	7,003	6,969	6,294	6,204	2,074	1,979	1,609	1,346
Helena, MT	7,389	6,579	6,547	6,034	5,946	1,929	1,839	1,583	1,325
Astoria, OR	5,564	5,168	5,146	5,087	5,048	1,424	1,324	1,370	1,150
Salem, OR	7,356	6,368	6,327	5,799	5,701	1,895	1,774	1,564	1,270
Eugene, OR	7,317	6,337	6,295	5,790	5,692	1,868	1,748	1,549	1,261
North Bend, OR	5,144	4,813	4,796	4,776	4,741	1,388	1,304	1,354	1,143
Arcata, CA	4,844	4,683	4,677	4,645	4,631	1,299	1,227	1,266	1,118
Medford, OR	8,383	7,157	7,107	6,145	6,007	2,443	2,320	1,794	1,460
Redmond, OR	7,678	6,751	6,711	5,996	5,909	2,166	2,058	1,634	1,354
Portland, OR	7,200	6,247	6,200	5,833	5,726	1,801	1,671	1,592	1,264
Yakima, WA	7,886	6,767	6,717	6,028	5,910	2,197	2,069	1,743	1,394
Burns, OR	7,717	6,790	6,750	6,033	5,943	2,172	2,064	1,639	1,356
Olympia, WA	6,817	6,022	5,988	5,586	5,516	1,724	1,618	1,467	1,226
Quillayuta, WA	5,708	5,385	5,367	5,276	5,247	1,399	1,315	1,324	1,140
Seattle, WA	6,569	5,877	5,842	5,636	5,553	1,610	1,505	1,498	1,209
Kalispell, MT	6,975	6,257	6,232	5,759	5,698	1,754	1,676	1,449	1,241
Cut Bank, MT	6,811	6,233	6,206	5,916	5,863	1,650	1,563	1,443	1,227

Table: C-2 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Small Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	1,567	1,278	1,254	1,056	1,012	933	909	797	729
Spokane, WA	1,436	1,220	1,204	1,040	1,010	872	856	757	708
Missoula, MT	1,369	1,142	1,129	988	966	795	781	713	674
Boise, ID	1,514	1,249	1,229	1,038	998	906	886	780	716
Pocatello, ID	1,464	1,255	1,240	1,070	1,046	848	832	733	688
Helena, MT	1,339	1,137	1,126	997	974	801	789	720	681
Astoria, OR	892	817	813	798	792	666	661	659	651
Salem, OR	1,353	1,077	1,059	925	898	792	769	715	672
Eugene, OR	1,322	1,060	1,042	922	895	779	757	712	670
North Bend, OR	797	766	763	760	756	654	652	653	650
Arcata, CA	753	730	729	724	722	653	652	651	650
Medford, OR	1,656	1,285	1,262	981	940	978	952	793	725
Redmond, OR	1,381	1,163	1,146	969	947	856	839	734	689
Portland, OR	1,317	1,061	1,044	955	928	759	737	710	669
Yakima, WA	1,511	1,206	1,183	1,008	974	855	829	752	697
Burns, OR	1,397	1,167	1,150	971	948	859	842	735	690
Olympia, WA	1,217	991	981	872	853	755	740	698	668
Quillayuta, WA	906	852	849	831	825	669	664	659	651
Seattle, WA	1,117	950	939	893	875	706	693	683	658
Kalispell, MT	1,311	1,127	1,116	1,002	984	763	749	696	665
Cut Bank, MT	1,272	1,153	1,146	1,085	1,073	717	709	681	661

Table: C-3 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Medium Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	79,175	53,671	50,502	46,511	40,163	40,668	34,234	36,150	26,297
Spokane, WA	64,622	44,962	42,440	40,085	35,152	33,626	28,078	30,603	22,487
Missoula, MT	62,728	42,734	40,485	38,352	32,924	31,002	25,726	28,970	20,739
Boise, ID	77,956	54,017	51,106	47,274	40,355	39,816	33,566	35,975	25,681
Pocatello, ID	68,392	47,456	44,887	41,926	35,700	34,576	28,852	31,582	22,203
Helena, MT	63,531	43,198	40,888	38,907	34,172	31,656	26,187	29,419	21,274
Astoria, OR	44,450	25,627	24,122	24,992	22,765	21,479	17,068	21,099	15,818
Salem, OR	65,589	39,395	36,735	35,238	30,045	30,636	24,639	28,548	20,019
Eugene, OR	66,006	39,257	36,501	35,450	29,781	30,381	24,388	28,472	20,053
North Bend, OR	42,258	25,084	23,813	24,622	22,671	21,127	16,859	20,788	15,602
Arcata, CA	35,808	23,228	22,287	22,830	21,449	19,747	15,995	19,457	15,022
Medford, OR	82,800	55,324	52,225	45,532	38,684	41,022	34,501	35,668	25,037
Redmond, OR	64,342	44,444	41,876	39,171	33,448	34,181	28,249	31,159	21,634
Portland, OR	64,469	37,582	34,729	34,826	29,890	29,877	23,507	28,534	19,888
Yakima, WA	72,383	48,051	45,044	42,318	35,879	36,402	30,234	33,371	23,679
Burns, OR	64,394	44,483	41,913	39,211	33,472	34,217	28,276	31,189	21,650
Olympia, WA	58,097	35,238	33,010	31,623	27,638	27,439	22,175	25,711	18,452
Quillayuta, WA	39,467	25,012	23,646	24,345	22,413	21,162	16,977	20,697	15,699
Seattle, WA	54,336	31,968	29,657	30,542	26,912	26,028	20,453	25,192	18,034
Kalispell, MT	55,169	37,411	35,525	34,170	29,994	27,933	23,113	26,368	19,047
Cut Bank, MT	50,711	35,212	33,314	33,235	29,800	26,646	21,482	25,518	18,568

Table: C-4 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Medium Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	30,872	21,007	19,524	18,556	15,804	14,065	12,162	12,839	9,589
Spokane, WA	24,469	17,472	16,419	15,683	13,730	11,833	10,394	10,873	8,557
Missoula, MT	22,944	15,944	15,059	13,426	12,190	10,923	9,667	10,328	7,936
Boise, ID	29,475	20,496	19,259	17,698	15,207	13,973	12,265	12,821	9,517
Pocatello, ID	24,222	16,889	15,841	14,003	12,521	12,214	10,684	11,368	8,484
Helena, MT	22,642	15,462	14,520	13,708	12,000	11,071	9,699	10,434	8,174
Astoria, OR	20,961	13,439	12,763	13,231	12,361	7,129	6,533	7,091	6,351
Salem, OR	26,300	16,168	14,937	14,544	12,574	10,121	8,712	9,702	7,468
Eugene, OR	26,022	16,110	14,863	14,677	12,561	10,012	8,603	9,615	7,434
North Bend, OR	21,089	13,857	13,278	13,723	12,906	6,717	6,220	6,703	6,078
Arcata, CA	19,447	13,658	13,213	13,543	12,941	6,548	6,086	6,535	5,943
Medford, OR	31,958	21,160	19,643	17,120	14,761	14,046	12,193	12,556	9,016
Redmond, OR	24,247	17,188	16,105	14,554	13,104	11,675	10,108	10,822	8,076
Portland, OR	25,928	15,675	14,394	14,789	12,632	9,850	8,382	9,555	7,481
Yakima, WA	27,497	18,185	16,747	16,197	13,587	12,270	10,356	11,516	8,473
Burns, OR	24,222	17,158	16,072	14,554	13,063	11,698	10,128	10,840	8,090
Olympia, WA	23,981	15,267	14,303	13,827	12,417	9,227	8,088	8,874	7,148
Quillayuta, WA	18,617	12,840	12,255	12,613	11,831	7,288	6,670	7,233	6,450
Seattle, WA	22,283	14,055	13,071	13,595	12,109	8,473	7,418	8,335	6,950
Kalispell, MT	20,522	14,229	13,442	12,696	11,387	9,697	8,615	9,346	7,496
Cut Bank, MT	17,761	12,456	11,704	11,675	10,524	9,275	8,126	9,058	7,461

Table: C-5 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Large Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	625,525	550,594	527,093	491,699	451,060	419,146	365,081	376,221	294,789
Spokane, WA	535,300	485,651	469,555	438,395	409,892	356,024	309,806	321,276	254,405
Missoula, MT	530,947	476,301	462,798	424,845	398,764	337,821	295,802	304,067	241,490
Boise, ID	655,594	608,431	589,447	540,036	504,986	428,624	379,151	380,040	305,582
Pocatello, ID	708,539	711,003	699,198	654,912	630,258	372,579	334,072	336,132	278,992
Helena, MT	628,500	632,101	621,000	587,862	565,095	344,904	308,218	314,305	258,587
Astoria, OR	337,961	230,427	217,465	223,374	203,817	232,365	183,427	227,466	163,299
Salem, OR	479,758	365,396	342,745	332,848	296,533	319,108	262,302	297,743	216,877
Eugene, OR	479,953	364,139	340,892	331,926	294,800	319,149	261,796	297,856	216,148
North Bend, OR	322,697	226,743	214,873	221,893	203,492	239,298	189,377	234,197	166,026
Arcata, CA	297,758	214,163	206,552	208,802	196,460	224,258	176,913	219,761	156,735
Medford, OR	568,231	562,086	538,328	490,903	447,585	422,471	366,123	375,863	289,805
Redmond, OR	558,967	503,103	488,134	445,467	417,376	371,901	328,289	328,240	261,042
Portland, OR	471,625	349,328	325,368	324,609	286,730	311,467	251,617	295,887	211,513
Yakima, WA	573,644	482,147	459,087	432,529	392,577	375,957	323,271	341,412	260,682
Burns, OR	559,294	503,382	488,411	445,723	417,630	371,982	328,368	328,303	261,097
Olympia, WA	426,075	320,402	301,645	293,553	263,673	285,563	232,026	269,025	196,203
Quillayuta, WA	307,169	226,256	214,430	218,683	202,687	229,033	182,076	222,494	161,560
Seattle, WA	404,817	293,904	274,624	278,613	249,802	274,608	221,307	263,888	189,867
Kalispell, MT	466,128	405,550	392,988	367,877	345,555	302,476	262,562	275,451	216,344
Cut Bank, MT	494,103	507,207	497,831	480,510	461,468	292,551	255,859	270,423	215,655

Table: C-6 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Large Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	206,939	166,782	154,800	148,191	128,126	161,998	144,473	149,138	121,804
Spokane, WA	165,517	136,170	128,177	119,955	106,315	138,934	125,721	128,424	108,770
Missoula, MT	159,408	129,500	123,130	115,003	103,134	132,178	120,929	122,772	104,123
Boise, ID	199,594	169,346	160,305	148,273	130,629	166,805	152,738	151,761	127,763
Pocatello, ID	189,386	163,874	158,630	137,519	123,881	150,559	141,946	132,388	116,936
Helena, MT	175,889	146,679	141,689	126,334	116,638	139,061	130,555	124,736	110,316
Astoria, OR	140,856	87,756	81,816	86,061	78,318	81,348	72,619	80,686	70,185
Salem, OR	178,058	125,258	114,402	115,255	98,382	119,878	102,284	114,554	90,323
Eugene, OR	175,872	123,488	112,499	113,939	97,138	118,226	101,133	113,122	89,318
North Bend, OR	133,075	87,745	82,954	86,452	79,608	79,690	71,038	79,101	68,362
Arcata, CA	126,258	84,147	80,865	82,964	78,476	74,245	69,019	73,941	66,829
Medford, OR	217,231	174,726	161,994	152,116	129,793	164,861	145,436	150,606	119,991
Redmond, OR	167,856	134,580	127,086	117,727	104,614	138,882	126,517	127,314	107,492
Portland, OR	174,053	118,765	107,438	111,345	94,543	115,404	97,481	111,640	87,673
Yakima, WA	191,369	146,085	133,865	132,667	113,396	143,248	124,868	134,804	107,117
Burns, OR	167,883	134,579	127,084	117,715	104,603	138,937	126,577	127,352	107,532
Olympia, WA	162,886	113,095	104,508	104,799	91,565	106,006	91,537	102,143	82,934
Quillayuta, WA	124,592	84,523	79,537	82,479	76,148	83,315	75,224	82,355	72,132
Seattle, WA	148,019	99,833	91,182	95,681	83,651	100,452	86,302	98,439	80,181
Kalispell, MT	141,589	110,363	104,345	100,912	90,709	117,002	106,330	110,953	94,214
Cut Bank, MT	139,664	104,572	100,435	96,152	88,580	112,077	103,069	106,527	92,570

Table: C-7 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Retail Strip Mall Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	81,844	70,149	69,171	64,944	61,052	33,276	31,740	29,776	25,100
Spokane, WA	74,669	66,708	66,046	62,938	60,193	29,819	28,681	27,109	23,743
Missoula, MT	75,083	66,922	66,318	62,985	60,303	28,865	27,821	26,438	22,986
Boise, ID	82,911	71,522	70,526	66,380	62,350	33,263	31,679	29,828	24,973
Pocatello, ID	79,797	70,391	69,682	65,176	62,526	31,095	29,823	28,019	23,837
Helena, MT	75,656	67,933	67,342	64,703	62,139	28,912	27,726	26,748	23,397
Astoria, OR	49,692	47,710	47,583	47,374	46,894	21,161	20,703	21,005	20,234
Salem, OR	68,075	59,208	58,563	56,422	53,486	26,513	25,335	25,024	21,866
Eugene, OR	67,989	59,077	58,430	56,438	53,331	26,594	25,407	25,151	21,788
North Bend, OR	45,014	43,960	43,877	43,841	43,656	20,580	20,244	20,506	20,035
Arcata, CA	43,569	43,019	42,990	42,878	42,743	20,319	20,139	20,258	19,969
Medford, OR	83,756	70,579	69,517	63,057	59,187	33,862	32,259	29,290	24,374
Redmond, OR	73,489	65,033	64,388	60,894	58,112	29,730	28,523	27,049	23,068
Portland, OR	66,850	58,342	57,618	56,462	53,781	25,761	24,421	24,808	21,892
Yakima, WA	77,700	66,625	65,736	62,505	58,582	30,961	29,410	28,255	23,736
Burns, OR	73,703	65,223	64,577	61,116	58,283	29,765	28,554	27,029	23,082
Olympia, WA	63,081	56,256	55,779	53,777	51,860	25,039	24,075	23,891	21,418
Quillayuta, WA	51,125	49,268	49,126	48,938	48,493	21,216	20,806	21,016	20,260
Seattle, WA	59,775	54,527	54,084	53,413	51,945	23,622	22,643	23,022	21,103
Kalispell, MT	70,211	63,762	63,347	61,017	58,903	26,572	25,729	24,809	22,150
Cut Bank, MT	68,972	64,277	63,901	62,795	61,196	25,779	24,859	24,714	22,382

Table: C-8 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Retail Strip Mall Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	25,753	20,193	19,595	17,561	16,105	16,854	16,251	15,573	13,578
Spokane, WA	21,539	18,166	17,812	16,016	15,282	15,332	14,957	14,194	12,974
Missoula, MT	20,208	16,829	16,488	14,514	14,064	14,711	14,378	13,840	12,569
Boise, ID	24,097	19,170	18,635	16,023	15,013	16,958	16,433	15,464	13,524
Pocatello, ID	21,925	18,020	17,643	15,222	14,654	15,668	15,268	14,508	12,881
Helena, MT	20,194	17,159	16,860	15,331	14,805	14,528	14,214	13,736	12,628
Astoria, OR	12,842	12,410	12,391	12,283	12,219	11,949	11,911	11,930	11,847
Salem, OR	18,956	15,564	15,200	13,791	13,253	13,822	13,492	13,250	12,291
Eugene, OR	18,947	15,495	15,134	13,708	13,246	13,797	13,451	13,293	12,261
North Bend, OR	11,456	11,388	11,384	11,366	11,358	11,825	11,821	11,823	11,814
Arcata, CA	10,897	10,823	10,821	10,790	10,781	11,822	11,817	11,820	11,809
Medford, OR	26,486	20,635	20,000	16,121	15,233	17,564	16,944	15,529	13,441
Redmond, OR	20,067	16,687	16,345	14,301	13,909	14,988	14,601	14,081	12,628
Portland, OR	18,614	15,388	15,051	14,425	13,640	13,314	13,003	13,039	12,212
Yakima, WA	22,925	18,101	17,579	15,747	14,665	15,446	14,903	14,443	12,892
Burns, OR	20,186	16,810	16,464	14,423	14,019	15,001	14,608	14,096	12,631
Olympia, WA	17,156	14,569	14,356	13,101	12,805	13,309	13,074	12,894	12,179
Quillayuta, WA	12,689	12,306	12,271	12,162	12,107	11,959	11,932	11,932	11,840
Seattle, WA	15,519	13,907	13,750	13,488	13,024	12,501	12,355	12,327	11,992
Kalispell, MT	18,742	16,183	15,931	14,648	14,286	13,612	13,359	13,048	12,257
Cut Bank, MT	17,561	15,969	15,817	15,168	14,920	13,060	12,893	12,785	12,208

Table: C-9 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Retail Stand-Alone Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	118,089	103,798	102,858	98,814	93,813	35,658	33,818	32,603	27,209
Spokane, WA	110,142	100,221	99,587	96,264	93,098	31,878	30,570	29,407	25,546
Missoula, MT	109,914	99,875	99,339	95,846	92,615	30,605	29,451	28,528	24,507
Boise, ID	119,369	105,874	105,047	100,449	95,875	35,721	34,052	32,446	27,006
Pocatello, ID	118,467	106,806	106,120	101,437	98,012	33,638	32,170	30,623	25,716
Helena, MT	111,572	102,112	101,541	98,781	95,654	30,769	29,399	28,745	24,873
Astoria, OR	79,247	76,500	76,330	76,163	75,660	23,200	22,500	23,020	21,956
Salem, OR	100,983	89,957	89,266	87,149	83,736	28,839	27,395	27,539	23,861
Eugene, OR	101,319	90,167	89,476	87,535	83,867	28,857	27,429	27,613	23,835
North Bend, OR	74,433	72,655	72,517	72,499	72,212	22,748	22,102	22,635	21,773
Arcata, CA	72,297	71,454	71,403	71,309	71,159	22,200	21,842	22,124	21,639
Medford, OR	120,264	104,347	103,387	96,724	91,944	36,612	34,852	32,353	26,603
Redmond, OR	108,931	98,599	97,906	94,097	90,907	32,229	30,684	29,491	24,890
Portland, OR	99,928	89,222	88,452	87,381	84,204	28,070	26,400	27,211	23,867
Yakima, WA	112,325	98,849	97,960	94,403	90,012	33,342	31,470	30,796	25,677
Burns, OR	109,217	98,853	98,159	94,337	91,139	32,266	30,718	29,527	24,906
Olympia, WA	94,844	86,166	85,657	83,812	81,368	27,144	25,943	26,111	23,262
Quillayuta, WA	80,522	77,978	77,788	77,640	77,072	23,132	22,499	22,918	21,919
Seattle, WA	91,403	84,601	84,107	83,433	81,765	25,639	24,415	25,103	22,920
Kalispell, MT	104,306	96,228	95,793	93,287	90,879	28,252	27,193	26,722	23,656
Cut Bank, MT	104,167	98,038	97,619	96,539	94,595	27,467	26,176	26,491	23,603

Table: C-10 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Retail Stand-Alone Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	40,281	33,044	32,401	30,383	28,326	17,947	17,231	16,893	14,616
Spokane, WA	35,469	30,784	30,396	28,696	27,471	16,115	15,638	15,226	13,887
Missoula, MT	33,689	28,982	28,640	26,384	25,751	15,592	15,162	15,018	13,480
Boise, ID	38,519	31,887	31,341	28,763	27,186	17,789	17,133	16,749	14,462
Pocatello, ID	36,108	30,705	30,279	27,594	26,754	16,512	15,990	15,661	13,767
Helena, MT	33,353	29,158	28,836	27,231	26,368	15,347	14,962	14,760	13,532
Astoria, OR	25,472	24,772	24,739	24,634	24,517	12,946	12,886	12,920	12,805
Salem, OR	32,839	28,062	27,644	26,114	25,297	15,153	14,686	14,696	13,380
Eugene, OR	32,889	28,014	27,600	26,109	25,264	15,100	14,621	14,662	13,340
North Bend, OR	23,961	23,779	23,770	23,743	23,718	12,798	12,785	12,794	12,772
Arcata, CA	23,581	23,465	23,460	23,415	23,396	12,796	12,787	12,791	12,771
Medford, OR	41,322	33,572	32,937	28,765	27,426	19,051	18,380	17,146	14,626
Redmond, OR	33,731	29,234	28,825	26,548	25,911	15,806	15,285	15,199	13,497
Portland, OR	32,458	27,925	27,523	27,104	25,773	14,602	14,067	14,363	13,294
Yakima, WA	37,203	30,788	30,210	28,250	26,746	16,723	16,039	15,813	13,992
Burns, OR	33,886	29,363	28,953	26,660	26,027	15,825	15,300	15,212	13,503
Olympia, WA	31,714	27,901	27,660	26,297	25,803	14,508	14,172	14,159	13,215
Quillayuta, WA	25,778	25,119	25,071	24,945	24,845	12,946	12,893	12,918	12,799
Seattle, WA	28,525	26,056	25,855	25,613	24,990	13,645	13,360	13,501	13,020
Kalispell, MT	31,289	27,717	27,444	26,035	25,450	14,629	14,292	14,242	13,218
Cut Bank, MT	29,294	26,997	26,800	26,154	25,694	13,884	13,642	13,715	13,069

Table: C-11 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Primary School Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	243,164	183,417	178,478	168,270	159,344	119,918	114,478	102,119	90,665
Spokane, WA	207,206	168,651	164,971	157,186	150,420	105,882	101,886	92,706	83,730
Missoula, MT	209,978	166,707	163,950	154,975	149,619	103,521	100,023	90,085	82,318
Boise, ID	241,603	194,085	190,416	172,703	164,458	125,007	120,582	102,143	91,418
Pocatello, ID	222,833	180,317	177,003	166,766	159,718	108,973	105,140	93,672	84,108
Helena, MT	211,233	173,213	170,265	159,483	153,838	106,026	102,479	91,484	83,153
Astoria, OR	155,433	120,879	117,860	116,778	112,484	80,200	76,558	75,343	68,630
Salem, OR	212,800	157,616	153,187	144,444	136,636	100,851	95,461	88,123	76,942
Eugene, OR	214,339	155,255	150,936	143,813	136,210	99,443	94,260	87,578	76,504
North Bend, OR	148,325	115,557	113,382	111,878	108,062	80,510	77,847	74,268	68,039
Arcata, CA	137,608	114,091	111,560	110,702	106,430	83,989	81,016	77,989	71,745
Medford, OR	251,753	185,511	180,714	167,488	157,926	124,348	118,874	104,249	91,464
Redmond, OR	211,203	168,925	165,223	155,403	148,387	108,724	104,630	92,728	83,412
Portland, OR	209,783	152,979	148,477	142,893	135,407	96,898	91,484	86,812	75,945
Yakima, WA	227,161	173,968	169,215	161,935	152,841	112,074	107,120	98,726	87,159
Burns, OR	211,814	169,419	165,709	155,891	148,842	108,910	104,802	92,895	83,532
Olympia, WA	192,964	143,838	139,993	134,551	128,348	92,608	87,801	83,043	74,143
Quillayuta, WA	149,228	121,682	118,780	117,413	113,526	78,808	75,216	73,763	67,505
Seattle, WA	182,022	136,846	132,824	131,955	126,138	86,898	82,366	80,832	72,092
Kalispell, MT	190,514	153,614	150,984	145,157	140,293	96,192	92,957	86,404	78,985
Cut Bank, MT	187,744	156,703	153,860	151,440	146,693	90,524	87,185	83,769	76,804

Table: C-12 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Primary School Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	69,733	48,771	46,887	42,105	38,590	43,914	41,786	37,214	32,555
Spokane, WA	56,133	43,316	41,878	38,523	35,855	38,653	37,111	33,876	30,495
Missoula, MT	56,342	41,533	40,618	36,322	34,402	37,694	36,549	32,550	29,656
Boise, ID	68,281	51,436	50,032	42,367	39,162	45,743	44,106	37,360	32,965
Pocatello, ID	57,722	43,879	42,694	38,282	35,668	39,100	37,783	33,760	30,187
Helena, MT	55,294	43,316	42,286	37,282	35,199	38,768	37,491	33,027	30,083
Astoria, OR	46,931	34,987	34,094	32,658	31,375	29,943	28,702	28,517	26,200
Salem, OR	60,536	42,112	40,403	36,809	34,067	36,963	34,818	32,700	28,489
Eugene, OR	60,572	40,932	39,302	36,413	33,776	36,060	34,043	32,348	28,164
North Bend, OR	44,961	34,345	33,915	32,196	31,444	29,858	29,185	27,909	26,309
Arcata, CA	41,825	34,649	34,074	32,341	31,597	31,366	30,566	29,646	28,036
Medford, OR	74,283	50,782	48,790	43,036	39,102	45,599	43,373	38,148	32,838
Redmond, OR	59,106	44,074	42,707	38,603	35,909	39,383	37,819	33,879	30,294
Portland, OR	59,119	40,140	38,389	36,379	33,582	35,103	32,933	32,194	27,982
Yakima, WA	63,733	45,331	43,437	40,687	36,779	40,230	38,179	35,908	31,023
Burns, OR	59,136	44,056	42,681	38,580	35,891	39,430	37,860	33,924	30,326
Olympia, WA	56,156	39,403	38,025	35,414	33,141	34,322	32,499	31,002	27,768
Quillayuta, WA	42,811	34,191	33,252	31,962	30,801	29,643	28,503	27,972	25,949
Seattle, WA	51,064	36,019	34,573	34,126	31,938	31,452	29,689	29,939	26,744
Kalispell, MT	50,914	38,146	37,212	34,571	32,786	34,751	33,648	31,231	28,579
Cut Bank, MT	45,639	36,008	35,042	33,830	32,237	31,968	30,854	29,932	27,635

Table: C-13 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Secondary School Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	802,983	625,907	615,936	571,889	552,114	335,320	323,315	306,907	282,968
Spokane, WA	702,242	573,984	567,001	541,877	527,736	298,316	289,929	282,043	265,362
Missoula, MT	726,628	599,930	593,768	560,348	545,636	308,195	299,983	288,322	270,527
Boise, ID	793,361	635,932	627,997	583,625	564,530	341,849	330,839	313,153	289,666
Pocatello, ID	728,178	600,999	594,572	558,178	543,235	318,101	309,538	295,227	276,437
Helena, MT	732,267	603,468	596,970	566,018	551,782	307,406	298,729	287,897	269,585
Astoria, OR	518,700	417,647	412,305	411,354	402,264	211,671	208,103	209,991	204,877
Salem, OR	669,486	506,810	496,755	479,774	460,683	265,442	254,510	253,639	233,919
Eugene, OR	670,319	506,042	495,906	479,656	460,441	264,713	253,939	253,331	233,390
North Bend, OR	484,289	400,133	396,578	395,325	387,595	200,650	197,881	199,971	196,241
Arcata, CA	467,536	390,046	387,301	386,292	380,793	200,996	199,566	200,620	198,806
Medford, OR	813,169	619,014	607,926	560,996	537,293	339,227	326,134	306,555	278,308
Redmond, OR	711,289	574,802	567,781	528,909	513,519	303,141	293,808	280,876	262,728
Portland, OR	662,236	500,200	490,085	478,416	458,862	260,990	249,264	252,346	232,033
Yakima, WA	744,086	575,712	565,414	541,438	520,931	309,250	295,361	291,703	264,923
Burns, OR	712,003	575,568	568,536	529,632	514,225	303,385	294,025	281,088	262,896
Olympia, WA	625,336	480,949	473,036	457,545	442,267	250,416	242,186	241,256	226,879
Quillayuta, WA	519,483	419,933	415,431	412,643	405,619	214,224	210,885	211,447	206,457
Seattle, WA	585,142	461,219	453,647	448,076	434,333	237,812	230,454	233,040	220,619
Kalispell, MT	659,825	553,735	548,667	521,960	510,367	283,389	276,877	269,110	254,914
Cut Bank, MT	662,458	558,709	553,387	541,288	531,066	281,167	273,689	271,821	258,033

Table: C-14 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Secondary School Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	339,264	241,933	236,923	211,086	198,361	158,723	153,976	142,065	130,428
Spokane, WA	280,167	213,442	209,970	191,425	183,088	139,757	136,410	128,336	120,485
Missoula, MT	277,278	212,041	209,299	188,472	179,925	137,193	134,524	128,003	119,901
Boise, ID	333,867	247,138	243,267	212,762	199,582	162,723	158,750	145,682	133,320
Pocatello, ID	288,739	220,852	217,683	195,636	185,423	145,212	141,995	132,633	123,512
Helena, MT	275,933	213,147	209,900	190,706	181,969	140,801	137,811	128,466	120,691
Astoria, OR	220,217	166,393	163,585	162,433	157,894	103,520	102,434	102,548	100,938
Salem, OR	283,981	199,590	194,540	184,225	174,274	126,370	122,451	119,997	111,981
Eugene, OR	282,244	198,112	193,054	184,009	174,409	124,463	120,946	118,764	111,040
North Bend, OR	208,964	165,176	163,819	162,416	158,979	100,927	100,260	100,727	99,779
Arcata, CA	206,736	162,059	161,335	159,058	156,589	102,301	101,626	102,056	101,135
Medford, OR	351,444	250,498	244,845	213,635	198,951	165,195	160,160	145,613	131,994
Redmond, OR	291,486	216,315	212,480	189,844	180,393	141,656	138,099	129,241	119,989
Portland, OR	277,589	194,274	189,091	183,200	173,050	122,285	118,124	117,971	110,076
Yakima, WA	307,633	218,514	213,176	199,274	187,687	139,186	133,781	131,385	120,332
Burns, OR	291,547	216,322	212,485	189,839	180,371	141,728	138,175	129,307	120,047
Olympia, WA	265,439	190,427	186,409	175,800	167,362	119,996	117,122	114,898	108,908
Quillayuta, WA	220,111	165,129	162,711	160,346	156,255	105,545	103,991	103,661	101,293
Seattle, WA	238,639	176,997	172,947	170,462	163,203	111,849	109,172	109,657	105,058
Kalispell, MT	249,097	196,585	193,874	178,801	172,343	126,807	124,454	120,336	113,317
Cut Bank, MT	238,931	188,780	186,071	179,761	174,262	123,218	120,917	119,539	114,571

Table: C-15 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Hotel Large Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	817,631	195,241	189,054	191,176	182,794	39,277	31,213	36,491	27,301
Spokane, WA	750,325	190,571	185,831	186,798	180,290	32,435	26,433	29,774	22,619
Missoula, MT	723,289	191,673	189,485	184,492	180,741	31,663	28,744	25,813	21,463
Boise, ID	817,242	204,283	198,892	197,683	189,248	42,513	35,459	37,751	29,302
Pocatello, ID	760,583	194,455	190,067	190,875	183,275	32,451	26,798	29,921	22,271
Helena, MT	752,392	190,395	186,417	186,977	180,800	29,363	23,944	27,051	20,152
Astoria, OR	637,206	158,017	154,122	157,196	152,293	20,557	13,850	20,010	12,759
Salem, OR	721,969	174,694	168,785	172,435	164,656	28,944	19,999	27,409	16,977
Eugene, OR	722,622	173,430	167,616	171,443	163,869	28,607	19,856	27,253	16,909
North Bend, OR	606,181	151,257	148,022	150,376	146,154	19,355	14,124	18,849	12,830
Arcata, CA	600,494	149,351	146,654	148,302	144,148	21,299	17,087	20,592	15,168
Medford, OR	799,061	191,881	184,794	188,154	178,397	39,177	30,020	36,440	25,460
Redmond, OR	751,189	184,156	179,727	181,421	174,090	28,935	23,321	27,105	19,228
Portland, OR	727,714	175,202	168,809	173,537	165,695	29,444	19,553	28,345	17,336
Yakima, WA	756,522	188,420	181,543	185,834	177,099	34,870	26,241	33,135	22,751
Burns, OR	751,228	184,171	179,743	181,428	174,104	28,940	23,325	27,109	19,231
Olympia, WA	691,589	169,545	164,910	167,726	161,335	25,258	17,658	24,075	15,167
Quillayuta, WA	668,167	160,287	156,962	159,323	155,256	18,681	13,485	18,013	12,055
Seattle, WA	683,158	169,704	164,489	168,551	162,477	24,372	16,418	23,590	14,857
Kalispell, MT	694,208	181,680	179,418	177,799	173,693	25,101	22,146	22,019	17,296
Cut Bank, MT	712,425	181,286	177,782	180,041	175,346	21,419	16,816	20,546	14,802

Table: C-16 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Hotel Large Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	301,508	67,681	64,316	65,916	60,428	18,069	13,735	16,852	11,171
Spokane, WA	258,425	63,686	61,391	61,741	57,787	14,072	11,194	12,741	8,640
Missoula, MT	254,875	60,678	58,993	59,118	55,403	11,779	9,496	10,696	6,612
Boise, ID	293,244	69,615	66,359	67,254	61,368	18,829	14,697	17,242	11,485
Pocatello, ID	260,633	64,229	61,862	62,636	57,717	14,108	11,102	13,012	8,010
Helena, MT	256,147	62,061	60,120	60,111	56,434	12,536	9,904	11,208	7,177
Astoria, OR	228,125	54,555	53,173	52,944	51,166	7,994	5,704	7,392	4,344
Salem, OR	266,417	61,346	59,099	58,808	54,556	13,513	10,413	11,730	6,716
Eugene, OR	266,489	60,804	58,645	58,608	54,410	13,255	10,243	11,807	6,675
North Bend, OR	220,633	53,671	52,727	51,880	50,667	7,401	6,084	6,516	4,252
Arcata, CA	229,053	52,976	51,931	51,563	50,077	6,859	5,271	6,357	3,910
Medford, OR	303,217	68,240	65,176	65,288	59,773	18,771	14,824	16,823	10,704
Redmond, OR	265,025	61,965	59,827	60,379	55,829	12,734	10,050	11,649	6,890
Portland, OR	268,494	61,225	58,726	59,260	55,003	13,594	9,974	12,392	7,335
Yakima, WA	274,075	65,724	62,790	63,747	58,391	16,510	12,786	15,194	9,652
Burns, OR	265,025	61,966	59,827	60,379	55,829	12,734	10,049	11,647	6,889
Olympia, WA	250,975	58,777	57,087	56,489	53,247	11,292	8,683	9,877	5,787
Quillayuta, WA	240,942	53,713	52,436	52,143	50,567	6,831	5,030	6,191	3,477
Seattle, WA	242,664	57,577	55,570	55,886	53,279	10,400	7,652	9,529	5,793
Kalispell, MT	233,550	57,967	56,424	56,711	53,728	9,544	7,551	8,691	5,243
Cut Bank, MT	228,033	57,073	55,500	56,166	53,514	8,286	6,241	7,740	4,612

Table: C-17 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Supermarket Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	202,942	186,574	184,747	183,393	179,233	65,278	62,260	63,118	57,892
Spokane, WA	200,614	188,304	187,108	185,559	183,074	62,181	59,991	60,320	56,956
Missoula, MT	235,408	222,354	221,308	219,816	216,958	62,176	60,158	60,908	57,088
Boise, ID	211,431	194,698	192,992	191,497	187,174	65,338	62,556	63,328	58,208
Pocatello, ID	261,675	247,016	245,739	243,711	240,121	64,189	61,867	62,379	57,629
Helena, MT	269,236	256,411	255,429	253,982	251,508	62,643	60,551	61,266	57,621
Astoria, OR	152,547	145,894	145,737	145,698	145,401	54,681	53,384	54,507	52,933
Salem, OR	175,083	161,481	160,309	159,864	157,148	59,555	57,021	58,497	54,700
Eugene, OR	173,656	160,217	159,010	158,731	156,000	59,362	56,780	58,390	54,718
North Bend, OR	149,531	143,453	143,372	143,344	143,183	54,407	53,355	54,259	52,826
Arcata, CA	148,997	143,610	143,587	143,475	143,410	54,042	53,081	53,907	52,702
Medford, OR	194,706	175,581	173,706	169,922	165,365	66,932	63,838	63,504	57,646
Redmond, OR	202,653	190,154	188,942	187,847	185,020	61,701	59,401	60,267	56,318
Portland, OR	171,717	159,383	158,247	158,302	156,056	58,758	56,136	58,053	54,486
Yakima, WA	197,844	181,429	179,750	178,533	175,120	63,649	60,720	61,941	57,289
Burns, OR	203,028	190,549	189,333	188,226	185,390	61,756	59,448	60,338	56,348
Olympia, WA	174,017	162,337	161,581	160,530	158,748	58,410	56,369	57,428	54,314
Quillayuta, WA	156,289	149,826	149,639	149,625	149,275	54,593	53,412	54,391	52,970
Seattle, WA	162,047	152,615	151,971	151,853	150,827	56,543	54,659	56,004	53,636
Kalispell, MT	232,578	221,455	220,669	219,384	217,768	60,330	58,556	59,407	56,443
Cut Bank, MT	266,031	256,543	255,940	255,613	254,188	59,644	57,923	59,038	56,582

Table: C-18 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Supermarket Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	76,131	67,888	67,315	66,190	65,458	34,553	33,913	33,955	32,426
Spokane, WA	76,214	69,534	69,287	67,942	67,675	33,841	33,543	33,002	32,236
Missoula, MT	78,386	71,506	71,296	70,025	69,816	33,740	33,483	32,979	32,331
Boise, ID	79,222	71,144	70,704	69,060	68,548	34,810	34,318	33,990	32,581
Pocatello, ID	80,311	73,107	72,854	71,296	71,035	34,128	33,826	33,101	32,396
Helena, MT	82,817	76,223	76,048	75,016	74,798	33,741	33,512	33,128	32,520
Astoria, OR	60,808	55,745	55,737	55,657	55,641	31,180	31,151	31,133	31,078
Salem, OR	67,164	60,289	59,987	59,169	58,952	32,608	32,214	32,330	31,466
Eugene, OR	66,817	59,924	59,616	58,846	58,593	32,579	32,186	32,293	31,416
North Bend, OR	58,406	53,463	53,463	53,443	53,441	31,084	31,071	31,071	31,052
Arcata, CA	58,503	53,550	53,556	53,511	53,509	31,086	31,081	31,065	31,056
Medford, OR	73,189	64,467	63,832	61,269	60,729	35,583	34,866	34,222	32,485
Redmond, OR	76,628	69,857	69,614	68,449	68,254	33,328	33,037	32,597	31,960
Portland, OR	65,922	59,341	59,081	58,666	58,341	32,294	31,935	32,122	31,389
Yakima, WA	74,417	66,637	66,143	65,008	64,485	34,028	33,444	33,370	32,196
Burns, OR	76,792	69,960	69,715	68,534	68,345	33,352	33,058	32,620	31,974
Olympia, WA	67,125	60,893	60,771	59,860	59,728	32,374	32,189	31,840	31,423
Quillayuta, WA	62,506	57,423	57,408	57,329	57,310	31,210	31,177	31,152	31,094
Seattle, WA	63,847	58,263	58,170	57,809	57,697	31,740	31,605	31,524	31,216
Kalispell, MT	77,472	71,203	71,057	70,222	70,070	33,092	32,897	32,547	32,119
Cut Bank, MT	82,067	76,294	76,209	75,811	75,717	32,821	32,691	32,586	32,283

Table: C-19 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Warehouse Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	7,228	6,440	6,338	5,846	5,713	2,664	2,461	2,221	1,903
Spokane, WA	6,656	6,191	6,121	5,746	5,655	2,435	2,277	2,087	1,850
Missoula, MT	7,256	6,737	6,677	6,345	6,266	2,231	2,098	1,956	1,743
Boise, ID	7,269	6,649	6,544	5,949	5,828	2,708	2,524	2,210	1,921
Pocatello, ID	7,261	6,710	6,634	6,240	6,140	2,445	2,285	2,090	1,838
Helena, MT	7,183	6,773	6,713	6,351	6,281	2,246	2,108	1,960	1,752
Astoria, OR	3,794	3,714	3,701	3,675	3,662	1,955	1,862	1,883	1,783
Salem, OR	5,922	5,432	5,358	5,008	4,937	2,278	2,127	2,033	1,843
Eugene, OR	5,903	5,338	5,269	4,968	4,894	2,242	2,098	2,023	1,830
North Bend, OR	3,617	3,563	3,556	3,545	3,538	1,950	1,879	1,878	1,788
Arcata, CA	3,583	3,567	3,564	3,545	3,540	1,755	1,658	1,669	1,548
Medford, OR	7,797	6,803	6,698	6,007	5,860	2,855	2,647	2,285	1,938
Redmond, OR	6,461	5,909	5,833	5,486	5,393	2,424	2,246	2,096	1,830
Portland, OR	5,658	5,195	5,125	4,903	4,834	2,168	2,022	1,994	1,817
Yakima, WA	6,794	6,113	6,015	5,627	5,512	2,479	2,278	2,145	1,844
Burns, OR	6,525	5,985	5,909	5,559	5,465	2,432	2,253	2,106	1,832
Olympia, WA	5,264	4,835	4,788	4,550	4,494	2,136	2,016	1,965	1,815
Quillayuta, WA	3,989	3,880	3,862	3,830	3,815	1,953	1,863	1,878	1,782
Seattle, WA	4,797	4,488	4,446	4,370	4,326	2,043	1,915	1,944	1,796
Kalispell, MT	7,008	6,609	6,560	6,388	6,325	2,061	1,929	1,889	1,700
Cut Bank, MT	8,444	8,164	8,123	8,010	7,964	2,004	1,871	1,869	1,693

Table: C-20 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Warehouse Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	1,350	1,240	1,216	1,086	1,066	1,147	1,136	1,028	995
Spokane, WA	1,267	1,199	1,167	1,079	1,065	1,105	1,098	1,012	987
Missoula, MT	1,353	1,246	1,241	1,173	1,161	1,019	1,012	978	958
Boise, ID	1,297	1,267	1,221	1,087	1,070	1,150	1,142	1,020	993
Pocatello, ID	1,286	1,200	1,179	1,091	1,077	1,089	1,082	1,008	982
Helena, MT	1,222	1,149	1,145	1,074	1,063	1,019	1,012	979	960
Astoria, OR	975	950	949	940	938	1,055	1,050	1,048	1,042
Salem, OR	1,219	1,136	1,117	1,036	1,024	1,105	1,096	1,065	1,049
Eugene, OR	1,222	1,128	1,126	1,035	1,022	1,103	1,094	1,063	1,048
North Bend, OR	936	937	936	935	934	1,051	1,047	1,046	1,041
Arcata, CA	928	938	937	935	934	869	868	868	866
Medford, OR	1,461	1,397	1,275	1,104	1,084	1,234	1,222	1,036	1,002
Redmond, OR	1,242	1,149	1,142	1,065	1,050	1,068	1,059	1,007	978
Portland, OR	1,186	1,066	1,060	1,003	993	1,081	1,072	1,061	1,046
Yakima, WA	1,289	1,161	1,153	1,069	1,052	1,049	1,036	1,003	973
Burns, OR	1,250	1,151	1,144	1,065	1,051	1,071	1,062	1,008	979
Olympia, WA	1,153	1,052	1,049	992	983	1,076	1,069	1,057	1,045
Quillayuta, WA	981	948	947	938	936	1,055	1,051	1,048	1,042
Seattle, WA	1,078	1,012	1,008	983	976	1,065	1,058	1,053	1,043
Kalispell, MT	1,361	1,267	1,263	1,220	1,210	995	989	970	952
Cut Bank, MT	1,817	1,770	1,767	1,738	1,732	984	979	965	952

Table: C-21 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Outpatient Health Care Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	42,047	38,444	38,157	36,549	36,067	9,138	8,351	8,204	6,706
Spokane, WA	39,017	36,620	36,430	35,199	34,908	7,839	7,280	7,100	6,008
Missoula, MT	38,314	35,923	35,772	34,418	34,190	7,349	6,863	6,433	5,584
Boise, ID	42,939	39,392	39,129	37,378	36,966	9,153	8,411	8,068	6,753
Pocatello, ID	40,842	38,002	37,803	36,215	35,927	8,077	7,471	6,989	5,923
Helena, MT	38,578	36,332	36,177	35,046	34,792	7,428	6,876	6,726	5,700
Astoria, OR	27,869	27,391	27,359	27,277	27,214	5,335	5,002	5,252	4,701
Salem, OR	37,047	34,749	34,570	33,481	33,201	7,074	6,461	6,455	5,282
Eugene, OR	37,042	34,683	34,501	33,393	33,124	7,093	6,478	6,520	5,302
North Bend, OR	25,064	24,876	24,861	24,840	24,813	5,209	4,922	5,150	4,648
Arcata, CA	24,367	24,248	24,244	24,204	24,190	4,920	4,726	4,882	4,579
Medford, OR	42,181	38,487	38,210	35,980	35,593	9,073	8,339	7,641	6,309
Redmond, OR	38,661	36,369	36,192	34,775	34,544	7,728	7,167	6,697	5,614
Portland, OR	36,592	34,271	34,073	33,311	32,961	7,015	6,328	6,695	5,343
Yakima, WA	39,597	36,480	36,234	34,711	34,381	8,290	7,596	7,400	6,011
Burns, OR	38,728	36,376	36,198	34,775	34,547	7,737	7,175	6,702	5,618
Olympia, WA	34,436	32,630	32,502	31,649	31,466	6,477	5,976	5,978	5,093
Quillayuta, WA	29,267	28,903	28,874	28,748	28,704	5,230	4,959	5,126	4,658
Seattle, WA	33,314	31,983	31,868	31,497	31,259	6,232	5,710	6,034	5,033
Kalispell, MT	36,167	34,398	34,288	33,321	33,144	6,639	6,216	6,029	5,197
Cut Bank, MT	35,486	34,272	34,174	33,611	33,457	6,394	5,935	6,030	5,115

Table: C-22 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Outpatient Health Care Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	9,697	8,365	8,198	7,762	7,611	3,736	3,538	3,373	3,088
Spokane, WA	8,469	7,656	7,561	7,231	7,143	3,392	3,266	3,110	2,934
Missoula, MT	8,322	7,548	7,454	7,153	7,089	3,184	3,079	2,945	2,807
Boise, ID	9,828	8,485	8,339	7,858	7,716	3,763	3,589	3,371	3,108
Pocatello, ID	8,989	8,074	7,960	7,583	7,503	3,364	3,227	3,047	2,871
Helena, MT	8,656	7,972	7,891	7,630	7,557	3,190	3,087	2,981	2,833
Astoria, OR	5,231	5,191	5,186	5,177	5,172	2,700	2,692	2,694	2,685
Salem, OR	7,897	7,243	7,154	6,926	6,862	3,046	2,940	2,876	2,755
Eugene, OR	7,886	7,159	7,065	6,848	6,777	3,057	2,942	2,886	2,759
North Bend, OR	4,583	4,557	4,556	4,556	4,555	2,684	2,684	2,684	2,683
Arcata, CA	4,433	4,384	4,384	4,381	4,381	2,685	2,684	2,684	2,683
Medford, OR	9,969	8,462	8,295	7,661	7,538	3,735	3,547	3,241	3,010
Redmond, OR	8,131	7,444	7,349	7,052	6,992	3,210	3,092	2,946	2,810
Portland, OR	7,733	7,105	7,022	6,854	6,783	3,021	2,910	2,902	2,758
Yakima, WA	8,869	7,749	7,605	7,244	7,138	3,381	3,213	3,097	2,888
Burns, OR	8,158	7,448	7,353	7,054	6,993	3,214	3,096	2,949	2,811
Olympia, WA	7,128	6,585	6,533	6,348	6,306	2,947	2,879	2,821	2,743
Quillayuta, WA	5,631	5,551	5,543	5,530	5,524	2,707	2,698	2,695	2,685
Seattle, WA	6,664	6,334	6,298	6,222	6,185	2,838	2,786	2,790	2,713
Kalispell, MT	7,719	7,278	7,214	7,043	6,998	2,962	2,890	2,824	2,735
Cut Bank, MT	7,742	7,486	7,447	7,355	7,325	2,865	2,813	2,784	2,720

Table: C-23 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Hospital Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	1,324,258	1,117,002	1,095,915	1,091,836	1,065,449	440,702	380,735	422,228	356,818
Spokane, WA	1,245,511	1,097,900	1,082,076	1,074,249	1,052,784	409,639	355,745	392,665	333,223
Missoula, MT	1,244,822	1,083,020	1,070,591	1,058,916	1,040,999	371,529	323,609	355,455	301,231
Boise, ID	1,345,011	1,185,125	1,168,529	1,151,263	1,130,000	456,289	402,908	433,492	375,726
Pocatello, ID	1,295,903	1,167,705	1,150,969	1,142,168	1,118,199	418,865	362,587	400,817	338,152
Helena, MT	1,272,125	1,193,306	1,176,173	1,177,855	1,154,496	354,358	298,212	345,055	281,041
Astoria, OR	1,093,803	895,651	875,778	888,520	863,377	334,863	267,851	329,485	252,889
Salem, OR	1,198,803	993,571	974,584	970,783	941,647	375,644	306,944	363,380	283,936
Eugene, OR	1,215,700	991,136	972,340	970,494	941,504	374,841	306,171	362,832	282,935
North Bend, OR	1,062,919	875,702	858,927	868,830	844,225	342,581	282,436	335,600	264,236
Arcata, CA	1,038,178	873,301	854,969	866,701	840,936	368,230	300,366	362,123	281,132
Medford, OR	1,308,969	1,102,225	1,079,997	1,074,957	1,043,199	435,389	367,235	417,158	339,510
Redmond, OR	1,254,928	1,098,585	1,081,427	1,077,405	1,053,925	416,000	364,142	394,764	333,907
Portland, OR	1,223,742	988,376	967,118	970,953	940,543	374,426	302,346	364,405	282,034
Yakima, WA	1,252,564	1,073,353	1,052,160	1,050,730	1,020,228	413,463	353,573	398,047	328,004
Burns, OR	1,255,433	1,099,002	1,081,836	1,077,819	1,054,327	416,096	364,197	394,865	333,968
Olympia, WA	1,154,597	956,063	938,990	938,491	912,270	353,569	286,408	344,217	266,262
Quillayuta, WA	1,055,489	897,132	880,628	889,015	868,322	329,762	266,849	323,173	249,561
Seattle, WA	1,165,511	953,780	933,034	942,645	915,197	356,993	287,623	349,398	270,608
Kalispell, MT	1,192,106	1,041,423	1,028,530	1,023,513	1,004,513	349,754	300,487	336,926	279,598
Cut Bank, MT	1,234,131	1,106,299	1,094,135	1,091,046	1,074,014	364,292	322,115	348,025	300,339

Table: C-24 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Hospital Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Ideal Low-Lift Chiller for LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	369,814	259,596	249,747	247,445	235,191	162,102	149,209	153,624	137,547
Spokane, WA	326,286	244,618	237,457	233,493	224,014	146,904	137,864	139,110	127,786
Missoula, MT	319,392	235,061	229,942	223,988	215,577	138,753	131,722	131,083	120,984
Boise, ID	365,064	275,983	268,020	256,480	245,544	171,059	160,266	158,012	145,863
Pocatello, ID	352,214	255,172	248,040	244,094	232,600	150,306	140,783	142,423	128,632
Helena, MT	340,056	242,444	235,943	232,024	222,427	141,366	132,251	134,275	122,491
Astoria, OR	288,947	196,993	190,503	194,662	186,303	101,175	94,566	100,061	92,181
Salem, OR	327,033	226,050	217,659	218,167	205,258	125,734	114,773	120,856	105,413
Eugene, OR	331,225	224,075	215,896	216,706	204,745	123,880	113,782	119,389	104,371
North Bend, OR	278,411	193,712	188,484	191,624	184,209	101,557	95,371	100,413	92,520
Arcata, CA	268,878	192,091	186,899	190,137	183,009	112,869	106,414	111,928	104,347
Medford, OR	367,911	260,313	250,070	247,316	233,504	161,285	147,660	152,748	133,319
Redmond, OR	324,636	240,724	233,639	231,329	219,557	143,529	134,348	136,743	122,396
Portland, OR	336,514	223,280	213,864	217,398	204,619	122,957	111,307	119,229	103,469
Yakima, WA	344,908	247,560	237,558	238,447	224,746	152,591	139,710	146,364	128,395
Burns, OR	324,628	240,700	233,613	231,312	219,539	143,460	134,276	136,680	122,332
Olympia, WA	311,586	214,483	207,602	207,964	197,429	114,950	106,004	111,811	99,215
Quillayuta, WA	269,622	194,663	189,215	192,098	185,384	100,695	95,588	99,198	92,422
Seattle, WA	309,617	209,403	201,384	205,886	195,679	112,497	102,861	110,328	97,822
Kalispell, MT	299,106	220,725	215,556	214,637	206,520	126,783	120,198	122,295	111,815
Cut Bank, MT	296,869	220,714	216,213	214,753	207,897	124,603	118,488	120,436	111,251

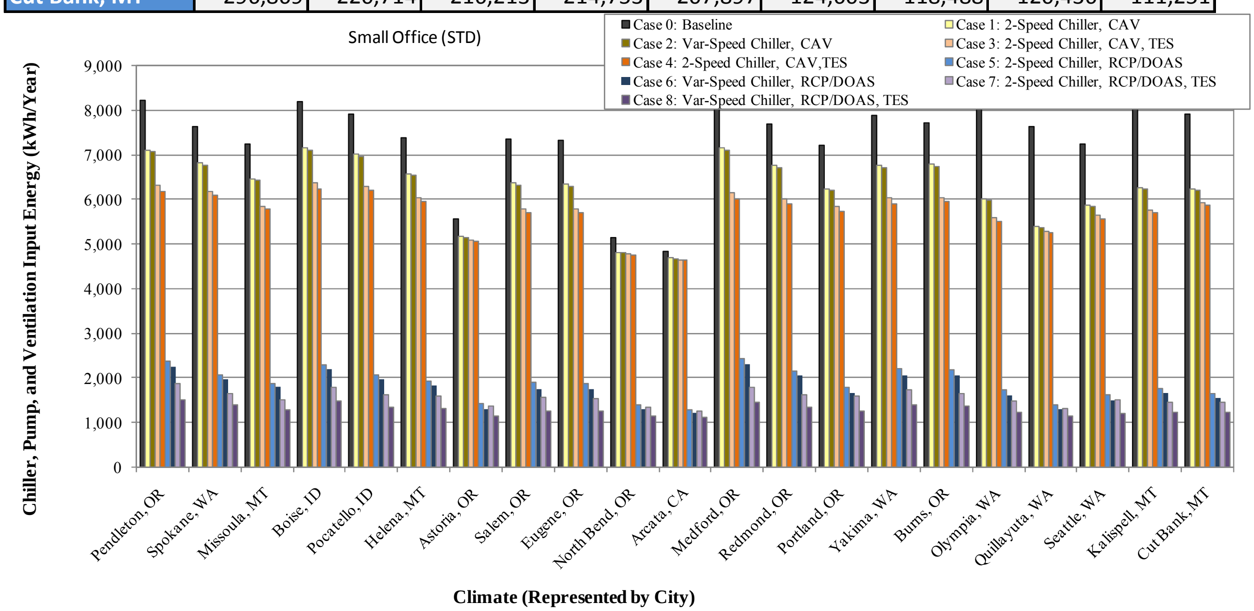

Figure: C-1 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Small Office Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

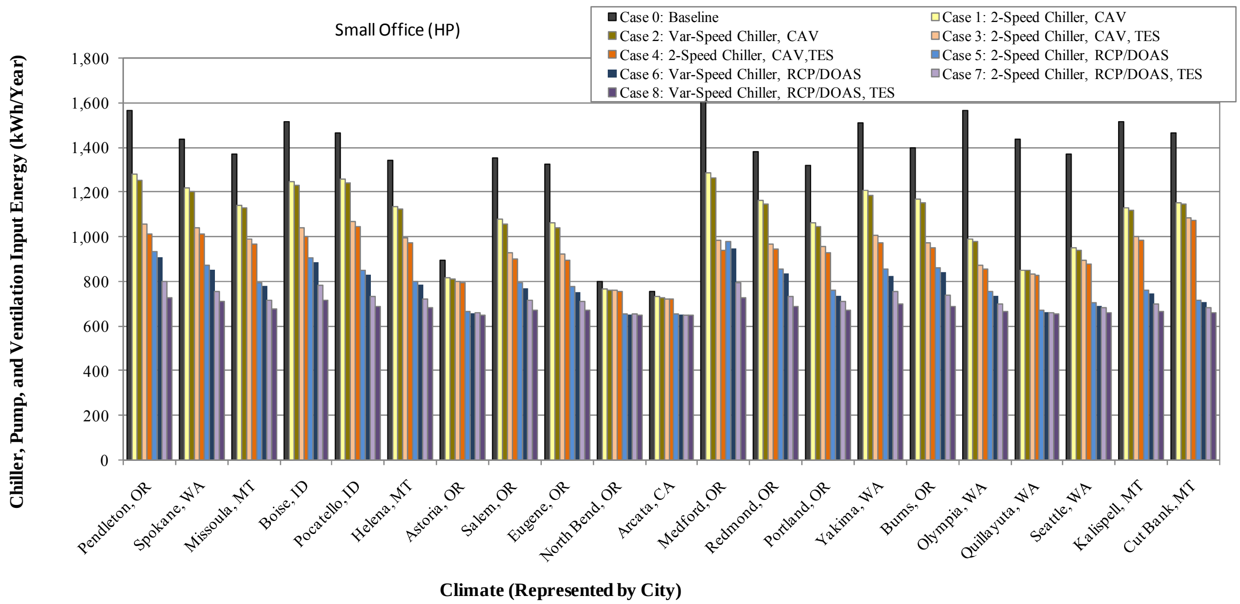

Figure: C-2 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Small Office Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

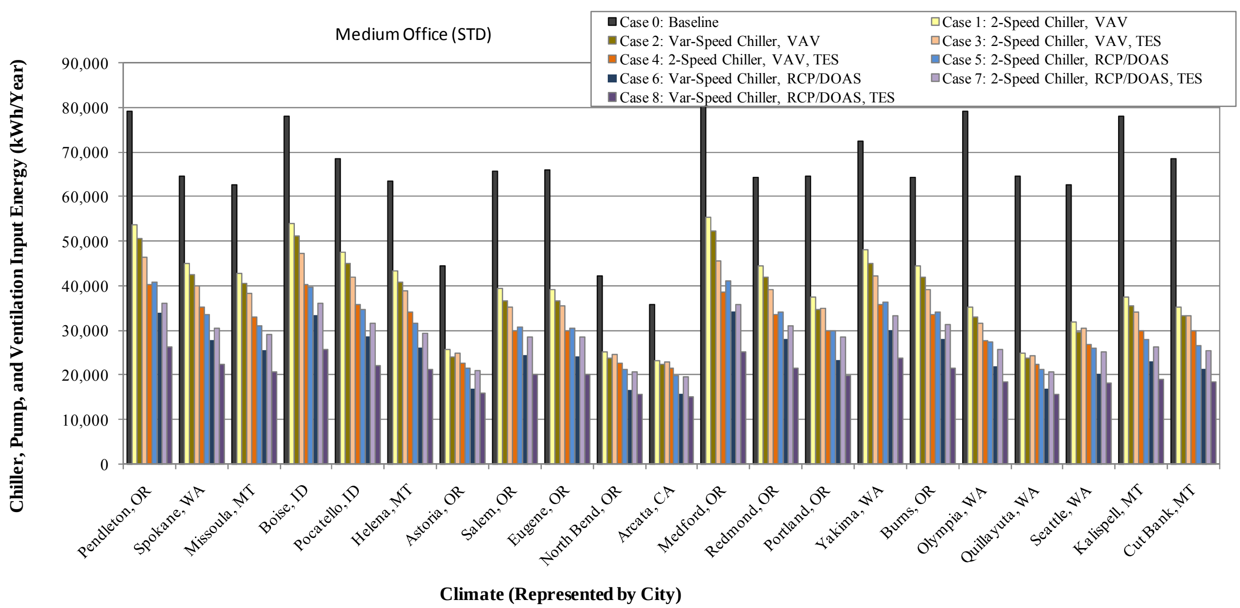

Figure: C-3 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Medium Office Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

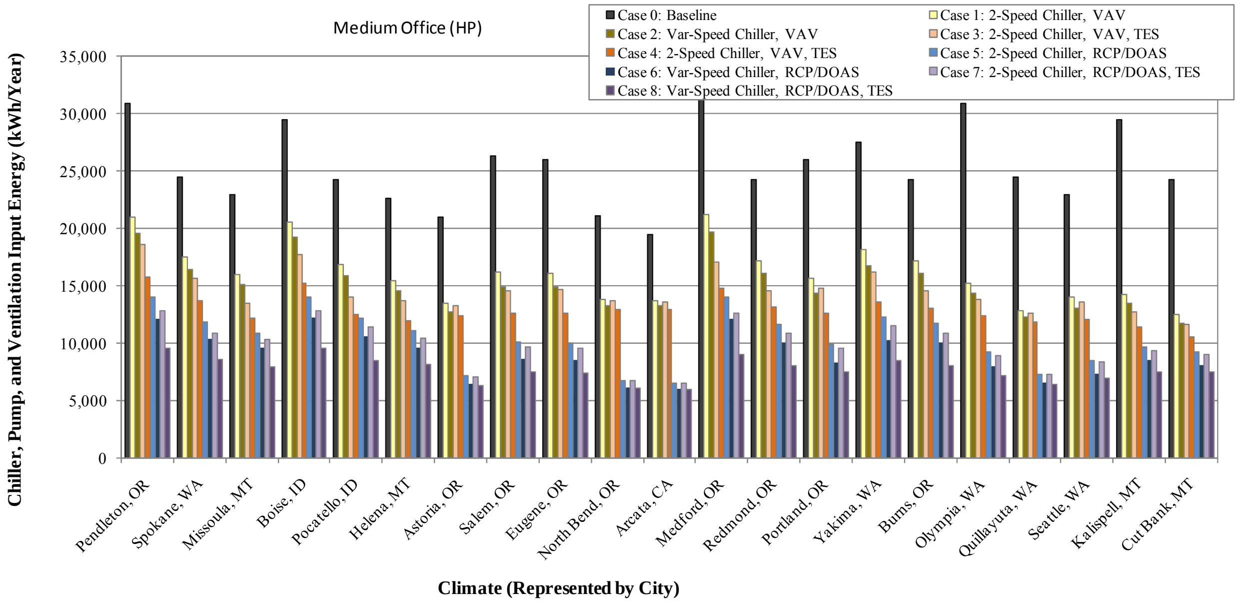

Figure: C-4 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Medium Office Building for Various System Configurations in 16 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

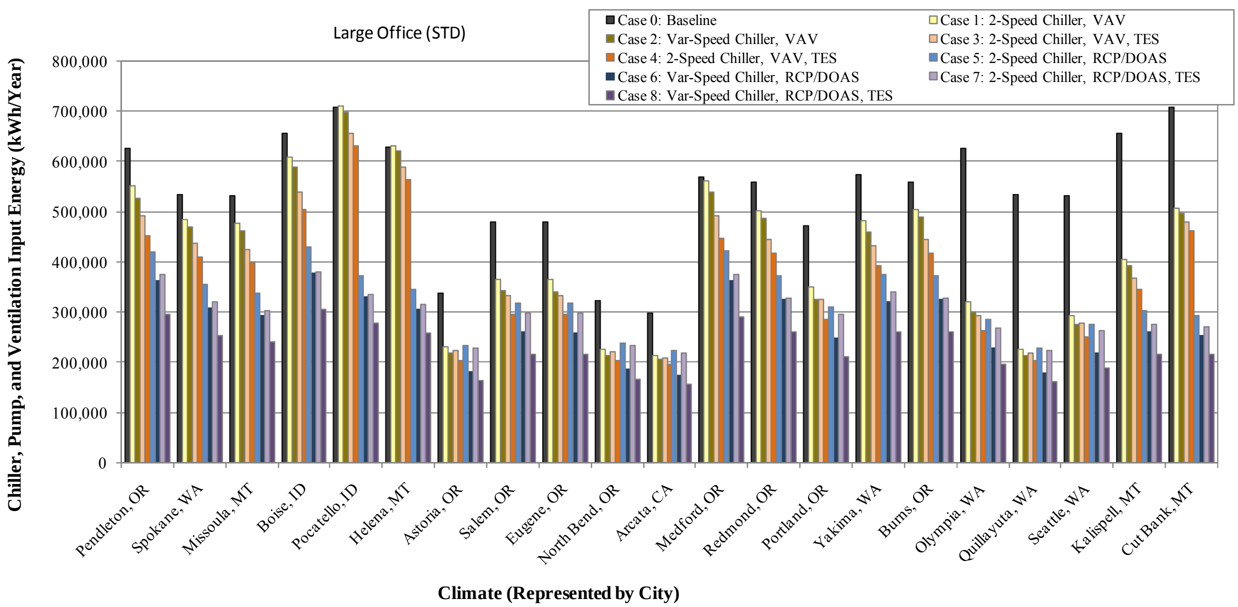

Figure: C-5 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Large Office Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

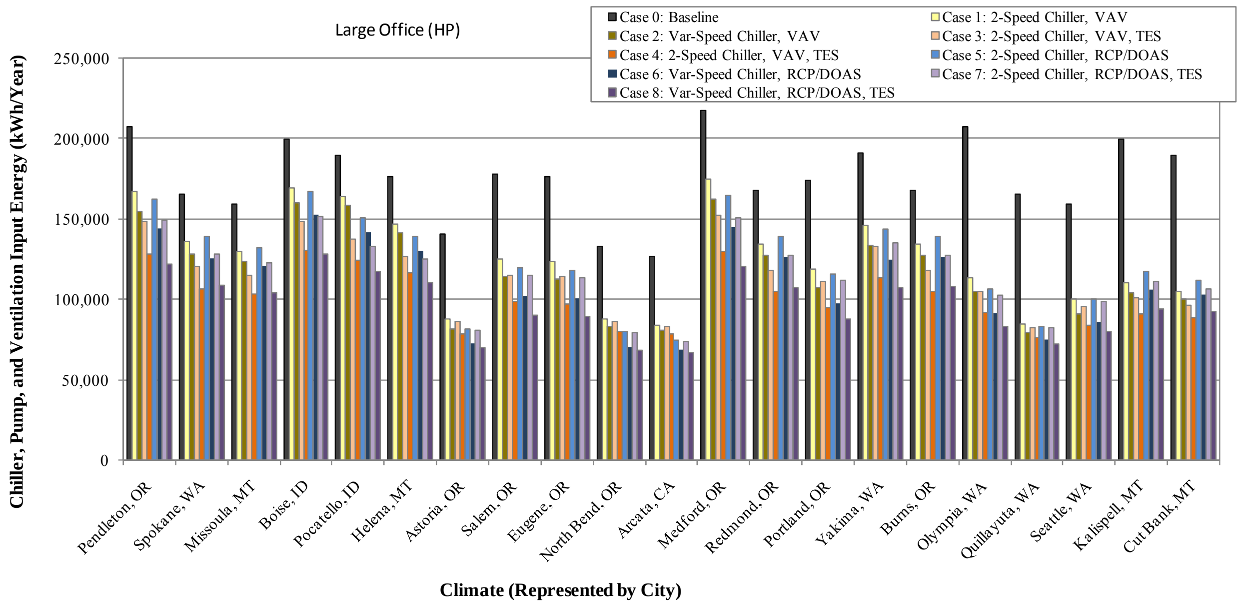

Figure: C-6 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Large Office Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

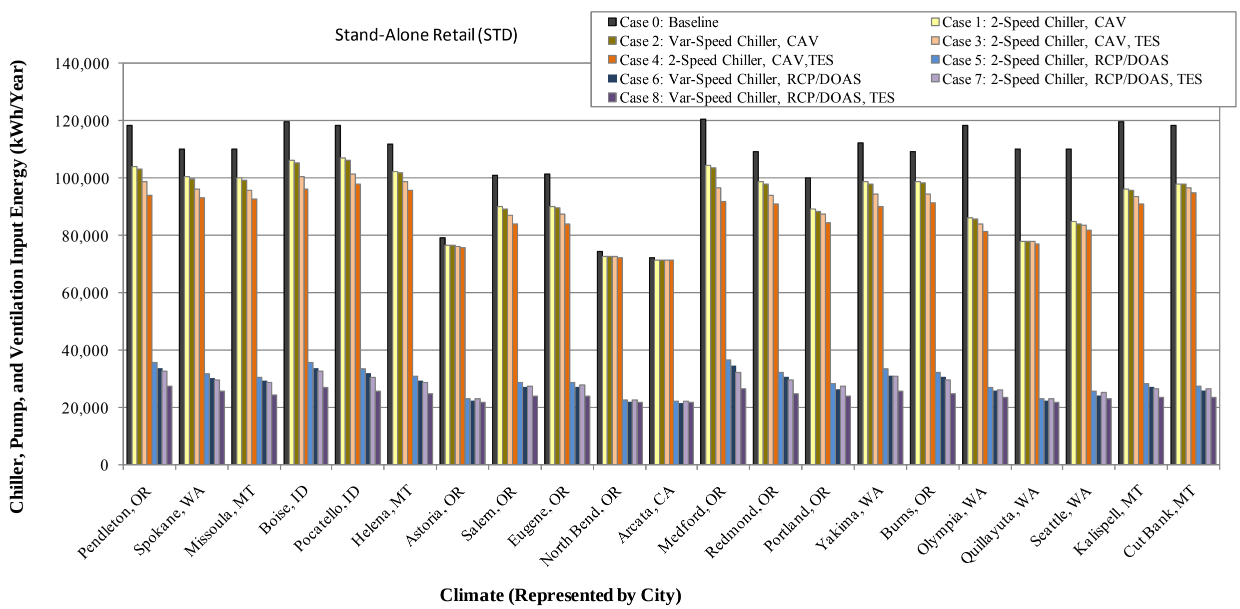

Figure: C-7 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Stand-Alone Retail Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

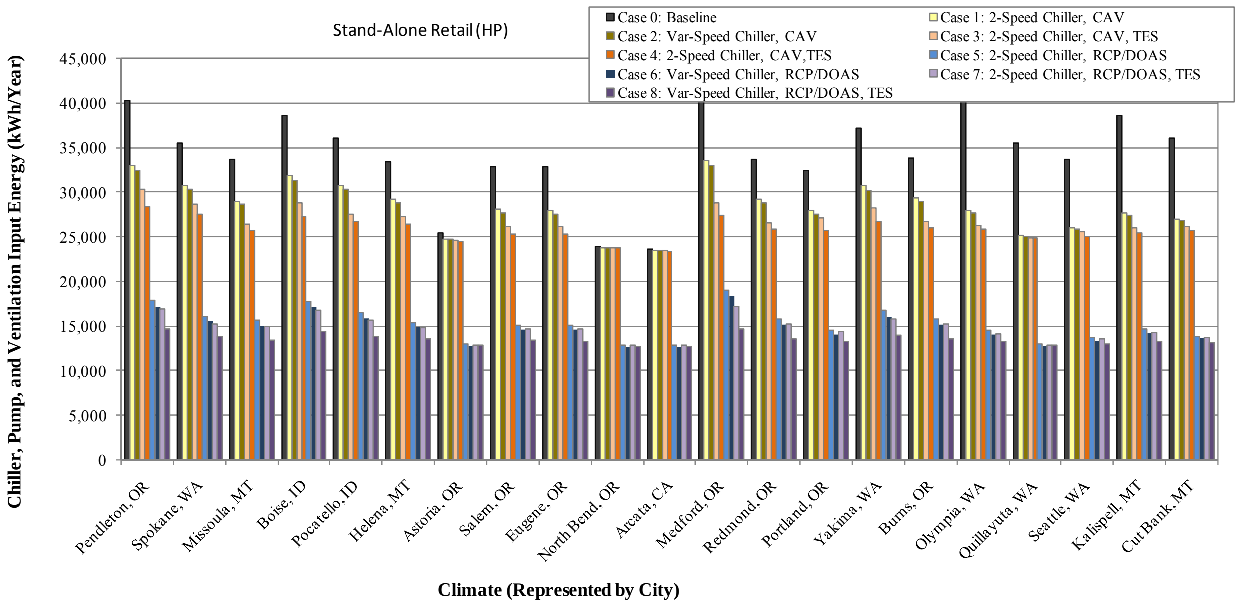

Figure: C-8 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Stand-Alone Retail Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

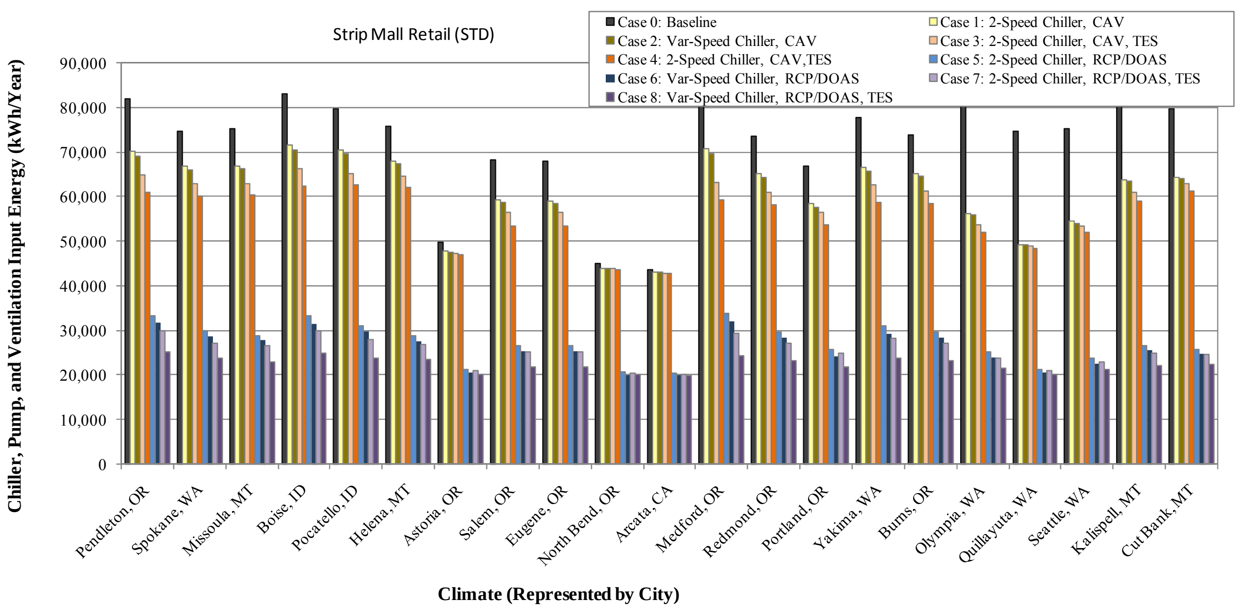

Figure: C-9 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Strip Mall Retail Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

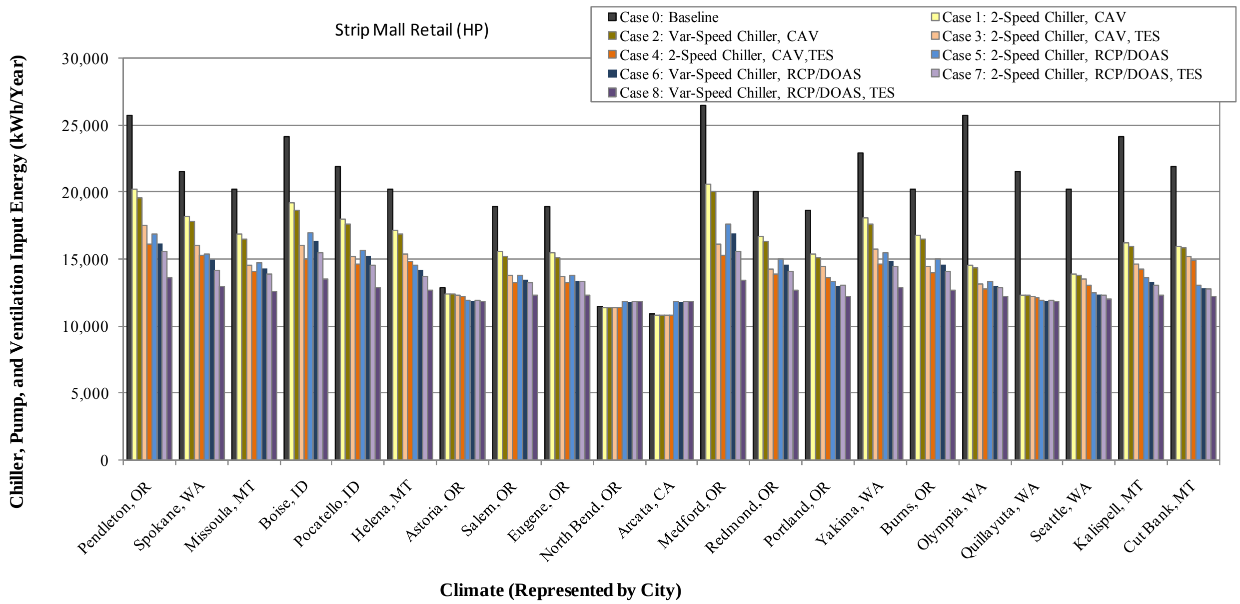

Figure: C-10 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Strip Mall Retail Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

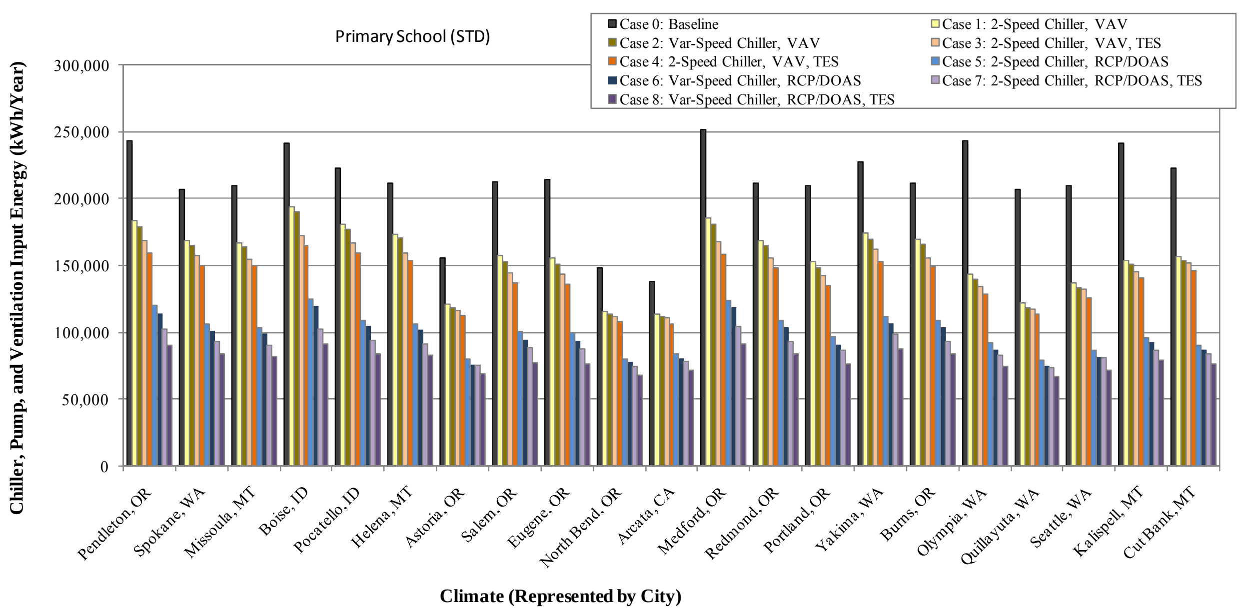

Figure: C-11 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Primary School Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

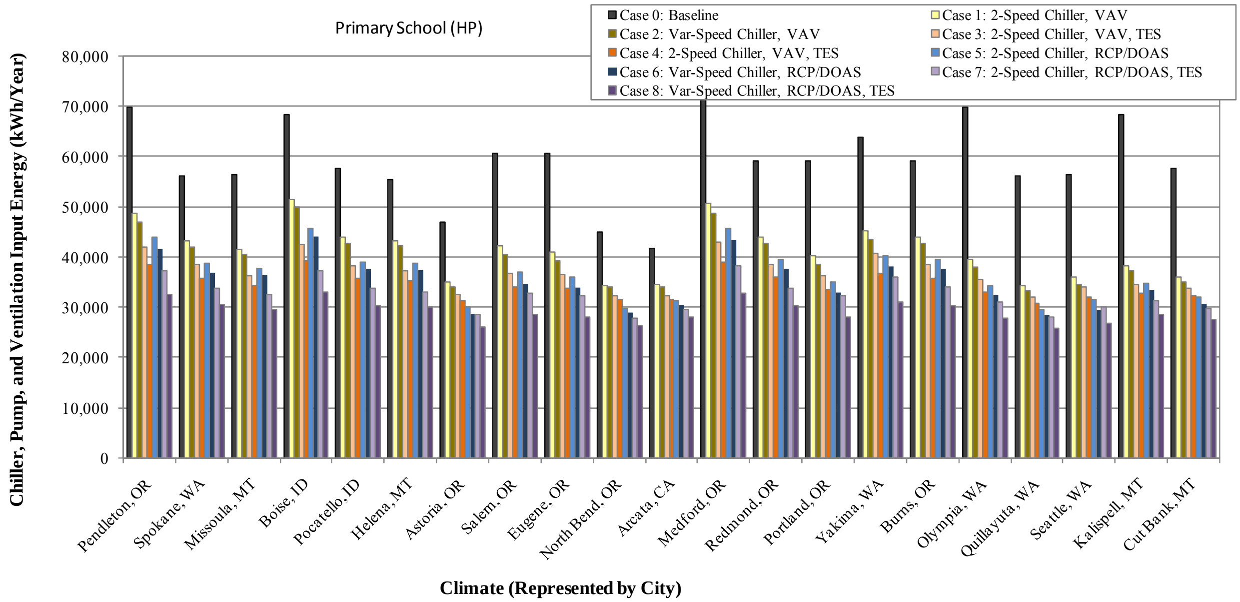

Figure: C-12 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Primary School Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

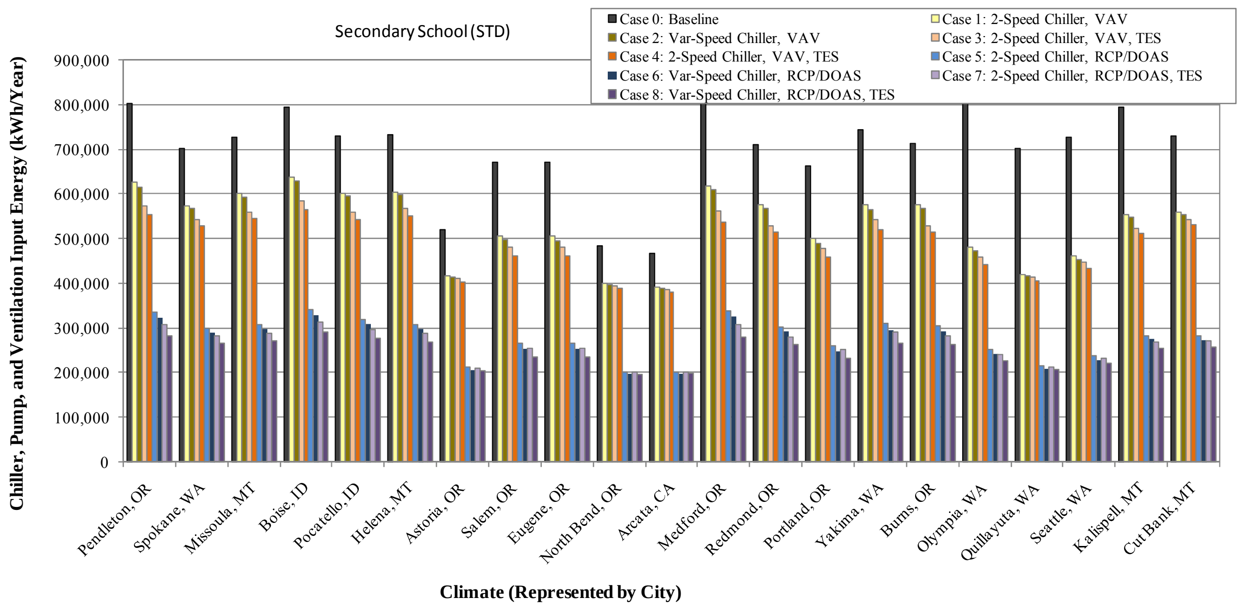

Figure: C-13 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Secondary School Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

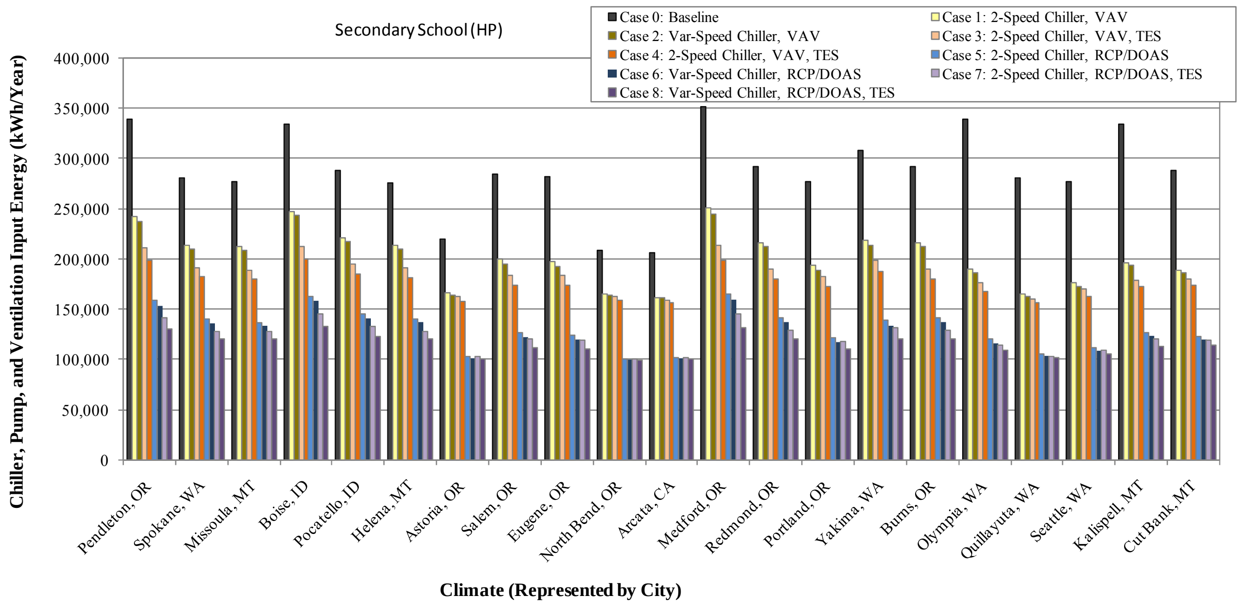

Figure: C-14 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Secondary School Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

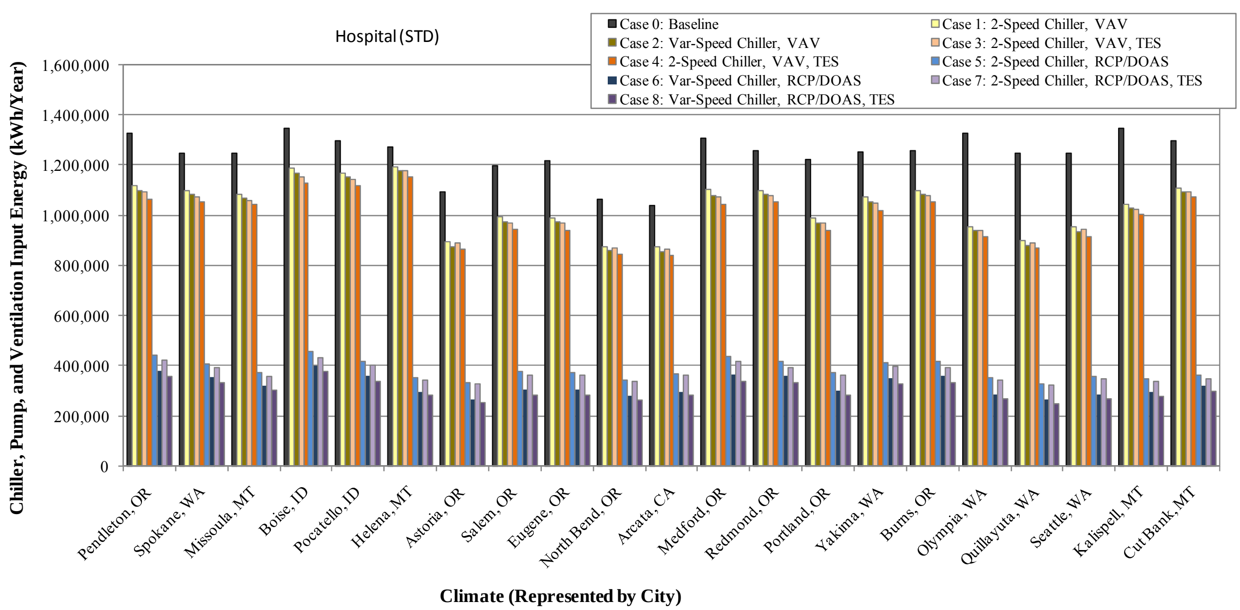

Figure: C-15 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Hospital Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

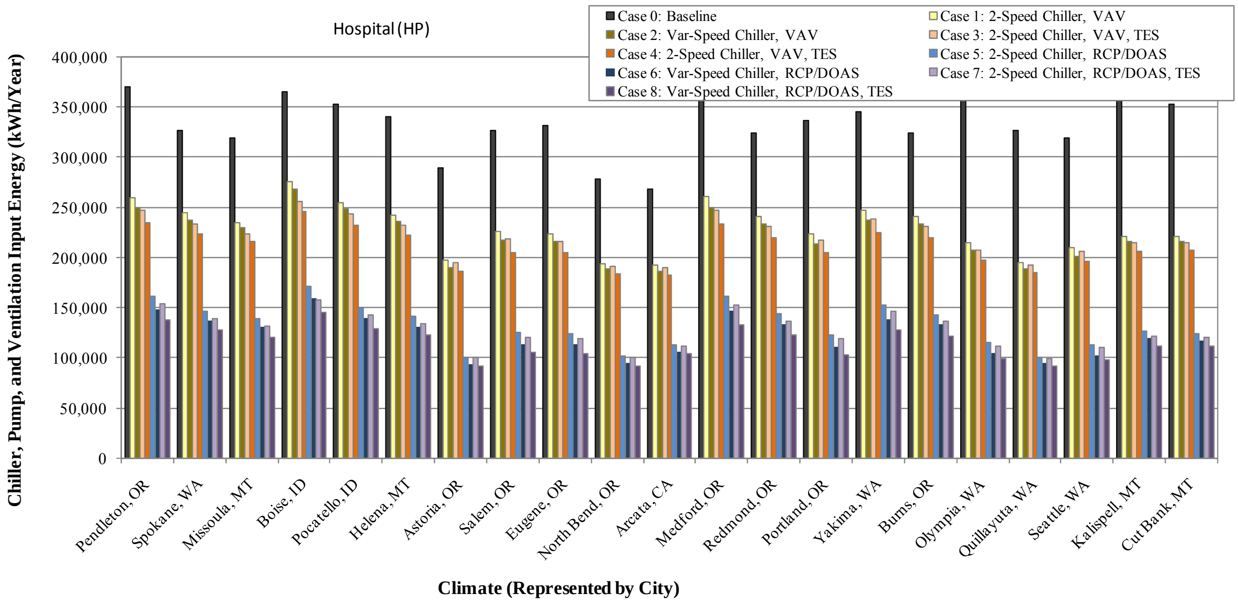

Figure: C-16 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Hospital Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

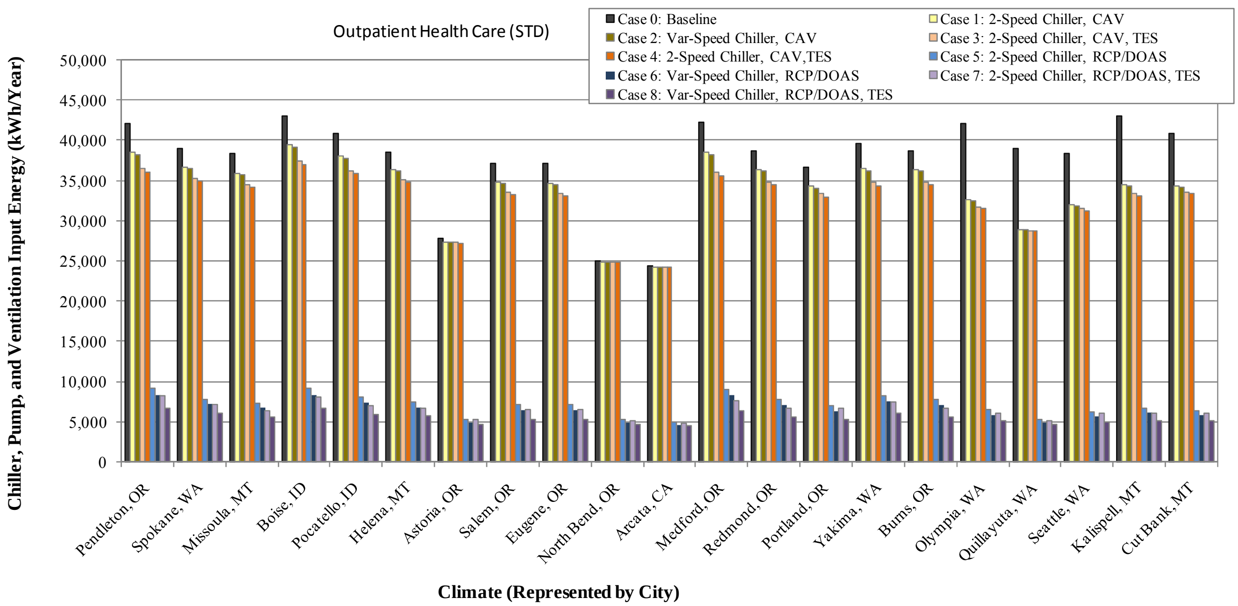

Figure: C-17 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Outpatient Health Care Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

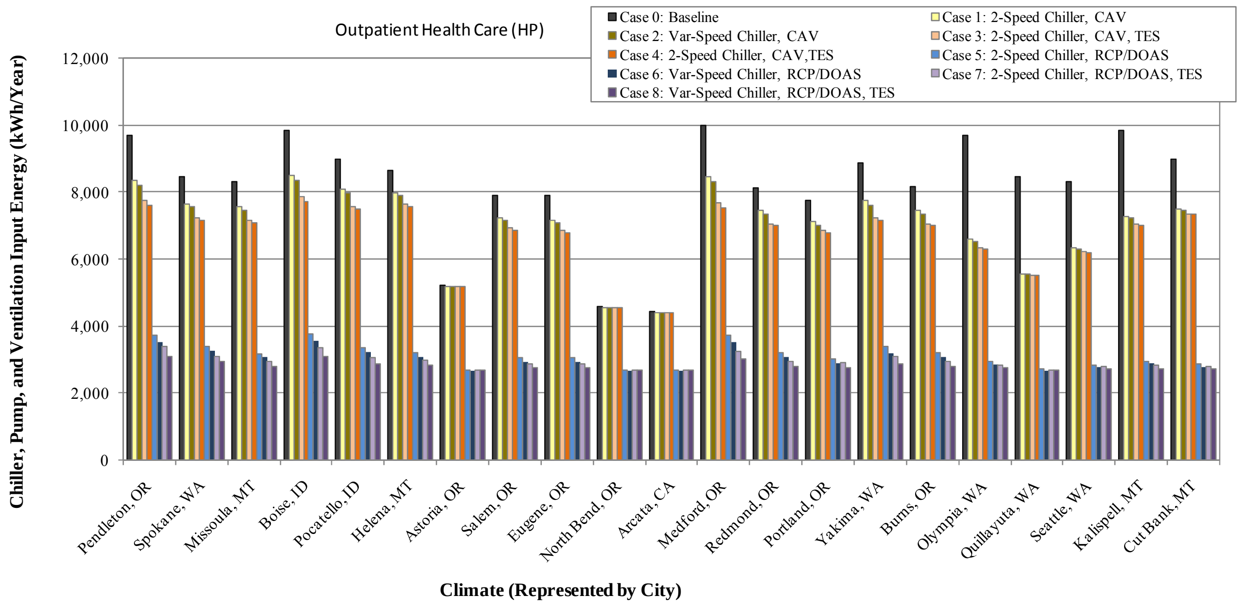

Figure: C-18 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Outpatient Health Care Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

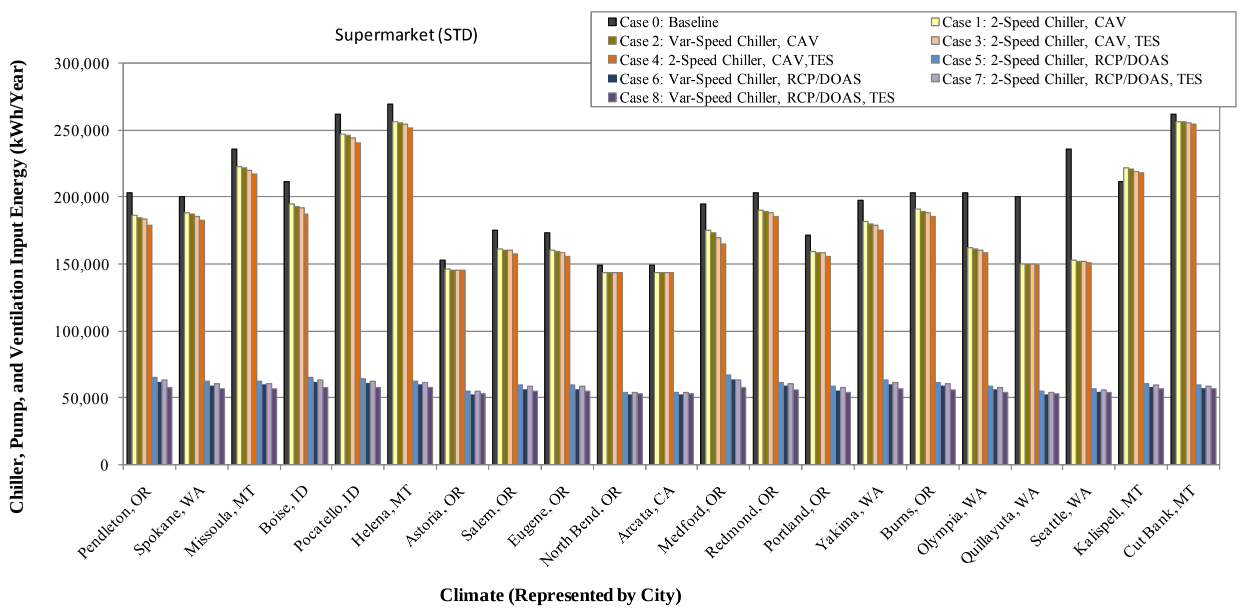

Figure: C-19 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Supermarket Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

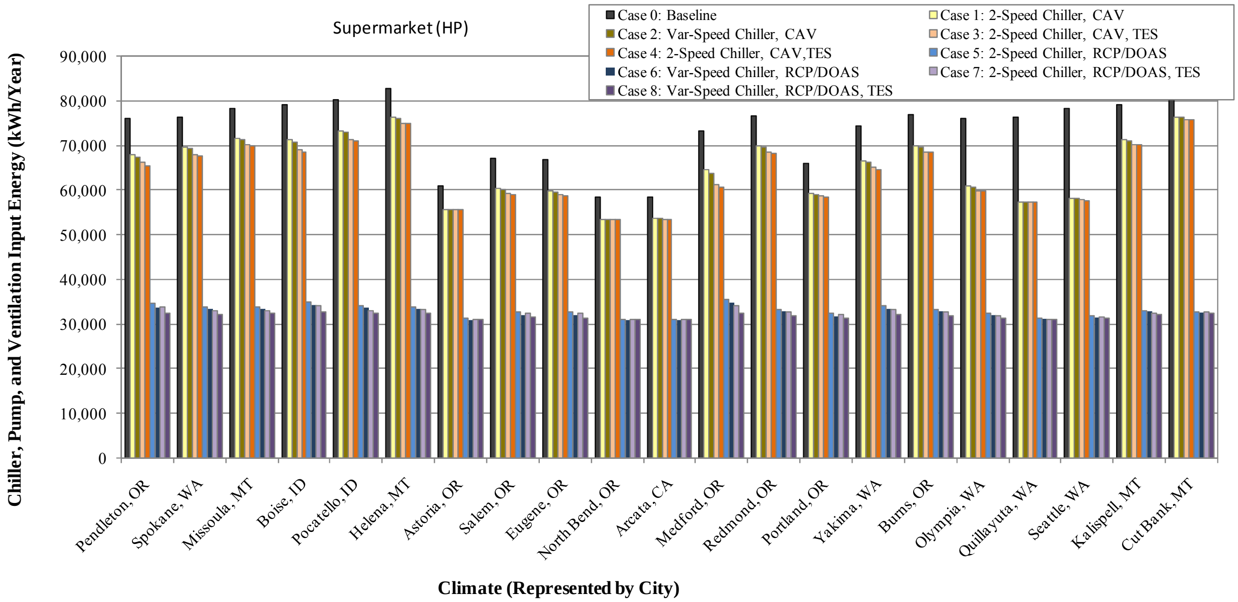

Figure: C-20 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Supermarket Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

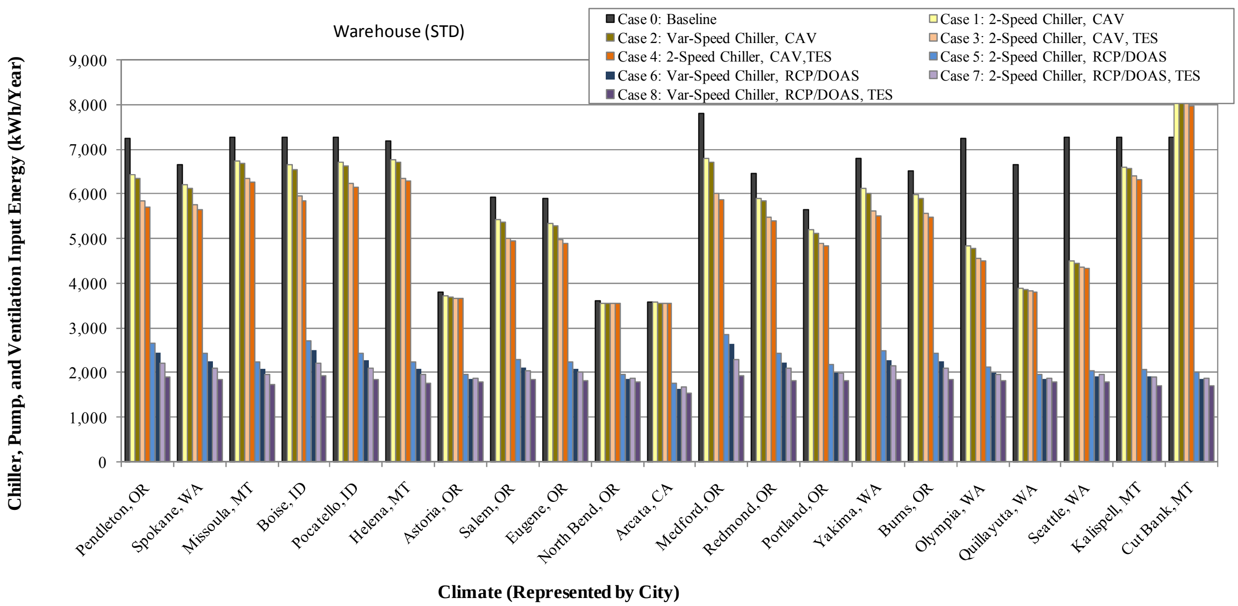

Figure: C-21 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Warehouse Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

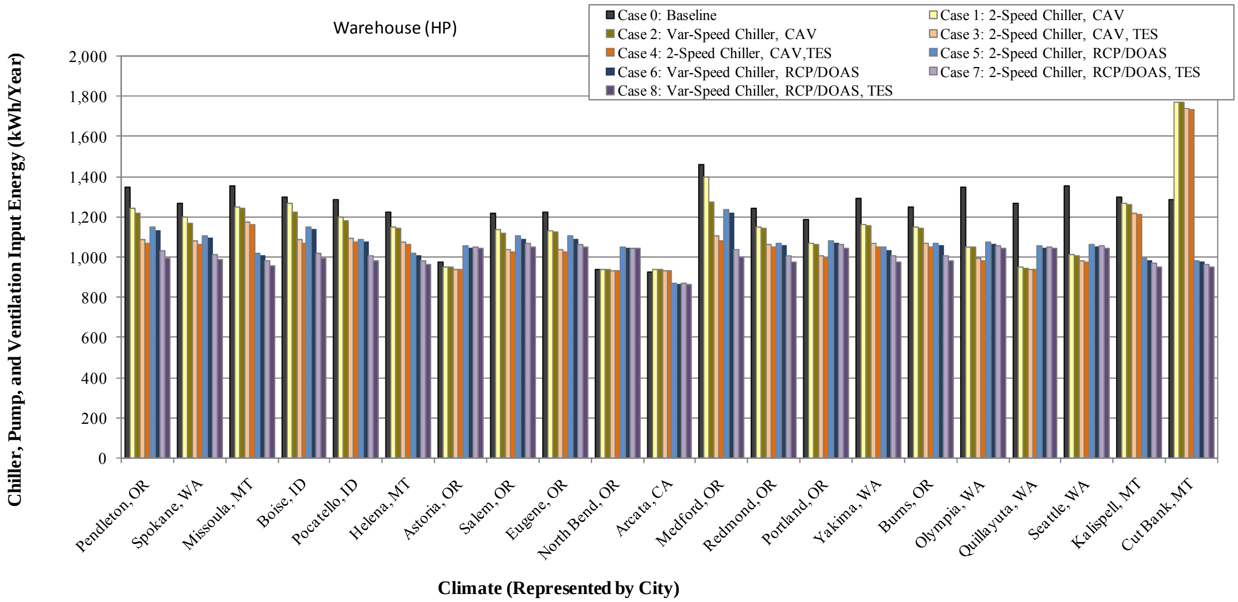

Figure: C-22 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Warehouse Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

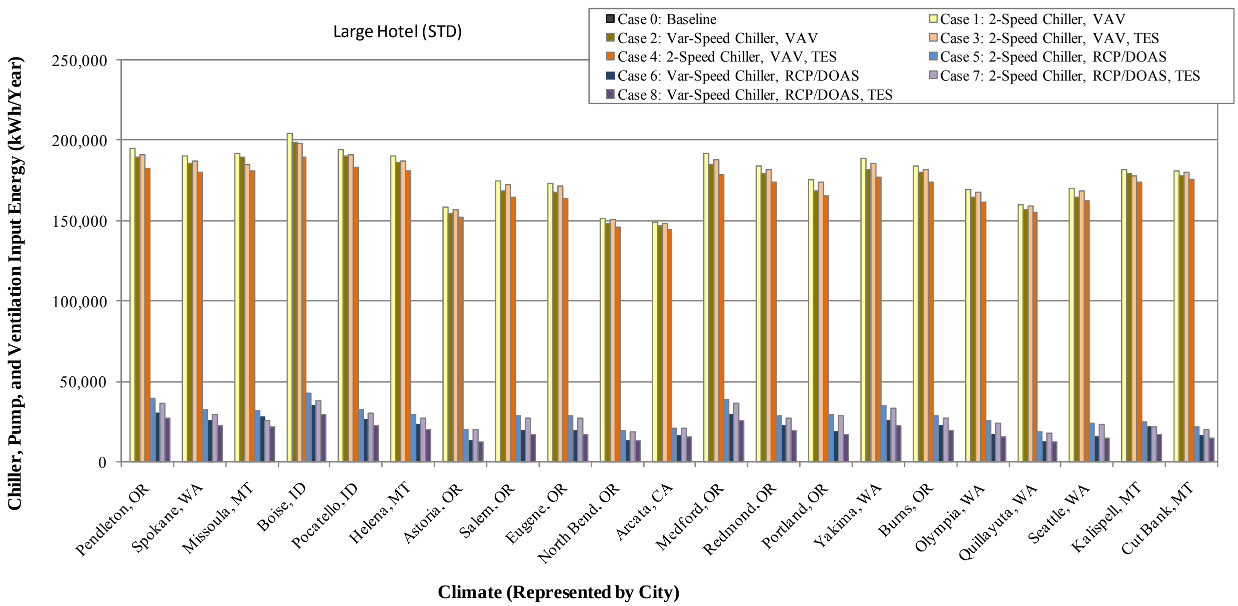

Figure: C-23 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Large Hotel Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

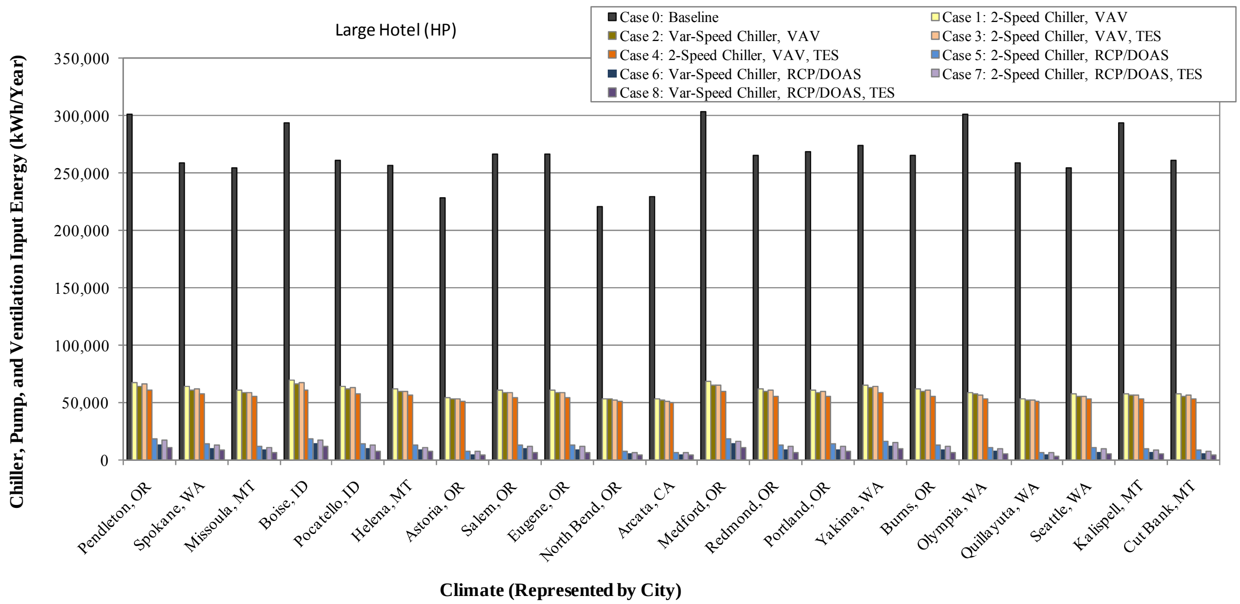

Figure: C-24 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Large Hotel Building for Various System Configurations in 21 Locations with Ideal Low-Lift Chiller for the LLCS Configurations

Table: C-25 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Small Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	8,231	7,931	7,860	6,735	6,589	2,672	2,537	1,928	1,672
Spokane, WA	7,636	7,400	7,350	6,483	6,384	2,301	2,190	1,654	1,495
Missoula, MT	7,250	6,950	6,910	6,077	5,995	2,049	1,951	1,476	1,343
Boise, ID	8,181	7,943	7,879	6,758	6,625	2,572	2,445	1,848	1,634
Pocatello, ID	7,914	7,616	7,566	6,575	6,480	2,286	2,173	1,544	1,402
Helena, MT	7,389	7,069	7,023	6,270	6,178	2,108	1,999	1,545	1,396
Astoria, OR	5,564	5,254	5,226	5,138	5,096	1,507	1,390	1,330	1,148
Salem, OR	7,356	6,857	6,800	6,034	5,921	2,072	1,937	1,482	1,290
Eugene, OR	7,317	6,808	6,750	6,028	5,906	2,038	1,906	1,457	1,284
North Bend, OR	5,144	4,866	4,845	4,812	4,776	1,464	1,363	1,287	1,134
Arcata, CA	4,844	4,717	4,709	4,665	4,650	1,347	1,255	1,198	1,117
Medford, OR	8,383	8,063	7,990	6,548	6,411	2,760	2,616	1,770	1,569
Redmond, OR	7,678	7,382	7,324	6,282	6,196	2,400	2,267	1,490	1,382
Portland, OR	7,200	6,649	6,588	6,044	5,919	1,959	1,819	1,572	1,310
Yakima, WA	7,886	7,462	7,392	6,367	6,249	2,438	2,294	1,677	1,488
Burns, OR	7,717	7,424	7,366	6,319	6,232	2,409	2,275	1,495	1,385
Olympia, WA	6,817	6,379	6,334	5,768	5,678	1,866	1,747	1,388	1,239
Quillayuta, WA	5,708	5,484	5,461	5,334	5,299	1,472	1,372	1,233	1,138
Seattle, WA	6,569	6,121	6,076	5,770	5,678	1,727	1,611	1,450	1,232
Kalispell, MT	6,975	6,654	6,618	5,949	5,874	1,893	1,798	1,334	1,241
Cut Bank, MT	6,811	6,503	6,465	6,058	5,993	1,762	1,664	1,349	1,239

Table: C-26 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Small Office Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	1,567	1,515	1,485	1,167	1,124	1,000	975	826	769
Spokane, WA	1,436	1,394	1,374	1,121	1,092	924	908	773	734
Missoula, MT	1,369	1,276	1,259	1,047	1,020	827	812	708	679
Boise, ID	1,514	1,469	1,444	1,137	1,099	965	945	806	752
Pocatello, ID	1,464	1,418	1,399	1,141	1,112	892	876	728	697
Helena, MT	1,339	1,266	1,251	1,054	1,029	835	822	727	694
Astoria, OR	892	834	830	808	801	669	665	658	651
Salem, OR	1,353	1,210	1,187	987	954	822	802	709	676
Eugene, OR	1,322	1,184	1,163	981	948	806	787	706	673
North Bend, OR	797	773	770	765	761	655	653	652	650
Arcata, CA	753	735	734	726	725	654	653	650	650
Medford, OR	1,656	1,563	1,533	1,096	1,054	1,059	1,033	806	754
Redmond, OR	1,381	1,328	1,307	1,039	1,015	902	884	722	697
Portland, OR	1,317	1,166	1,145	1,007	974	782	763	716	677
Yakima, WA	1,511	1,400	1,371	1,097	1,061	900	877	759	716
Burns, OR	1,397	1,334	1,313	1,041	1,017	906	887	723	697
Olympia, WA	1,217	1,090	1,076	918	895	778	764	694	671
Quillayuta, WA	906	872	867	841	835	673	669	656	651
Seattle, WA	1,117	1,007	994	925	903	718	707	686	661
Kalispell, MT	1,311	1,232	1,217	1,049	1,027	787	774	682	664
Cut Bank, MT	1,272	1,213	1,203	1,114	1,099	731	723	676	662

Table: C-27 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Retail Standalone Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	118,089	114,142	112,917	102,043	99,065	38,757	36,932	34,725	29,447
Spokane, WA	110,142	107,187	106,353	98,578	96,543	34,113	32,794	30,754	26,864
Missoula, MT	109,914	106,285	105,569	97,082	95,413	32,462	31,279	28,965	25,294
Boise, ID	119,369	116,013	114,919	103,599	100,941	38,806	37,113	34,322	29,187
Pocatello, ID	118,467	114,833	113,921	103,639	101,592	36,171	34,638	31,123	26,851
Helena, MT	111,572	108,050	107,295	100,351	98,499	32,662	31,269	29,736	25,877
Astoria, OR	79,247	77,234	77,020	76,563	76,001	23,584	22,852	23,247	22,038
Salem, OR	100,983	95,537	94,656	88,097	86,223	30,393	29,078	28,451	24,319
Eugene, OR	101,319	95,776	94,897	88,284	86,424	30,400	29,097	28,624	24,294
North Bend, OR	74,433	73,025	72,854	72,824	72,463	23,051	22,359	22,833	21,887
Arcata, CA	72,297	71,671	71,609	71,451	71,272	22,359	21,947	22,144	21,683
Medford, OR	120,264	115,903	114,637	99,467	96,992	40,130	38,359	33,649	28,360
Redmond, OR	108,931	105,408	104,500	95,641	93,947	34,477	32,872	29,156	25,632
Portland, OR	99,928	94,086	93,124	89,059	86,496	29,449	27,978	28,347	24,736
Yakima, WA	112,325	107,408	106,265	96,519	94,115	35,870	34,056	31,929	27,162
Burns, OR	109,217	105,680	104,771	95,882	94,190	34,522	32,913	29,184	25,634
Olympia, WA	94,844	90,341	89,682	84,775	83,200	28,341	27,231	26,677	23,812
Quillayuta, WA	80,522	78,762	78,526	78,013	77,504	23,499	22,862	23,017	22,080
Seattle, WA	91,403	87,310	86,692	85,079	83,140	26,530	25,420	25,791	23,403
Kalispell, MT	104,306	100,761	100,188	94,256	92,848	29,606	28,563	26,461	23,916
Cut Bank, MT	104,167	101,101	100,564	97,260	96,077	28,576	27,312	26,920	24,089

Table: C-28 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Retail Standalone Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	40,281	37,902	37,125	31,646	30,676	19,114	18,470	17,683	15,433
Spokane, WA	35,469	33,946	33,468	29,576	28,934	16,881	16,456	15,551	14,307
Missoula, MT	33,689	31,800	31,380	27,389	26,873	16,187	15,814	14,550	13,667
Boise, ID	38,519	36,627	35,961	30,317	29,404	18,930	18,335	17,375	15,242
Pocatello, ID	36,108	34,256	33,733	28,822	28,206	17,326	16,856	15,085	14,062
Helena, MT	33,353	31,686	31,287	27,996	27,470	15,896	15,553	14,842	13,763
Astoria, OR	25,472	24,967	24,926	24,701	24,604	12,982	12,934	12,912	12,797
Salem, OR	32,839	30,464	29,959	26,850	26,270	15,660	15,267	14,492	13,479
Eugene, OR	32,889	30,403	29,907	26,865	26,242	15,588	15,191	14,614	13,444
North Bend, OR	23,961	23,822	23,812	23,761	23,738	12,805	12,794	12,789	12,771
Arcata, CA	23,581	23,507	23,502	23,432	23,413	12,801	12,794	12,782	12,773
Medford, OR	41,322	39,231	38,454	30,537	29,700	20,582	19,947	16,977	15,321
Redmond, OR	33,731	32,133	31,635	27,590	27,103	16,448	15,994	14,312	13,672
Portland, OR	32,458	29,910	29,428	27,289	26,578	14,977	14,555	14,671	13,485
Yakima, WA	37,203	34,642	33,948	29,198	28,434	17,593	17,004	15,899	14,396
Burns, OR	33,886	32,276	31,777	27,723	27,222	16,471	16,014	14,338	13,682
Olympia, WA	31,714	29,665	29,365	26,884	26,495	14,873	14,590	13,903	13,319
Quillayuta, WA	25,778	25,336	25,276	25,017	24,945	12,983	12,939	12,872	12,797
Seattle, WA	28,525	27,022	26,780	25,864	25,406	13,830	13,605	13,656	13,109
Kalispell, MT	31,289	29,601	29,266	26,636	26,203	15,015	14,728	13,659	13,230
Cut Bank, MT	29,294	28,125	27,886	26,519	26,200	14,098	13,896	13,566	13,129

Table: C-29 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Retail Strip Mall Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	81,844	79,354	78,109	68,188	65,628	36,269	34,669	31,601	27,045
Spokane, WA	74,669	72,906	72,058	64,909	63,203	31,994	30,798	28,407	24,949
Missoula, MT	75,083	72,642	71,863	64,071	62,782	30,682	29,569	26,474	23,711
Boise, ID	82,911	80,614	79,358	69,065	66,770	36,244	34,576	31,613	26,930
Pocatello, ID	79,797	77,410	76,490	67,115	65,534	33,443	32,065	28,150	24,770
Helena, MT	75,656	73,182	72,418	66,069	64,542	30,718	29,461	27,547	24,251
Astoria, OR	49,692	48,337	48,177	47,654	47,224	21,440	20,967	21,153	20,292
Salem, OR	68,075	64,169	63,351	57,136	55,665	27,924	26,825	25,566	22,259
Eugene, OR	67,989	64,050	63,233	57,068	55,520	28,011	26,890	25,767	22,267
North Bend, OR	45,014	44,210	44,107	44,008	43,808	20,751	20,391	20,616	20,068
Arcata, CA	43,569	43,206	43,170	42,971	42,846	20,420	20,217	20,233	19,992
Medford, OR	83,756	80,919	79,574	65,574	63,566	37,184	35,550	30,288	25,905
Redmond, OR	73,489	71,034	70,196	62,002	60,714	31,808	30,499	26,334	23,632
Portland, OR	66,850	62,605	61,705	57,666	55,757	26,997	25,791	25,773	22,520
Yakima, WA	77,700	74,183	73,059	64,182	62,145	33,359	31,805	29,321	24,978
Burns, OR	73,703	71,242	70,402	62,180	60,882	31,851	30,536	26,357	23,652
Olympia, WA	63,081	59,976	59,365	54,690	53,451	26,128	25,212	24,197	21,891
Quillayuta, WA	51,125	49,927	49,749	49,219	48,791	21,504	21,087	21,047	20,295
Seattle, WA	59,775	56,902	56,351	54,599	53,113	24,424	23,519	23,637	21,502
Kalispell, MT	70,211	67,782	67,243	61,817	60,624	27,892	26,995	24,337	22,317
Cut Bank, MT	68,972	66,935	66,455	63,457	62,492	26,813	25,836	24,999	22,661

Table: C-30 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Retail Strip Mall Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	25,753	24,304	23,588	18,785	18,049	18,004	17,431	16,249	14,341
Spokane, WA	21,539	20,831	20,402	16,973	16,503	16,140	15,787	14,500	13,418
Missoula, MT	20,208	19,173	18,761	15,385	14,984	15,322	15,005	13,404	12,737
Boise, ID	24,097	23,217	22,576	17,544	16,870	18,142	17,625	15,996	14,300
Pocatello, ID	21,925	20,952	20,491	16,283	15,807	16,512	16,116	13,987	13,170
Helena, MT	20,194	19,250	18,884	16,103	15,683	15,102	14,802	13,763	12,889
Astoria, OR	12,842	12,550	12,526	12,338	12,280	11,974	11,943	11,904	11,840
Salem, OR	18,956	17,507	17,071	14,455	14,017	14,255	13,964	12,977	12,373
Eugene, OR	18,947	17,416	16,987	14,449	14,000	14,218	13,921	13,029	12,362
North Bend, OR	11,456	11,409	11,404	11,377	11,367	11,828	11,824	11,819	11,814
Arcata, CA	10,897	10,850	10,846	10,802	10,792	11,825	11,821	11,816	11,809
Medford, OR	26,486	25,461	24,702	17,804	17,119	18,985	18,392	15,280	14,025
Redmond, OR	20,067	19,063	18,648	15,213	14,841	15,662	15,297	13,356	12,794
Portland, OR	18,614	16,955	16,552	14,736	14,269	13,627	13,365	13,238	12,347
Yakima, WA	22,925	21,290	20,671	16,609	16,031	16,251	15,772	14,473	13,268
Burns, OR	20,186	19,198	18,778	15,334	14,961	15,677	15,308	13,352	12,799
Olympia, WA	17,156	15,998	15,738	13,636	13,353	13,628	13,418	12,635	12,259
Quillayuta, WA	12,689	12,460	12,416	12,223	12,176	11,987	11,963	11,877	11,838
Seattle, WA	15,519	14,651	14,466	13,622	13,340	12,647	12,533	12,433	12,043
Kalispell, MT	18,742	17,718	17,413	15,201	14,894	13,982	13,752	12,625	12,259
Cut Bank, MT	17,561	16,861	16,676	15,524	15,304	13,282	13,133	12,596	12,275

Table: C-31 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Primary School Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	243,164	214,781	208,853	188,616	178,150	130,238	126,058	105,157	96,872
Spokane, WA	207,206	191,977	187,557	171,660	163,939	114,419	111,084	96,540	88,767
Missoula, MT	209,978	186,149	182,712	167,159	160,770	109,997	106,935	91,917	85,473
Boise, ID	241,603	228,325	223,562	193,821	184,087	138,322	133,781	107,607	98,965
Pocatello, ID	222,833	205,268	201,199	181,448	174,273	117,578	114,165	96,740	89,384
Helena, MT	211,233	193,876	190,146	172,104	165,660	114,142	110,702	93,539	86,775
Astoria, OR	155,433	130,619	127,022	122,802	118,078	83,472	80,446	76,179	69,676
Salem, OR	212,800	179,660	174,127	158,221	149,490	108,986	103,104	90,203	80,441
Eugene, OR	214,339	176,280	170,971	157,364	148,824	106,298	101,378	88,768	79,700
North Bend, OR	148,325	124,041	121,484	116,881	113,559	83,044	81,207	73,345	68,533
Arcata, CA	137,608	122,781	119,997	113,994	111,335	86,904	85,364	79,175	74,699
Medford, OR	251,753	219,853	214,034	189,205	178,465	135,664	131,364	108,138	99,266
Redmond, OR	211,203	193,020	188,600	169,982	163,111	116,151	113,290	95,272	88,877
Portland, OR	209,783	173,053	167,567	155,745	147,132	103,359	98,123	88,632	79,331
Yakima, WA	227,161	202,224	196,476	180,363	168,753	121,389	116,674	102,731	93,639
Burns, OR	211,814	193,572	189,140	170,519	163,598	116,357	113,488	95,427	89,019
Olympia, WA	192,964	161,036	156,352	145,778	138,791	98,555	94,113	85,015	77,182
Quillayuta, WA	149,228	130,513	127,078	122,571	118,203	81,978	78,838	74,585	68,696
Seattle, WA	182,022	150,545	145,740	140,583	133,836	91,478	87,188	82,066	73,954
Kalispell, MT	190,514	168,840	165,644	154,100	149,002	101,246	98,413	87,022	81,091
Cut Bank, MT	187,744	168,906	165,521	158,751	153,429	94,371	91,444	84,578	78,797

Table: C-32 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Primary School Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	69,733	60,235	58,001	48,298	45,175	47,741	46,041	38,627	34,664
Spokane, WA	56,133	51,626	49,966	42,510	40,455	41,678	40,519	35,322	32,098
Missoula, MT	56,342	48,470	47,321	40,127	38,416	40,030	38,936	33,003	30,572
Boise, ID	68,281	64,220	62,402	49,386	46,238	50,653	48,810	39,603	35,570
Pocatello, ID	57,722	52,584	51,142	42,590	40,561	42,104	40,905	34,730	31,881
Helena, MT	55,294	50,755	49,513	41,541	39,415	41,816	40,737	33,929	31,293
Astoria, OR	46,931	38,397	37,381	34,667	33,306	31,023	30,112	28,227	26,251
Salem, OR	60,536	49,651	47,526	41,084	38,239	39,720	37,355	33,357	29,334
Eugene, OR	60,572	47,942	45,936	40,376	37,692	38,379	36,270	32,481	28,839
North Bend, OR	44,961	37,280	36,798	34,122	33,337	30,687	30,431	27,403	26,547
Arcata, CA	41,825	37,598	37,104	34,011	33,317	32,224	32,449	29,830	28,706
Medford, OR	74,283	63,433	61,057	49,666	46,186	49,883	47,950	39,647	35,225
Redmond, OR	59,106	52,724	51,100	42,949	40,850	41,983	40,744	34,812	31,981
Portland, OR	59,119	46,737	44,604	39,937	37,340	37,235	34,998	32,811	28,653
Yakima, WA	63,733	55,162	52,899	45,325	42,292	43,460	41,440	37,469	33,216
Burns, OR	59,136	52,719	51,085	42,918	40,839	42,035	40,789	34,862	32,016
Olympia, WA	56,156	45,375	43,714	38,649	36,542	36,336	34,663	31,688	28,451
Quillayuta, WA	42,811	37,204	36,146	33,574	32,414	30,667	29,800	27,687	26,066
Seattle, WA	51,064	40,331	38,605	36,313	34,463	32,813	31,096	30,168	26,955
Kalispell, MT	50,914	43,449	42,321	37,193	35,782	36,513	35,500	31,432	29,174
Cut Bank, MT	45,639	39,888	38,737	35,736	34,411	33,173	32,122	29,962	27,909

Table: C-33 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Large Hotel Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	817,631	217,275	209,992	207,120	198,098	44,572	37,498	40,160	32,557
Spokane, WA	750,325	207,686	202,071	197,733	191,501	37,138	31,527	33,288	26,819
Missoula, MT	723,289	205,872	203,160	194,349	190,633	35,780	32,736	27,736	23,914
Boise, ID	817,242	228,388	221,772	214,993	205,341	50,079	42,768	43,261	35,343
Pocatello, ID	760,583	211,913	206,727	201,403	194,515	36,731	31,745	33,149	26,234
Helena, MT	752,392	204,647	199,747	197,362	190,161	33,855	28,007	30,272	23,662
Astoria, OR	637,206	165,601	161,011	162,230	157,534	22,573	16,277	21,596	14,897
Salem, OR	721,969	188,506	181,421	182,918	173,071	33,376	24,159	30,721	20,430
Eugene, OR	722,622	186,932	180,051	181,747	172,743	32,187	23,876	29,793	20,394
North Bend, OR	606,181	158,251	154,473	154,526	150,740	20,615	16,139	19,548	14,090
Arcata, CA	600,494	156,172	153,139	150,956	148,149	23,134	20,018	22,185	17,975
Medford, OR	799,061	214,030	205,765	205,430	192,314	44,722	36,608	40,690	31,541
Redmond, OR	751,189	199,297	194,155	189,989	183,390	32,401	27,631	29,727	23,369
Portland, OR	727,714	189,210	181,656	184,835	175,059	33,008	23,614	31,059	20,989
Yakima, WA	756,522	207,708	199,697	200,336	188,783	39,736	32,042	37,041	28,066
Burns, OR	751,228	199,316	194,174	190,023	183,410	32,407	27,637	29,726	23,373
Olympia, WA	691,589	180,710	175,195	175,996	168,225	28,411	21,097	26,392	18,067
Quillayuta, WA	668,167	166,679	162,770	163,090	159,022	20,624	15,645	19,469	13,674
Seattle, WA	683,158	180,234	174,098	176,545	169,906	26,836	19,447	25,389	17,560
Kalispell, MT	694,208	192,209	189,474	183,886	180,484	28,042	25,130	23,469	18,652
Cut Bank, MT	712,425	190,316	186,208	185,934	181,016	23,571	19,431	22,134	17,165

Table: C-34 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Large Hotel Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	301,508	79,605	75,645	72,253	68,509	21,002	17,154	19,047	13,774
Spokane, WA	258,425	72,702	69,969	66,120	63,717	16,560	13,837	14,643	10,452
Missoula, MT	254,875	67,660	65,617	62,377	59,978	13,620	11,358	11,894	7,786
Boise, ID	293,244	82,244	78,324	73,423	69,568	22,632	18,532	20,311	14,519
Pocatello, ID	260,633	73,441	70,659	66,364	63,667	16,384	13,744	14,817	9,922
Helena, MT	256,147	69,554	67,157	64,039	61,369	14,942	12,080	12,729	8,688
Astoria, OR	228,125	58,562	56,895	55,425	53,674	9,183	6,916	7,184	4,559
Salem, OR	266,417	69,209	66,434	62,647	59,522	16,162	12,697	13,062	7,666
Eugene, OR	266,489	68,476	65,846	62,587	59,431	15,502	12,398	12,734	7,538
North Bend, OR	220,633	57,323	56,191	54,472	53,214	8,234	7,013	5,753	4,565
Arcata, CA	229,053	56,239	55,061	53,109	51,954	7,622	6,441	6,700	4,779
Medford, OR	303,217	80,552	76,906	71,723	67,801	22,006	18,348	19,017	13,150
Redmond, OR	265,025	70,140	67,642	63,419	60,885	14,686	12,344	13,074	8,571
Portland, OR	268,494	69,186	66,155	63,491	60,386	15,804	12,133	13,529	8,176
Yakima, WA	274,075	76,526	73,057	68,901	65,448	19,354	15,936	17,398	11,879
Burns, OR	265,025	70,140	67,641	63,409	60,888	14,686	12,343	13,070	8,568
Olympia, WA	250,975	65,118	63,048	59,763	57,132	13,183	10,512	10,675	6,350
Quillayuta, WA	240,942	57,013	55,495	53,867	52,462	7,842	6,083	5,852	3,604
Seattle, WA	242,664	63,305	60,906	59,389	57,053	11,867	9,207	9,811	6,137
Kalispell, MT	233,550	63,331	61,497	58,953	56,923	10,997	9,098	9,451	5,826
Cut Bank, MT	228,033	61,686	59,832	58,294	56,347	9,454	7,577	8,260	5,196

Table: C-35 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard Performance Warehouse Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	7,228	7,042	6,921	6,138	6,005	2,878	2,689	2,218	2,009
Spokane, WA	6,656	6,635	6,553	5,959	5,866	2,608	2,463	2,094	1,935
Missoula, MT	7,256	7,082	7,013	6,508	6,418	2,352	2,229	1,915	1,781
Boise, ID	7,269	7,326	7,203	6,249	6,125	2,958	2,781	2,246	2,047
Pocatello, ID	7,261	7,176	7,086	6,462	6,355	2,614	2,468	2,087	1,921
Helena, MT	7,183	7,135	7,064	6,507	6,431	2,385	2,249	1,922	1,796
Astoria, OR	3,794	3,752	3,738	3,694	3,679	1,997	1,910	1,846	1,782
Salem, OR	5,922	5,789	5,701	5,164	5,079	2,395	2,248	1,971	1,854
Eugene, OR	5,903	5,661	5,579	5,121	5,032	2,341	2,207	1,951	1,833
North Bend, OR	3,617	3,581	3,573	3,556	3,547	1,984	1,921	1,845	1,790
Arcata, CA	3,583	3,584	3,583	3,552	3,547	1,805	1,727	1,682	1,592
Medford, OR	7,797	7,546	7,423	6,354	6,203	3,108	2,920	2,279	2,056
Redmond, OR	6,461	6,334	6,245	5,689	5,589	2,578	2,417	2,087	1,914
Portland, OR	5,658	5,461	5,379	5,029	4,947	2,250	2,114	1,930	1,820
Yakima, WA	6,794	6,624	6,509	5,867	5,746	2,653	2,466	2,137	1,937
Burns, OR	6,525	6,415	6,325	5,761	5,662	2,588	2,425	2,090	1,918
Olympia, WA	5,264	5,074	5,019	4,661	4,597	2,215	2,099	1,916	1,815
Quillayuta, WA	3,989	3,928	3,907	3,854	3,837	1,993	1,911	1,843	1,781
Seattle, WA	4,797	4,613	4,564	4,442	4,389	2,101	1,981	1,893	1,795
Kalispell, MT	7,008	6,824	6,766	6,498	6,425	2,144	2,022	1,833	1,714
Cut Bank, MT	8,444	8,321	8,273	8,095	8,038	2,077	1,955	1,821	1,708

Table: C-36 Annual Energy Consumption (Chiller, Fan, and Pump) for the High Performance Warehouse Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	1,350	1,358	1,372	1,141	1,121	1,193	1,239	1,035	1,010
Spokane, WA	1,267	1,291	1,303	1,121	1,107	1,143	1,180	1,020	1,000
Missoula, MT	1,353	1,308	1,303	1,202	1,188	1,034	1,028	977	962
Boise, ID	1,297	1,389	1,410	1,139	1,122	1,205	1,265	1,032	1,011
Pocatello, ID	1,286	1,287	1,291	1,130	1,116	1,122	1,142	1,014	995
Helena, MT	1,222	1,213	1,207	1,101	1,089	1,036	1,029	981	965
Astoria, OR	975	959	957	944	941	1,058	1,054	1,046	1,042
Salem, OR	1,219	1,207	1,209	1,066	1,052	1,120	1,123	1,063	1,051
Eugene, OR	1,222	1,196	1,203	1,065	1,050	1,116	1,132	1,060	1,048
North Bend, OR	936	939	939	936	935	1,053	1,050	1,045	1,041
Arcata, CA	928	940	940	935	935	870	869	868	866
Medford, OR	1,461	1,567	1,649	1,175	1,154	1,304	1,450	1,044	1,019
Redmond, OR	1,242	1,226	1,220	1,100	1,086	1,095	1,087	1,013	991
Portland, OR	1,186	1,119	1,111	1,028	1,014	1,090	1,082	1,058	1,046
Yakima, WA	1,289	1,252	1,243	1,112	1,094	1,071	1,059	1,008	985
Burns, OR	1,250	1,230	1,223	1,102	1,087	1,098	1,090	1,014	992
Olympia, WA	1,153	1,099	1,095	1,014	1,003	1,084	1,077	1,055	1,046
Quillayuta, WA	981	957	955	943	940	1,058	1,055	1,047	1,042
Seattle, WA	1,078	1,039	1,034	997	988	1,070	1,064	1,051	1,043
Kalispell, MT	1,361	1,309	1,304	1,241	1,230	1,006	999	966	953
Cut Bank, MT	1,817	1,800	1,796	1,754	1,745	992	987	964	953

Table: C-37 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Outpatient Healthcare Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	42,047	41,089	40,728	37,976	37,539	10,165	9,346	8,404	7,392
Spokane, WA	39,017	38,366	38,124	36,122	35,842	8,583	7,978	7,027	6,442
Missoula, MT	38,314	37,481	37,289	35,146	34,916	7,960	7,431	6,237	5,809
Boise, ID	42,939	42,086	41,751	38,842	38,465	10,183	9,399	8,145	7,430
Pocatello, ID	40,842	39,932	39,680	37,134	36,857	8,849	8,202	6,739	6,215
Helena, MT	38,578	37,797	37,598	35,794	35,539	8,062	7,463	6,545	6,016
Astoria, OR	27,869	27,527	27,489	27,348	27,283	5,543	5,158	5,193	4,683
Salem, OR	37,047	36,074	35,852	34,097	33,803	7,639	7,018	6,080	5,407
Eugene, OR	37,042	36,025	35,801	34,024	33,738	7,657	7,040	6,061	5,436
North Bend, OR	25,064	24,923	24,906	24,872	24,841	5,387	5,047	5,047	4,626
Arcata, CA	24,367	24,284	24,279	24,221	24,207	5,016	4,773	4,761	4,575
Medford, OR	42,181	41,295	40,946	37,316	36,932	10,122	9,353	7,495	6,771
Redmond, OR	38,661	37,976	37,751	35,534	35,311	8,425	7,816	6,095	5,749
Portland, OR	36,592	35,460	35,218	33,852	33,525	7,569	6,886	6,637	5,571
Yakima, WA	39,597	38,554	38,249	35,771	35,444	9,117	8,402	7,127	6,415
Burns, OR	38,728	37,986	37,761	35,546	35,316	8,435	7,825	6,094	5,754
Olympia, WA	34,436	33,604	33,443	32,096	31,907	6,914	6,402	5,645	5,175
Quillayuta, WA	29,267	29,054	29,018	28,829	28,781	5,402	5,096	4,899	4,651
Seattle, WA	33,314	32,613	32,469	31,791	31,567	6,626	6,078	6,078	5,155
Kalispell, MT	36,167	35,442	35,300	33,813	33,627	7,099	6,638	5,564	5,240
Cut Bank, MT	35,486	34,966	34,842	33,960	33,799	6,794	6,297	5,601	5,196

Table: C-38 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Outpatient Health Care Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	9,697	9,188	8,996	8,184	8,035	3,970	3,799	3,493	3,263
Spokane, WA	8,469	8,174	8,062	7,488	7,399	3,552	3,442	3,177	3,034
Missoula, MT	8,322	7,956	7,850	7,333	7,258	3,289	3,202	2,945	2,842
Boise, ID	9,828	9,335	9,167	8,284	8,151	4,003	3,852	3,499	3,293
Pocatello, ID	8,989	8,599	8,469	7,819	7,728	3,510	3,394	3,046	2,924
Helena, MT	8,656	8,363	8,268	7,815	7,737	3,299	3,211	3,017	2,894
Astoria, OR	5,231	5,205	5,199	5,185	5,178	2,703	2,697	2,692	2,685
Salem, OR	7,897	7,565	7,463	7,073	6,992	3,122	3,038	2,865	2,771
Eugene, OR	7,886	7,484	7,376	6,997	6,911	3,135	3,043	2,878	2,775
North Bend, OR	4,583	4,559	4,558	4,557	4,556	2,684	2,684	2,684	2,683
Arcata, CA	4,433	4,387	4,386	4,383	4,382	2,686	2,685	2,684	2,683
Medford, OR	9,969	9,360	9,169	8,050	7,924	3,983	3,821	3,300	3,128
Redmond, OR	8,131	7,840	7,731	7,229	7,160	3,320	3,223	2,916	2,837
Portland, OR	7,733	7,392	7,296	6,991	6,904	3,090	3,002	2,928	2,790
Yakima, WA	8,869	8,341	8,176	7,527	7,416	3,531	3,393	3,126	2,970
Burns, OR	8,158	7,847	7,738	7,232	7,163	3,326	3,227	2,920	2,839
Olympia, WA	7,128	6,817	6,757	6,450	6,399	3,002	2,947	2,816	2,754
Quillayuta, WA	5,631	5,571	5,562	5,540	5,533	2,711	2,704	2,691	2,685
Seattle, WA	6,664	6,461	6,418	6,285	6,240	2,870	2,829	2,797	2,724
Kalispell, MT	7,719	7,510	7,437	7,148	7,094	3,020	2,962	2,797	2,738
Cut Bank, MT	7,742	7,624	7,580	7,422	7,385	2,902	2,859	2,777	2,727

Table: C-39 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Hospital Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	1,324,258	1,245,818	1,220,033	1,204,512	1,178,354	452,531	432,418	427,642	409,741
Spokane, WA	1,245,511	1,200,253	1,180,545	1,159,713	1,135,149	424,103	401,359	400,960	379,491
Missoula, MT	1,244,822	1,164,680	1,148,947	1,125,308	1,105,620	379,103	363,082	357,007	341,909
Boise, ID	1,345,011	1,322,603	1,300,570	1,254,561	1,241,311	475,146	454,901	443,342	428,029
Pocatello, ID	1,295,903	1,276,165	1,255,517	1,236,876	1,209,284	429,907	408,647	405,302	385,358
Helena, MT	1,272,125	1,268,814	1,247,470	1,244,483	1,218,863	353,446	334,769	339,700	319,747
Astoria, OR	1,093,803	942,853	919,255	932,872	903,404	324,686	291,594	314,785	277,245
Salem, OR	1,198,803	1,078,720	1,054,835	1,046,236	1,011,105	376,390	335,393	356,323	312,082
Eugene, OR	1,215,700	1,074,925	1,051,799	1,045,294	1,011,690	370,544	335,148	351,321	311,794
North Bend, OR	1,062,919	919,922	900,225	910,267	882,005	327,403	301,679	315,629	284,922
Arcata, CA	1,038,178	915,419	894,955	905,267	877,062	373,955	341,245	365,012	327,808
Medford, OR	1,308,969	1,230,304	1,203,242	1,189,916	1,155,066	445,609	421,937	420,335	396,777
Redmond, OR	1,254,928	1,196,202	1,175,517	1,155,709	1,130,594	426,141	407,862	397,612	381,018
Portland, OR	1,223,742	1,074,298	1,048,260	1,050,407	1,014,316	368,405	332,988	351,947	312,318
Yakima, WA	1,252,564	1,189,910	1,164,070	1,155,104	1,121,377	426,029	400,104	404,394	377,651
Burns, OR	1,255,433	1,196,646	1,175,953	1,156,147	1,131,019	426,225	407,942	397,702	381,106
Olympia, WA	1,154,597	1,025,181	1,004,251	999,289	968,303	351,051	313,296	335,365	293,015
Quillayuta, WA	1,055,489	936,966	917,414	925,532	901,427	322,058	289,348	310,448	272,991
Seattle, WA	1,165,511	1,019,063	994,243	1,003,544	971,252	348,629	315,777	335,768	298,284
Kalispell, MT	1,192,106	1,106,922	1,091,128	1,081,607	1,060,017	352,940	335,649	334,901	316,701
Cut Bank, MT	1,234,131	1,166,394	1,151,542	1,140,831	1,122,580	368,121	356,486	346,707	337,186

Table: C-40 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Hospital Building Design for Various HVAC Combinations across 21 Climate Locations (units in kWh) with Prototype Low-Lift Chiller for the LLCS Configurations

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Pendleton, OR	369,814	307,544	295,671	284,989	267,199	174,763	162,638	161,959	149,352
Spokane, WA	326,286	281,292	272,619	263,772	247,254	157,674	148,722	146,208	136,062
Missoula, MT	319,392	264,192	257,768	243,800	232,720	146,859	139,356	135,363	126,846
Boise, ID	365,064	328,553	318,306	295,221	278,947	188,428	176,040	168,829	157,428
Pocatello, ID	352,214	294,250	285,575	274,017	255,144	160,775	151,775	149,008	138,297
Helena, MT	340,056	273,758	265,550	255,767	241,581	151,499	141,176	140,783	129,786
Astoria, OR	288,947	211,214	203,519	207,919	196,752	103,627	97,524	101,816	94,701
Salem, OR	327,033	255,988	245,629	241,437	223,409	133,948	122,539	126,454	111,765
Eugene, OR	331,225	253,176	243,217	241,161	224,090	130,865	121,019	123,991	110,442
North Bend, OR	278,411	206,524	200,381	202,326	193,224	103,381	98,227	101,495	94,993
Arcata, CA	268,878	203,542	197,777	200,343	192,080	114,518	110,019	113,286	108,035
Medford, OR	367,911	309,528	297,160	284,775	263,569	174,091	161,243	161,452	145,860
Redmond, OR	324,636	274,941	266,483	256,773	239,875	152,262	143,841	142,619	131,172
Portland, OR	336,514	252,755	241,364	243,651	224,973	129,472	118,373	123,683	109,636
Yakima, WA	344,908	290,134	278,180	274,406	252,003	163,923	151,822	154,806	139,450
Burns, OR	324,628	274,904	266,444	256,715	239,847	152,188	143,766	142,553	131,105
Olympia, WA	311,586	238,107	229,741	227,540	212,210	120,254	111,659	115,393	103,842
Quillayuta, WA	269,622	206,567	200,157	202,121	193,829	103,187	98,449	100,867	94,764
Seattle, WA	309,617	230,280	220,753	225,038	211,028	116,796	107,859	113,248	102,169
Kalispell, MT	299,106	242,664	236,430	231,785	219,546	132,540	126,113	125,944	116,890
Cut Bank, MT	296,869	239,843	234,409	230,456	220,260	129,757	123,776	123,361	115,911

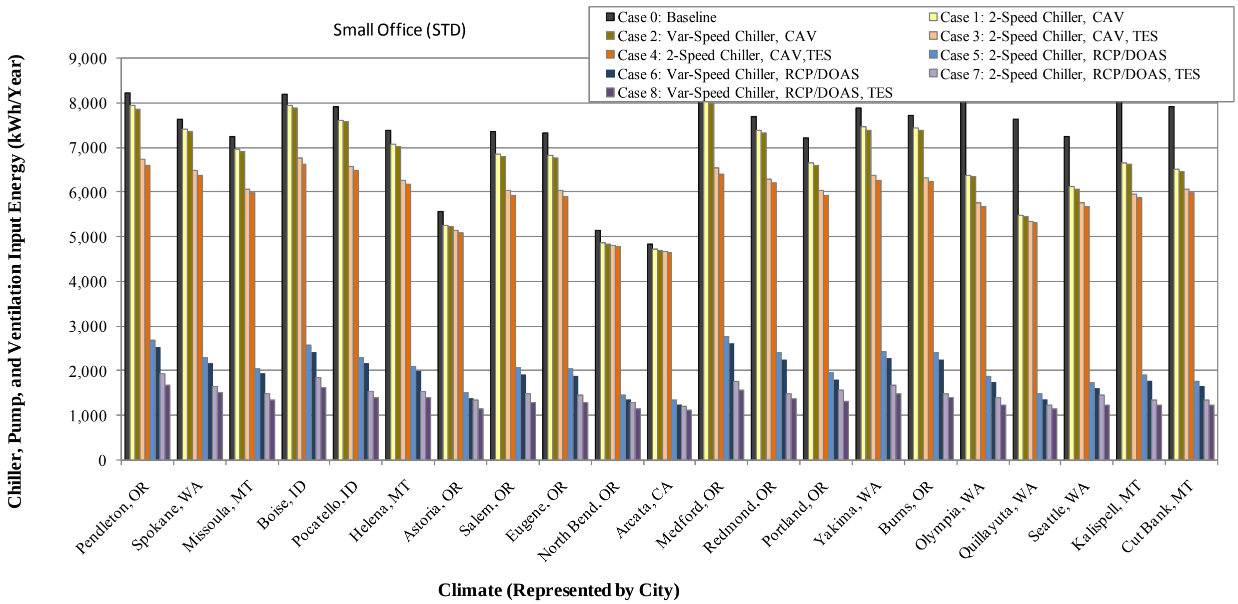

Figure: C-25 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Small Office Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

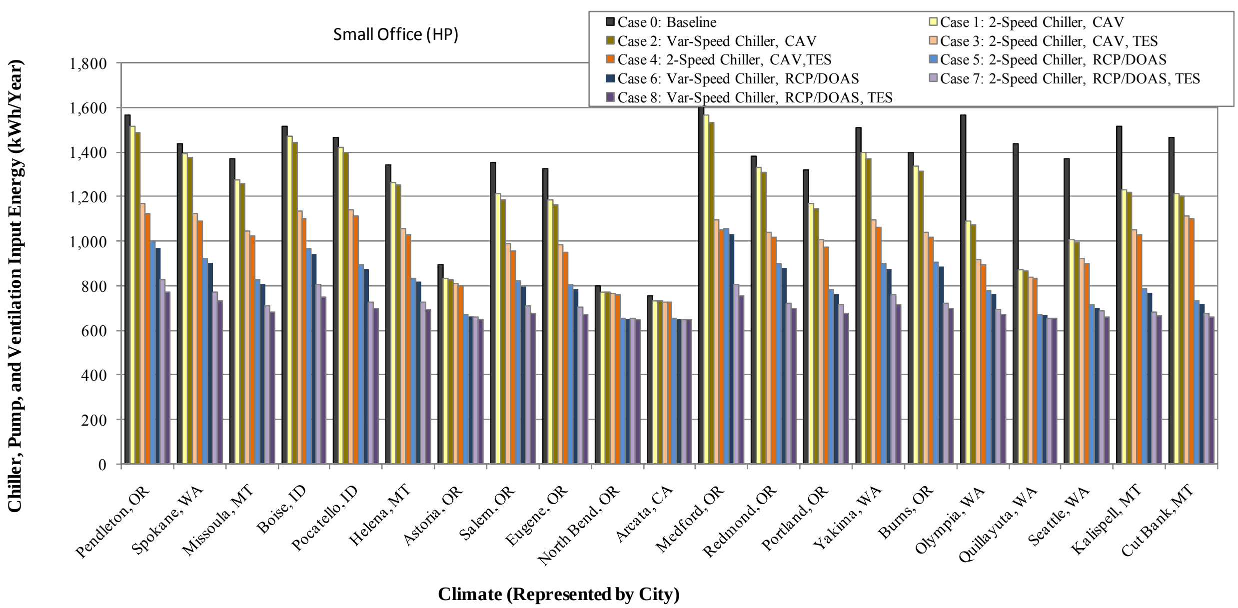

Figure: C-26 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Small Office Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

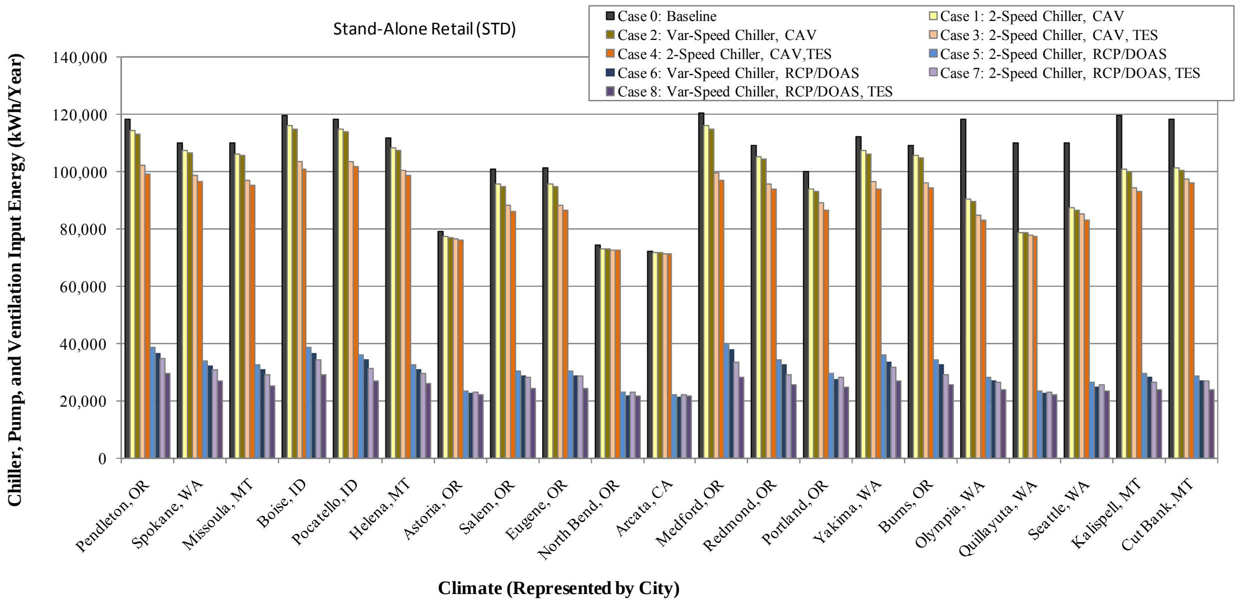

Figure: C-27 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Standalone Retail Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

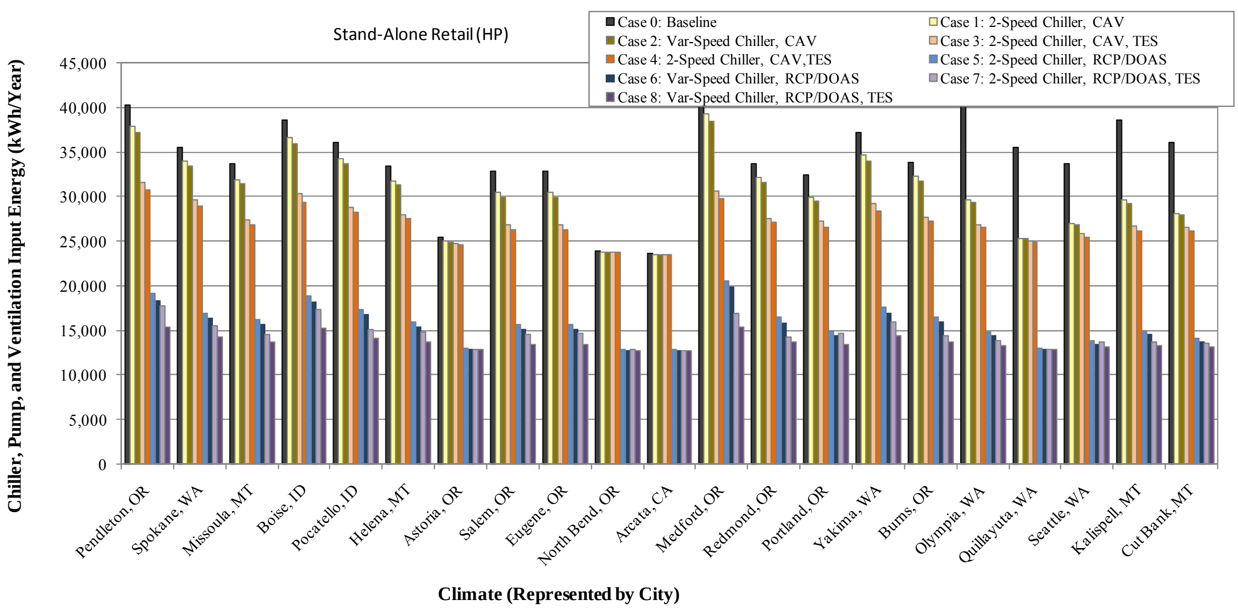

Figure: C-28 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Standalone Retail Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

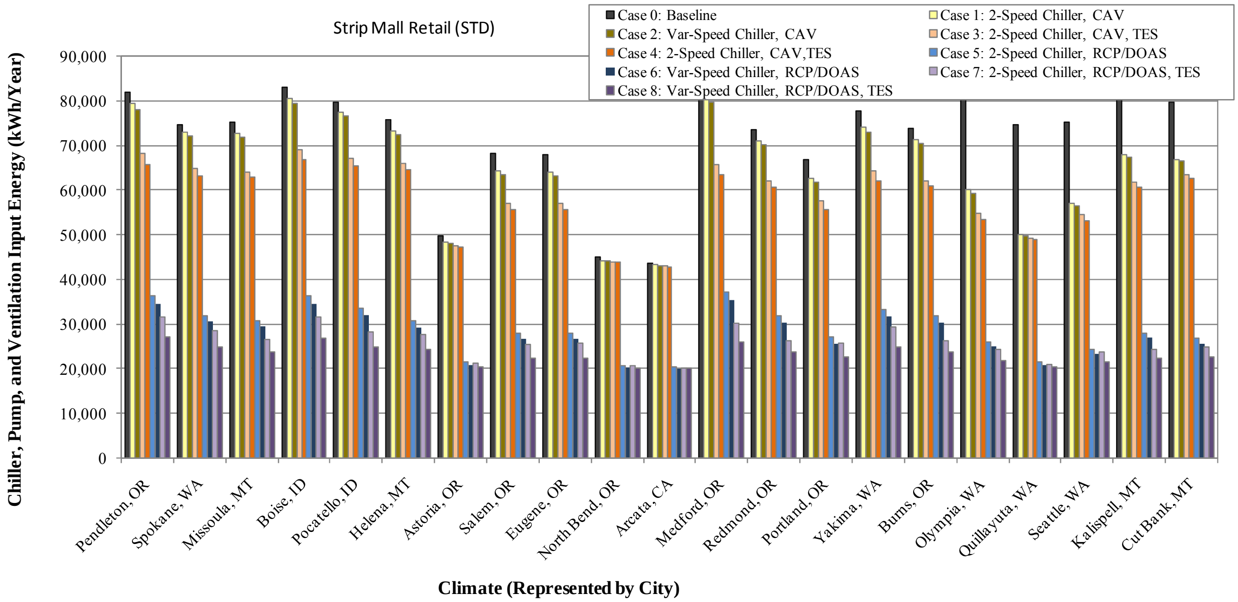

Figure: C-29 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Strip Mall Retail Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

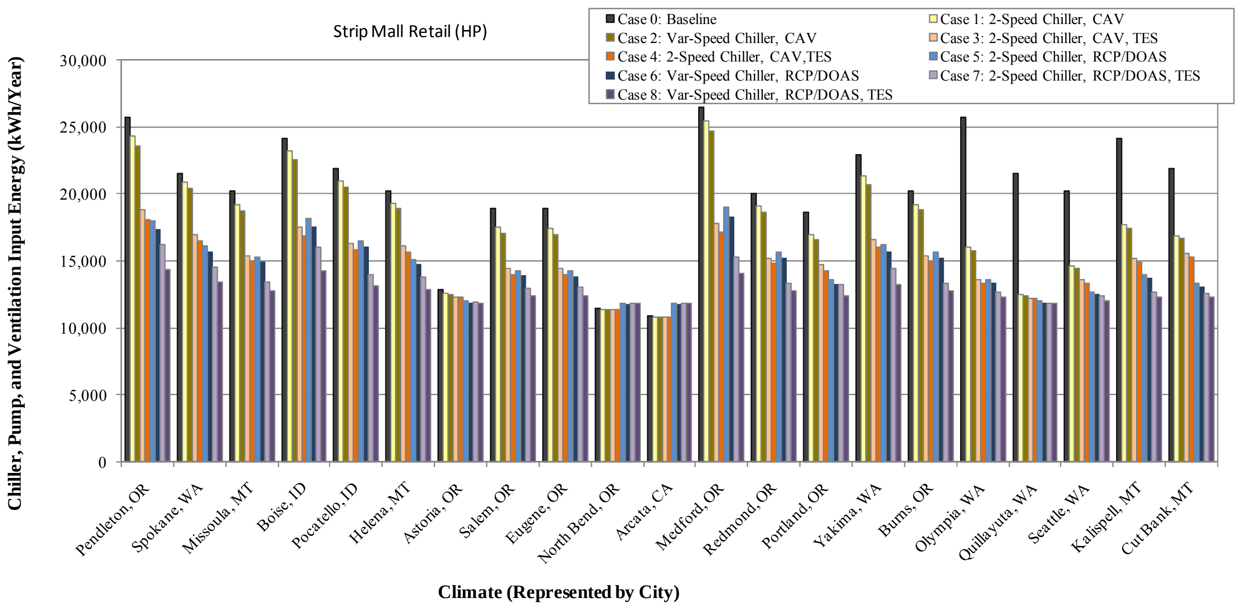

Figure: C-30 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Strip Mall Retail Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

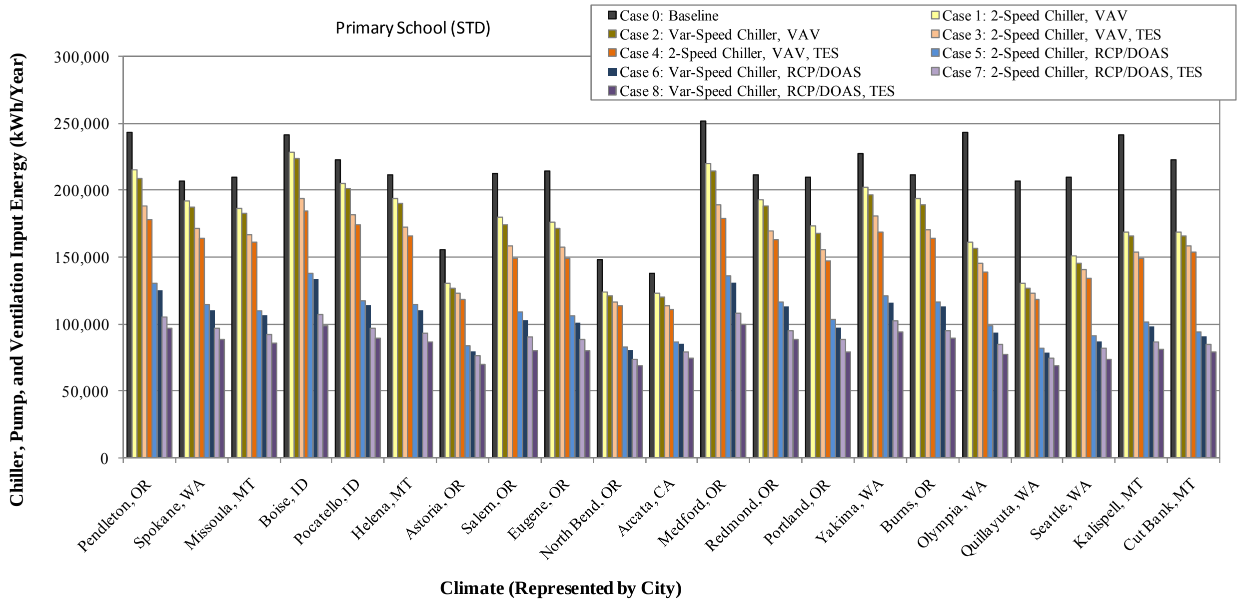

Figure: C-31 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Primary School Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

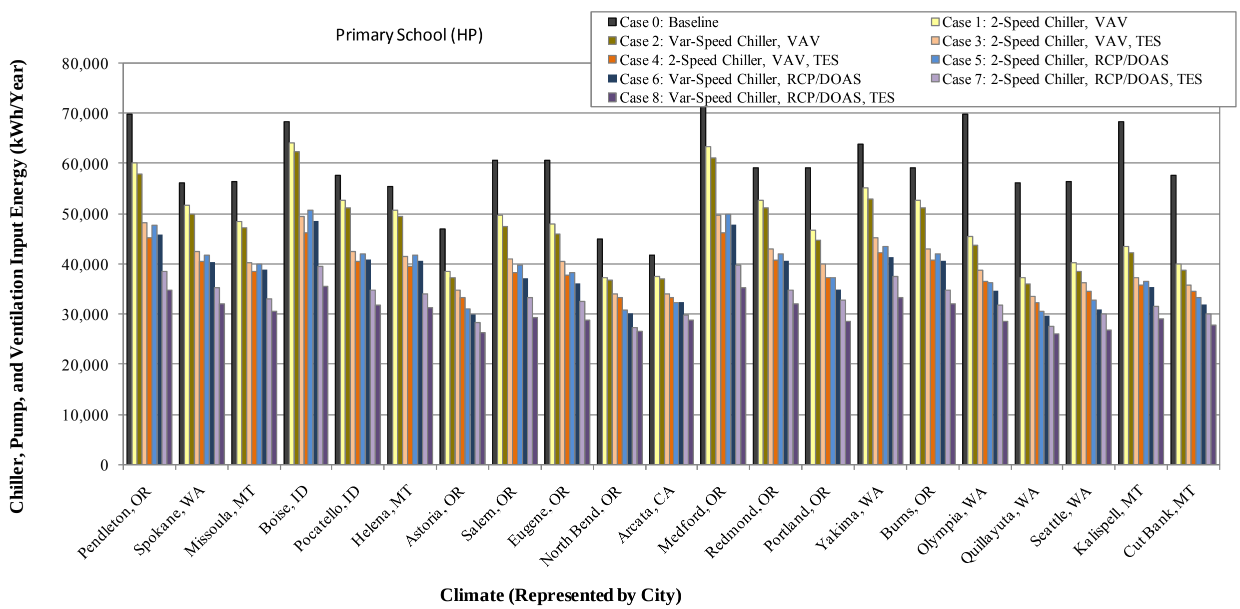

Figure: C-32 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Primary School Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

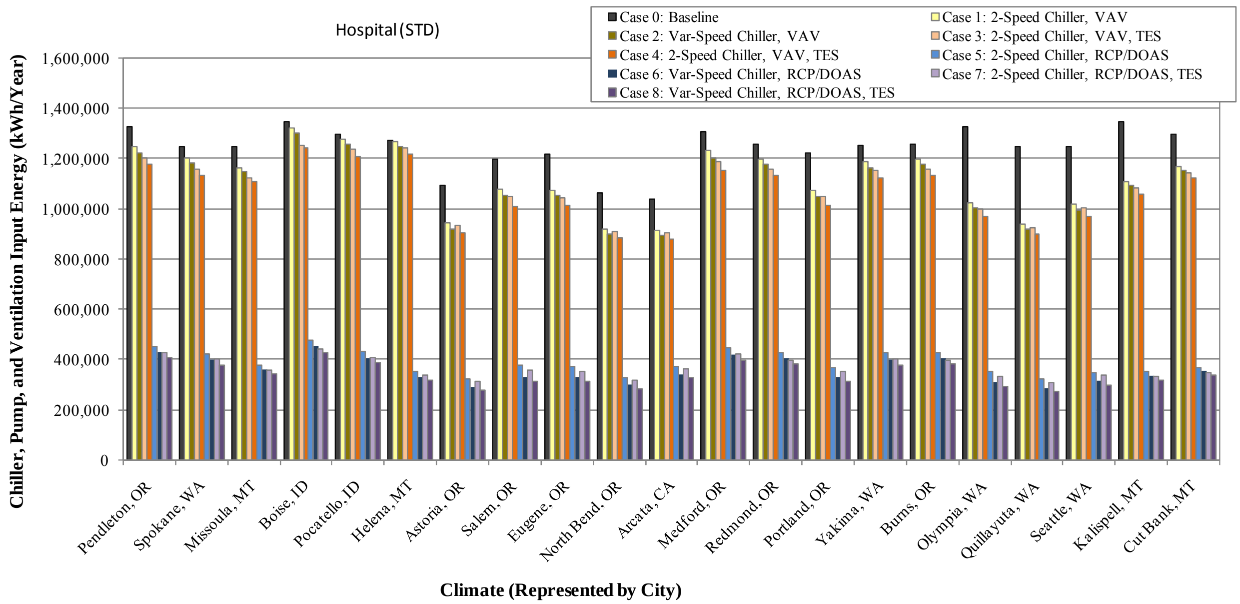

Figure: C-33 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Hospital Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

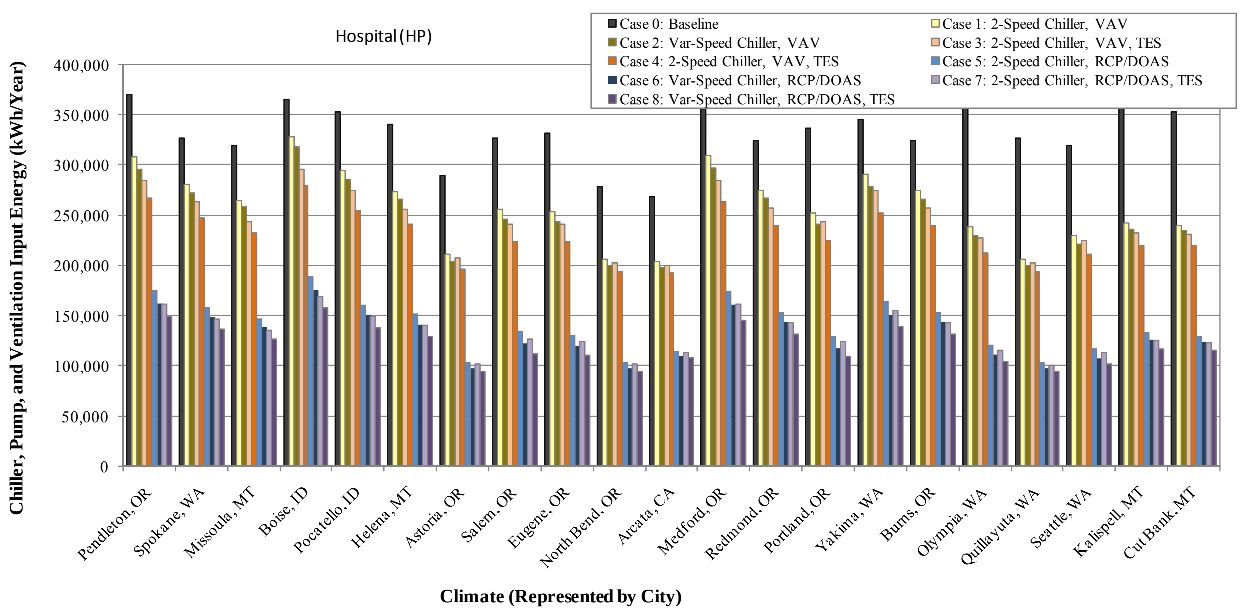

Figure: C-34 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Hospital Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

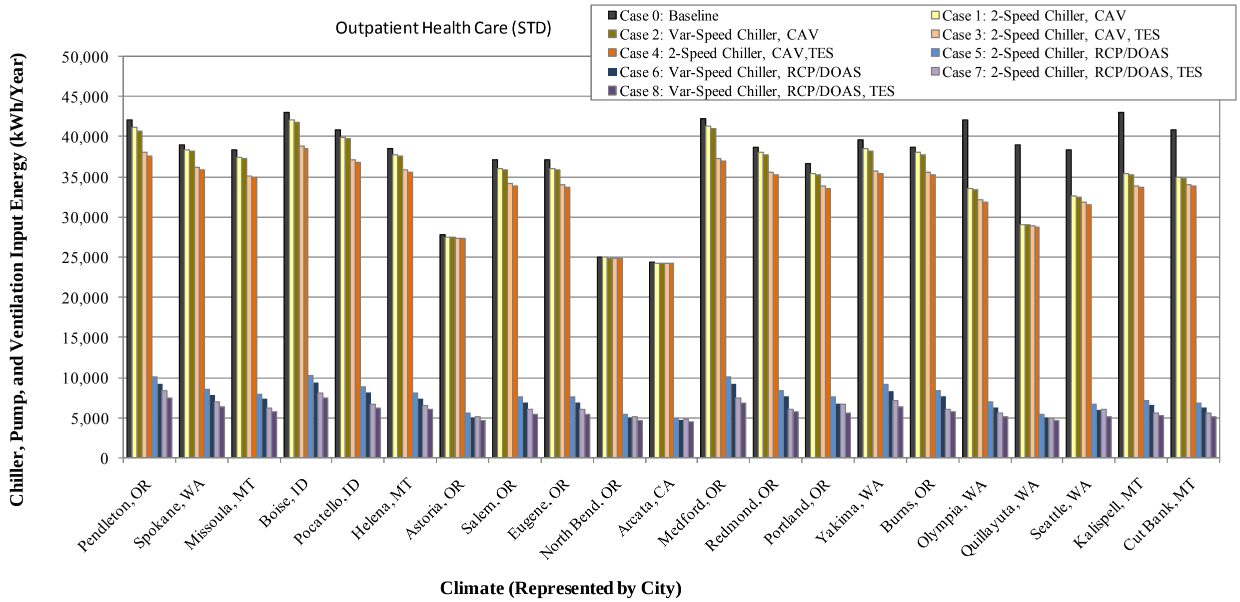

Figure: C-35 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Outpatient Health Care Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

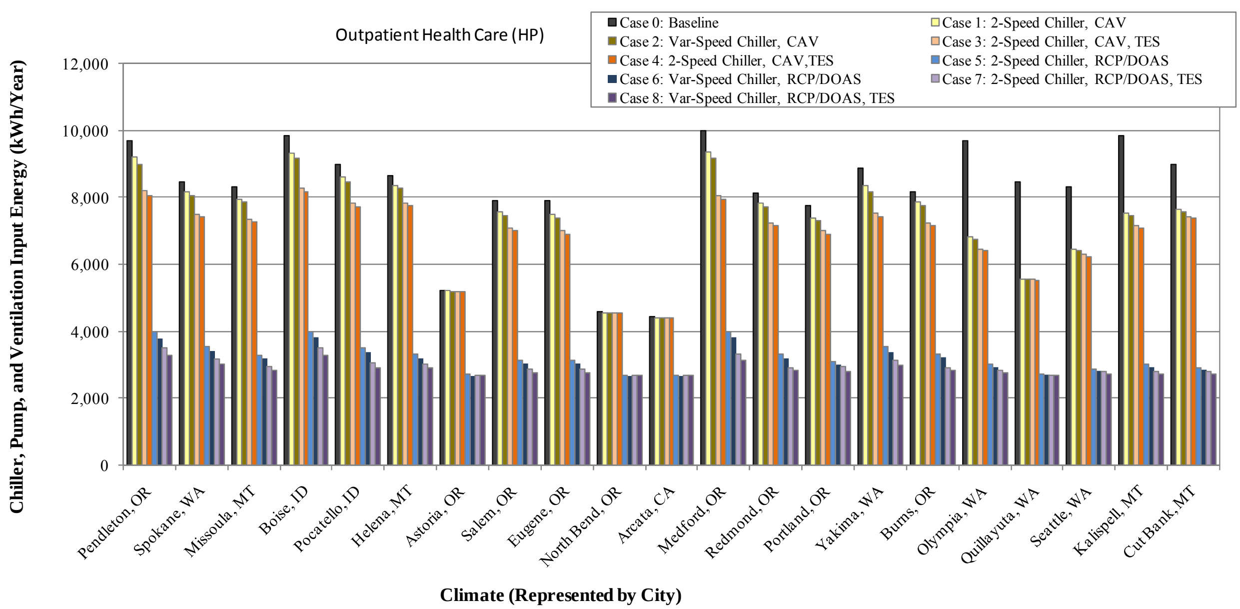

Figure: C-36 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Outpatient Health Care Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

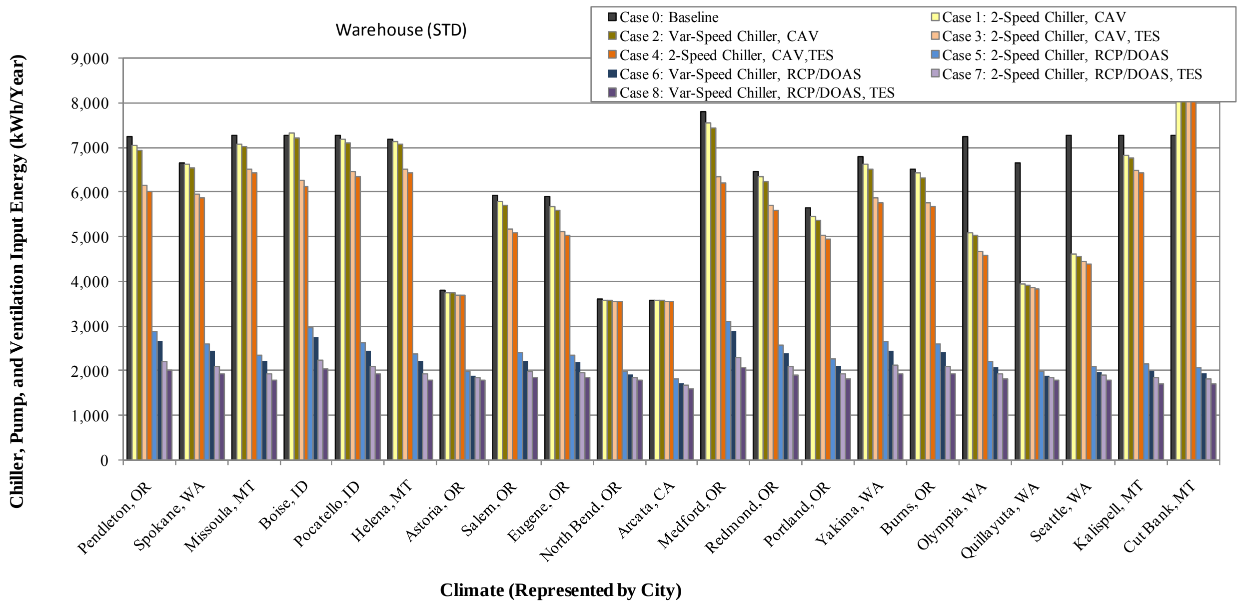

Figure: C-37 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Warehouse Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

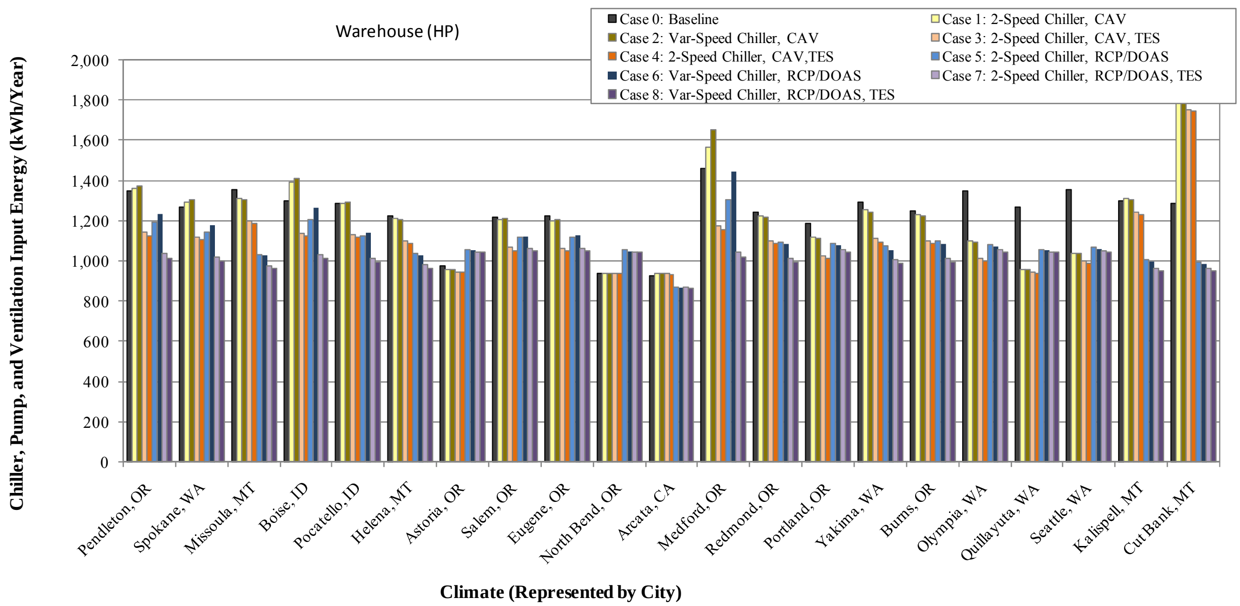

Figure: C-38 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Warehouse Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

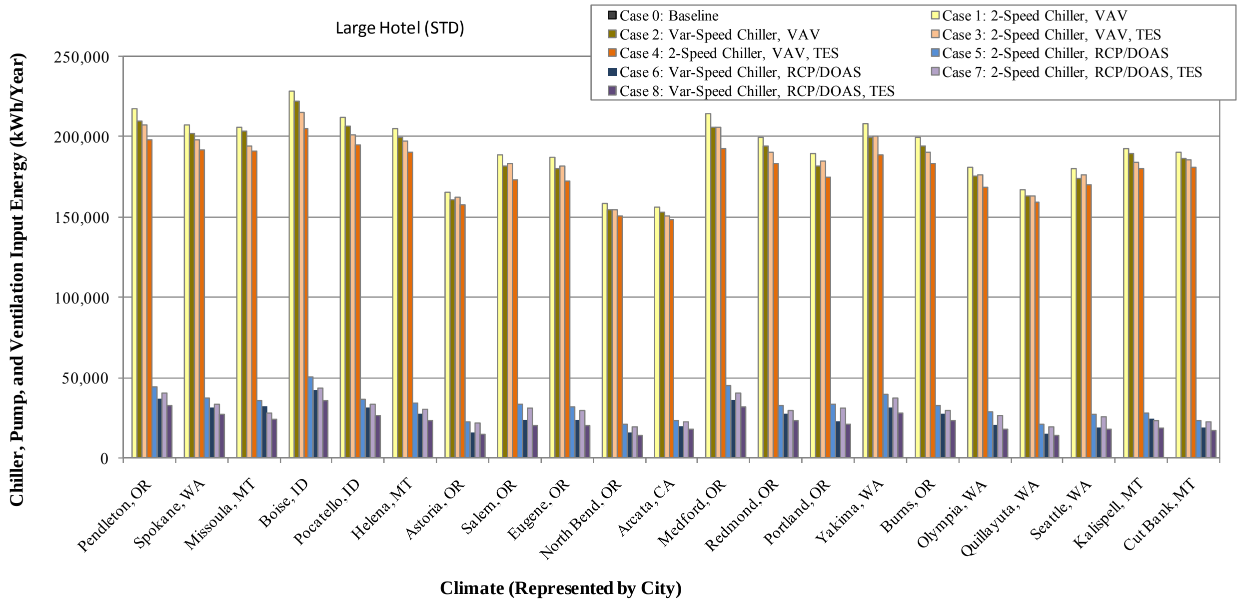

Figure: C-39 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Large Hotel Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

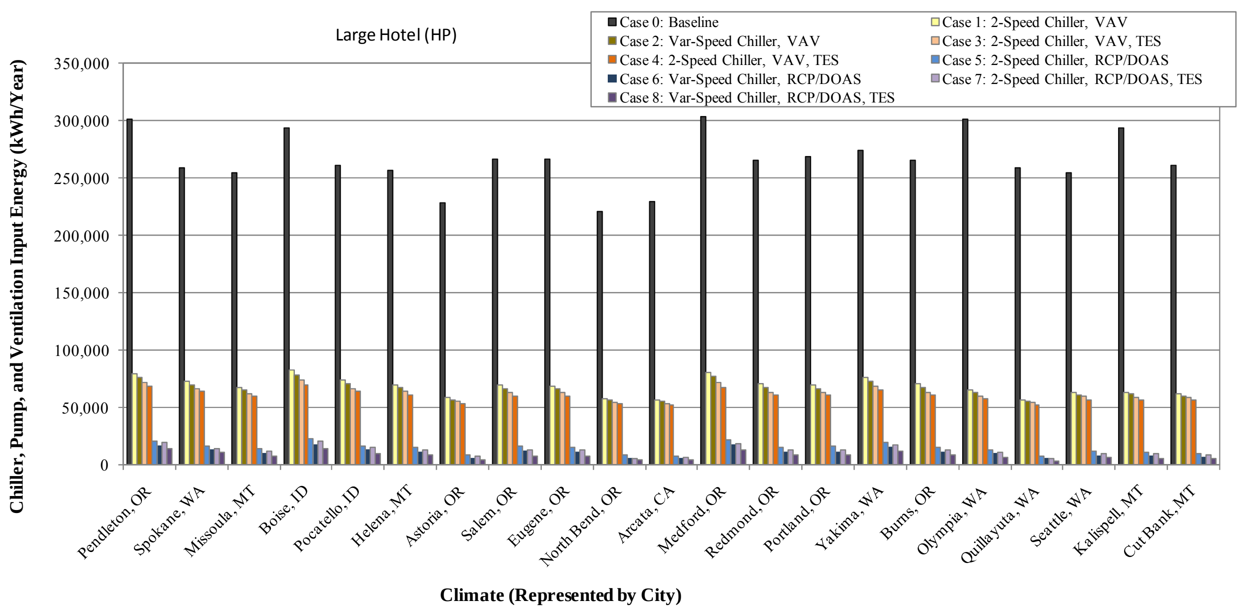

Figure: C-40 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Large Hotel Building for Various System Configurations in 21 Locations with Prototype Low-Lift Chiller for the LLCS Configurations

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