PNNL-19114

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Cost-Effective Integration of Efficient Low-Lift Baseload Cooling Equipment: FY08 Final Report

S Katipamula
PR Armstrong
W Wang
N Fernandez
H Cho
W Goetzler
J Burgos
R Radhakrishnan
C Ahlfeldt

January 2010

Pacific Northwest
NATIONAL LABORATORY

DISCLAIMER

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

PNNL-19114

Cost-Effective Integration of Efficient Low-Lift Baseload Cooling Equipment: FY08 Final Report

S Katipamula
PR Armstrong*
W Wang
N Fernandez
H Cho
W Goetzler†
J Burgos†
R Radhakrishnan†
C Ahlfeldt†

January 2010

* Associate Professor Masdar Institute of Science and Technology
† Navigant Consulting Inc. contributed to the Market Assessment and Incremental Cost Estimate sections of the report

Executive Summary

A long-term goal of Department of Energy's (DOE's) Commercial Buildings Integration Program is to develop cost-effective technologies and building practices that will enable the design and construction of cost-effective net-zero energy buildings — commercial buildings that produce as much energy as they use on an annual basis — by 2025.[3] In response, Pacific Northwest National Laboratory (PNNL) proposed and DOE initiated a study to investigate one heating, ventilation and air conditioning (HVAC) system option, low-lift cooling that offers potentially exemplary HVAC energy performance relative to American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 90.1-2004. This analysis shows that significant *cooling system efficiency gains* can be achieved by integrating *low-lift cooling system*: 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 37% to 84% and, for a very high-performance building, from -9% to 70%.

The low-lift cooling system (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.

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 same set of climate locations as used for the ASHRAE Standard 90.1 work were used for this study, except for Riyadh (Zone 1B) and Vancouver (Zone 5C). To translate per-building savings into national savings, PNNL employed the building weights ASHRAE is using in its ongoing 90.1 model code work to achieve 30% savings over the current standard.

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.

---

[3] Per the most recent publicly available *Building Technologies Program Multi-Year Program Plan* available at http://www.eere.energy.gov/buildings/publications/pdfs/corporate/myp08complete.pdf. Accessed 2009-12-04

PNNL calculated the energy consumption estimates and savings in two steps: 1) estimated the building thermal loads for 12 different building types (at two different performance levels) and 16 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 in fiscal year 2007 and enhanced this year (FY08) in the Matlab[4] environment.

Market Assessment

To address a requirement in DOE's March 2008 Stage Gate Decision Memorandum, PNNL contracted with Navigant Consulting, Inc. (NCI) to conduct an independent assessment of the potential market for the LLCS.[5] The NCI market assessment consisted of four steps: 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 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 DOE and PNNL to consider accelerating market adoption (Table E-1).

NCI concluded that the LLCS is an attractive option worthy of further research, development and deployment (RD&D). NCI noted that the stakeholders were generally very receptive, and that there did not seem to be any "deal-breakers." NCI observed that 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 "becoming interested in green buildings". In NCI's view, 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 recommendations provide useful insight to DOE 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

---

[4] 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.

[5] Navigant also provides technical support and analysis to DOE's HVAC and refrigeration program.

integrated systems, which will need advanced controls and diagnostic tools that can help even an unsophisticated operator to manage the buildings efficiently.

Table E-1 Recommendations for Broad Market Adoption of Low-Lift Technologies

Technology	Market Adoption Methods
Variable Capacity Chillers	Continue development of improved drives, compressors etc. and improved integration with other HVAC components in the building.
Advanced Controls	Create user-friendly interfaces and better training/education programs to make users aware of benefits. For example, public data on building energy savings with and without advanced controls.
Dedicated Outdoor Air System (DOAS) + Enthalpy Wheel	Improve efficiency of enthalpy wheels through development of better desiccant materials. Acquire more field data for multiple building use case scenarios.
Radiant cooling/heating	Enhance training of architects and engineers on incorporation of these as part of standard high efficiency building designs.
Thermal energy storage (TES)	Develop low footprint, high energy density TES solutions (active and passive), and suitable engineering modeling tools.
All	Integrated, packaged solution with corresponding engineering modeling tools will be most attractive to customers.

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 building (ZEB) goal of 5 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 in the open literature. To estimate the incremental cost for the components that make up the LLCS, PNNL retained the services of NCI. The incremental cost of four building types for Houston estimated by NCI are provided in Table E-2.

Table E-2 Increment Cost per Square Foot by Building Type for Houston

	Cost Increments per Square Foot by Building Type (Houston Costs)		
	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

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 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 significant and needs to be validated further.

In addition, there are additional items to consider:

- Some components of the LLCS, particularly radiant cooling, are 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 LLCS 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 at the national level is fairly involved, due to the number of variables:

- 16 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, meeting Standard 90.1-2004, and High-Performance, with significantly lower thermal loads (due to decreased internal gains from better lighting and equipment efficiencies, and to superior envelope performance)

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-3 and E-4. These estimates, which include cooling, fans and pumps, are scaled up from the savings from the prototype buildings used in the analysis. Table E-3 summarizes the national technical energy savings 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. Table E-4 summarizes the national technical energy savings 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-3 Summary of Annual National *Technical Site* Electricity Savings Potential for the Low-Lift Cooling System Compared to Conventional HVAC System (assuming 100% Penetration)

Building Performance Level	National Cooling and Fan and Pump Electricity Savings	
	Quad	Percentage
Standard	0.011	72.1%
High Performance	0.004	62.9%

Table E-4 Summary of Annual National *Technical Site* Electricity Savings Potential for the Low-Lift Cooling System Compared to Two-Speed Chiller as the Baseline

Building Performance Level	National Cooling and Fan and Pump Electricity Savings	
	Quad	Percentage
Standard	0.005	56.7%
High Performance	0.001	31.7%

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 0.011 Quads of site electricity use *in 1 year of new construction* with the full LLCS being applied to approximately 58% of floor area[6] of total new construction in 2010 U.S. new commercial building stock. The annual site electricity savings are about 0.004 for high-performance buildings. Assuming the new construction growth rates remain the same for the next 10 years (through the year 2020), the total national technical site energy savings potential (again assuming 100% penetration) for the baseline building would be 0.12 Quads in 2020 (Figure E-1). To reiterate, all of these savings are in site energy terms; to calculate source energy savings at the power plant, using average fossil-steam heat rates, the previous estimates should be multiplied by 3.[7] The total savings potential – relative to the baseline building – is therefore 0.36 Quads in 2020.[8]

[6] assuming 100% penetration in that 58% of total new floor area

[7] Per the *2007 Buildings Energy Databook,* the stock average fossil fuel steam heat rate (Btu/kWh) will be 10,181 in 2020 – see Table 6.2.5 in http://buildingsdatabook.eren.doe.gov/docs/6.2.5.pdf. This compares to the electricity consumption heat rate of 3412 Btu/kWh, about a factor of three difference.

[8] For reference, one quadrillion Btu is equivalent to the output of 47 gigawatts of coal-fired capacity at current heat rates and capacity factors. See Table 6.1.2 http://buildingsdatabook.eren.doe.gov/docs/6.1.2.pdf

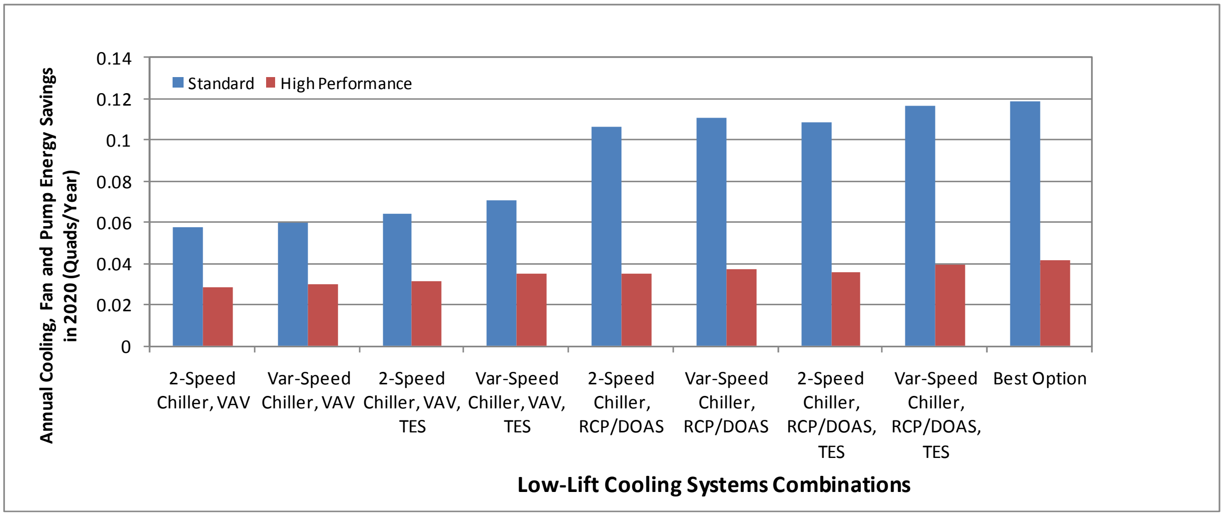


Figure E-1 National Technical Site Electricity Savings in 2020 over the Standard HVAC System for Different System Configurations for 2020 Assuming 100% Penetration over 10 Years of New Construction

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 high-performance supermarkets. Depicted in Figure E-2 are simulated electricity consumption per year, for the eight cases, for sixteen U.S. cities. Similar analysis was conducted for the other building types, and then aggregated to provide the national savings shown earlier.

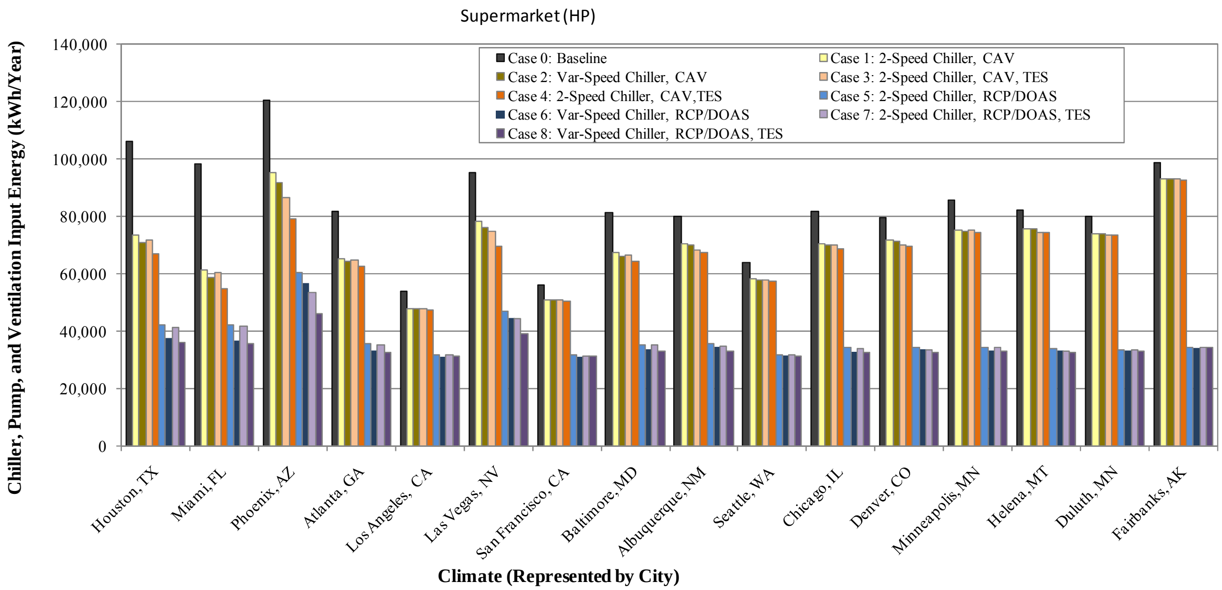


Figure E-2 Comparison of Annual Chiller and Distribution Energy Consumption for a High-Performance Supermarket Building for Various System Configurations in 16 Locations

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-2 are for Houston). The medium size office buildings typical use a multi-zone packaged system which are relative more expensive than single-zone packaged units, so cost of these systems 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. Large office and secondary school buildings in cooling dominated climate regions have 5 to 10 year paybacks, which is reasonable 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 mild climates, such as in Los Angeles, San Francisco and

Seattle and heating dominated climates, such as in Chicago, Minneapolis, Duluth and Fairbanks, this LLCS may not be favorable, absent 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, 9.3 and 8.8 years, respectively.

Table E-5 Simple Payback by Building Type for each Climate Location

	Office Medium	Office Large	Supermarket	Secondary School
Houston	0	5.9	12.3	4.8
Miami	0	5.0	12.4	4.0
Phoenix	0	7.6	16.4	7.4
Atlanta	0	9.8	19.2	9.1
Los Angeles	0	7.6	23.1	9.6
Las Vegas	0	7.8	18.5	9.2
San Francisco	0	15.3	28.0	16.0
Baltimore	0	8.8	12.7	7.0
Albuquerque	0	4.8	21.2	13.4
Seattle	0	19.9	40.9	30.3
Chicago	0	14.4	21.0	13.5
Denver	0	6.6	18.9	17.1
Minneapolis	0	18.7	21.5	16.8
Duluth	0	20.0	19.0	20.9
Fairbanks	0	18.1	12.5	19.6
Aggregate Payback	0	**9.3**	**17.3**	**8.8**

Acknowledgement

The authors would like to acknowledge the Buildings Technologies Program of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy for supporting the research and development effort. The authors would also like to thank Alan Schroeder (Technology Development Manager), Dru Crawley (Commercial Buildings Integration Lead), Terry Logee and Andrew Nicholls (Program Manager at PNNL) for their thoughtful comments and insights and Sue Arey for the editorial support. Support of the Masdar author by the Masdar Initiative is gratefully acknowledged. Thanks to Tom Watson of McQuay and numerous PNNL colleagues for thoughtful discussions on the low-lift systems approach.

Contents

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
BT	Building Technologies Program
CBECS	Commercial Building Energy Consumption Survey
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
ERV	energy recovery ventilation
EUI	energy use intensity
FLEOH	full-load-equivalent operating hours
FDD	fault detection and diagnostics
GIS	geographical information systems
GSA	General Services Administration
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
LLC	low-lift cooling
LLCS	low-lift cooling system
NZEB	Net-Zero Energy Building
NREL	National Renewable Energy Laboratory

OEM	original equipment manufacturer
PCM	phase change materials
PNNL	Pacific Northwest National Laboratory
PLR	part load ratio
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
VRV	variable volume refrigeration
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, ventilation and air condition (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, and beginning in 2007, DOE has supported Pacific Northwest National (PNNL) to evaluate one such integrated HVAC design option, low-lift cooling.

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

1. Peak-load shifting by means of active or passive (pre-cooling of building mass) – thermal energy storage (TES).[9]
2. Dedicated outdoor air system (DOAS) and enthalpy heat recovery from exhaust air.
3. Radiant heating and cooling panels (RCP) or floor system.
4. Low-lift[10] vapor compression cooling equipment.
5. Advanced controls at the HVAC equipment and HVAC system (supervisory) levels.

In January 2008, a final report of the FY07 work was submitted to the U.S. Department of Energy (DOE) for a Stage Gate review by PNNL. This report summarized results from a preliminary analysis of this integrated approach.[11] The savings estimates were based on thermal loads estimated from DOE 2.2 simulation runs. Because PNNL was not able to simulate the systems entirely in DOE 2.2 (including pre-cooling with TES, DOAS and radiant slab), component models for low-lift chiller, ideal TES and DOAS were developed in Matlab.[12] The loads from DOE 2.2 were then used to estimate the energy consumption for chiller, pumps and DOAS. For the details of the component models refer to FY07 final report. Because of the limited scope of work (in FY07), only one building type (medium office) was actually simulated in five climate locations.

---

[9] 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.

[10] The American Refrigeration Institute (ARI) 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).

11 Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-17157.pdf

[12] 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.

This report describes the work performed after FY07 for the LLCS. The objectives of the work are to:

1. estimate the national technical savings potential from the LLCS using EnergyPlus and Matlab component models

2. conduct a market assessment to understand the barriers and perceived benefits of the LLCS

3. estimate the incremental cost for selected building prototypes using LLCS compared to the building with standard systems

4. estimate a simple payback for selected buildings.

The national savings estimates reported are based on thermal loads from the EnergyPlus simulations and the energy consumption estimates from the component models developed last year (FY07). In addition, the savings are based on use of a larger set of building types (12) and climate locations (16).

The report provides a brief background about the technology options (Background), followed by a section that describes the EnergyPlus prototype benchmarks that were used to generate the thermal loads (Commercial Building Benchmarks). 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. In addition to the market assessment, PNNL also contracted with NCI to develop incremental cost estimates for the low-lift option; a summary of that work is described in 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. The energy savings for various combinations of low-lift technologies for selected building types are presented in Energy Savings Estimates for the Various LLCS Combinations. The simple payback estimates are described in Economic Analysis section. The methodology used to estimate the national technical energy savings potential is described in National Energy Savings Estimation Methodology. The national technical potential savings estimates and estimates for energy savings estimates for year 2020 are presented in National Technical Energy Savings Potential. Finally, the main portion of the reports ends with Discussion, Recommendations and Future Work section.

Background

All the component technologies that comprise the LLCS have been in use, to some extent, for a number of years but on 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[13] 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°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°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°F condenser, 60°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

[13] 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.

Commercial Building Benchmarks

To estimate the national energy savings potential, energy use for a number of prototypical buildings for which this LLCS applies has to be simulated and scaled to a national 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[14] (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 (EnergPlus 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.

DOE Commercial Benchmark Buildings

The DOE Benchmark building models are comprised of two parts—the building models consisting of the energy modeling descriptions and the national sector model consisting of the sets of building types, 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 16 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 work was of different set of building types.

Table 1 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.

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

Table 1 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

Table 2 summarizes the city locations selected in the 2.2 version of the benchmarks to represent the building stock and the different climate locations in the U.S. Approximately 78% of the U.S. population is located in 5 of the 15 climate locations (2A, 3A, 3B, 4A, 5A).

Table 2 Selected Commercial Building Benchmark Locations

Number	Climate Location	Thermal Criteria	Representative City	TMY2 Weather file location
1	1A	5000 < CDD10 °C	Miami FL	Miami FL
2	2A	3500 < CDD10 °C ≤ 5000	Houston TX	Houston TX
3	2B	3500 < CDD10 °C ≤ 5000	Phoenix AZ	Phoenix AZ
4	3A	2500 < CDD10 °C ≤ 3500	Atlanta GA	Atlanta GA
5	3B-CA	2500 < CDD10 °C ≤ 3500	Los Angeles CA	Los Angeles CA
6	3B-other	2500 < CDD10 °C ≤ 3500	Las Vegas NV	Las Vegas, NV
7	3C	HDD 18 °C ≤ 2000	San Francisco CA	San Francisco CA
8	4A	CDD10 °C ≤ 2500 and HDD18 °C ≤ 3000	Baltimore MD	Baltimore MD
9	4B	CDD10 °C ≤ 2500 and HDD18 °C ≤ 3000	Albuquerque NM	Albuquerque NM
10	4C	2000 < HDD18 °C ≤ 3000	Seattle WA	Seattle WA
11	5A	3000 < HDD18 °C ≤ 4000	Chicago IL	Chicago-Ohare IL
12	5B	3000 < HDD18 °C ≤ 4000	Denver CO	Denver CO
13	6A	4000 < HDD18 °C ≤ 5000	Minneapolis MN	Minneapolis MN
14	6B	4000 < HDD18 °C ≤ 5000	Helena MT	Helena MT
15	7	5000 < HDD18 °C ≤ 7000	Duluth MN	Duluth MN
16	8	7000 < HDD18 °C	Fairbanks AK	Fairbanks AK

TMY2 – Typical Meteorological Year; CDD – Cooling Degree Days;
HDD – Heating Degree Days;

ASHRAE-Modified DOE Commercial Benchmark Buildings

Under the Building Energy Codes Program, PNNL is developing a set of building prototypes for use in support of ASHRAE 90.1 Standard by modifying version 2.2 of the DOE Benchmark buildings (this building set is referred as 90.1 Prototypes). One of the main purposes of the 90.1 Prototypes is to serve as a yardstick in tracking the energy saving from addenda proposals during the development of the ASHRAE Standard 90.1-2010 (this 2010 standard has a stated goal of 30% energy savings over ASHRAE Standard 90.1-2004).

The 90.1 Prototypes include 17 building prototypes (15 commercial building prototypes and 2 residential building prototypes,), covering 8 CBECS principal commercial building activities. The 90.1 Prototypes have the public assembly building type (represented by movie theater/cinema building prototype) and the 90.1 Prototypes that are not part of DOE Prototypes. Another difference between the DOE and ASHRAE prototypes is that the ASHRAE prototypes do not include the supermarket prototype.

Table 3 summarizes the set of 90.1 Prototypes (excluding residential building prototypes) and their building floor areas, as well as the priority ranking for further development of these prototypes and the starting source for each of the 90.1 Prototypes.

Table 3 ASHRAE 90.1 Building Prototypes (Excluding Residential Building Prototypes)

Building Type	Building Prototype	Floor area (ft^2)	Priority Ranking	Model Source
Office	Small office	5,000	2	AEDG Small Office
	Medium office	53,630	1	DOE's Commercial Benchmark Buildings
	Large office	460,240	1	DOE's Commercial Benchmark Buildings
Mercantile	Standalone retail	15,000	2	AEDG Small Retail
	Strip mall	7,500	2	AEDG Small Retail
School	Primary school	73,960	3	AEDG K-12 School
	Secondary school	210,890	2	AEDG K-12 School
Health Care	Outpatient health care	10,000	3	DOE's Commercial Benchmark Buildings
	Hospital	201,250	1	DOE's Commercial Benchmark Buildings
Lodging	Small hotel/motel	43,200	2	AEDG Highway Lodging
	Large hotel	100,820	3	DOE's Commercial Benchmark Buildings
Warehouse	Non-refrigerated warehouse	50,000	1	AEDG Warehouse
Food Service	Fast food	2,500	2	DOE's Commercial Benchmark Buildings
	Restaurant	5,500	3	DOE's Commercial Benchmark Buildings
Public Assembly	Movie theater/cinema	TBD	3	PNNL will develop

AEDG: ASHRAE's *Advanced Energy Design Guide* series
ESC: ASHRAE SSPC 90.1 envelope subcommittee

Table 4 summarizes the 17 locations recommended by the ASHRAE 90.1 working group. These 17 locations cover all the climate locations specified in the ASHRAE Standard 90.1. Among these locations, 11 of them are the same as those selected in the DOE Benchmark buildings.

Table 4 Selected ASHRAE 90.1 Locations

Location	Climate Location Name & Type	Thermal Criteria	ASHRAE 90.1 Working Group Recommendations
1A	Very Hot - Humid	5000 < CDD10 °C	Miami, FL
1B	Very Hot - Dry	5000 < CDD10 °C	Riyadh, Saudi Arabia
2A	Hot – Humid	3500 < CDD10 °C ≤ 5000	Houston, TX
2B	Hot – Dry	3500 < CDD10 °C ≤ 5000	Phoenix, AZ
3A	Warm - Humid	2500 < CDD10 °C ≤ 3500	Memphis, TN
3B	Warm – Dry	2500 < CDD10 °C ≤ 3500	El Paso, TX
3C	Warm - Marine	HDD 18 °C ≤ 2000	San Francisco, CA
4A	Mixed - Humid	CDD10 °C ≤ 2500 and HDD18 °C ≤ 3000	Baltimore, MD
4B	Mixed – Dry	CDD10 °C ≤ 2500 and HDD18 °C ≤ 3000	Albuquerque, NM
4C	Mixed - Marine	2000 < HDD18 °C ≤ 3000	Salem, OR
5A	Cool - Humid	3000 < HDD18 °C ≤ 4000	Chicago, IL
5B	Cool – Dry	3000 < HDD18 °C ≤ 4000	Boise, ID
5C	Cool - Marine	3000 < HDD18 °C ≤ 4000	Vancouver, Canada
6A	Cool - Humid	4000 < HDD18 °C ≤ 5000	Burlington, VT
6B	Cool – Dry	4000 < HDD18 °C ≤ 5000	Helena, MT
7	Very Cold	5000 < HDD18 °C ≤ 7000	Duluth, MN
8	Subarctic	7000 < HDD18 °C	Fairbanks, AK

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

As in the FY07 work, 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.[15] 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[16] to be used for ASHRAE 90.1 work. These prototypes (referred to as

[15] We do not rule out that future developments in occupancy forecasting may make some theater applications of LLCS attractive and feasible.
[16] http://www.ashrae.org/technology/page/938

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, due in large measure to 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 5 highlights any additional changes made to the benchmarks by PNNL for this analysis. Table 6 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.)

The same set of climate locations as used for ASHRAE 90.1 (Table 4) are used for this study, except for Riyadh (Zone 1B) and Vancouver (Zone 5C), which do not have any significant presence in the U.S.. The building weights being developed by PNNL for the ASHRAE 90.1 30% model code work are used in this analysis.

Table 5 Modifications to the DOE and ASHRAE-Modified Benchmarks Made by PNNL for Analysis of Low-Lift Cooling Analysis

Building Prototype	Benchmark Model	Changes for Low Lift
Large Office	ASHRAE 30% June 2008 model	Removed latent heat to the occupied space service hot water consumption.
Medium Office	ASHRAE 30% June 2008 model	Removed latent heat to the occupied space service hot water consumption.
Small Office	ASHRAE 30% June 2008 model	Removed latent heat to the occupied space service hot water consumption.
Hospital	ASHRAE 30% June 2008 model	Removed latent heat to the occupied space service hot water consumption. Removed exhaust fan when ERV[17] is used.
Outpatient Healthcare	DOE Benchmark model 3.0	Removed latent heat to the occupied space 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[17] is used.
Secondary School	ASHRAE 30% June 2008 model	Removed exhaust fan when ERV[17] is used.
Large Hotel	ASHRAE 30% June 2008 model	Removed latent heat to the occupied space due to service hot water consumption. Removed exhaust fan when ERV[17] is used.
Warehouse	ASHRAE 30% June 2008 model	NA
Supermarket	DOE Benchmark model 3.0	Removed latent heat to the occupied space because of service hot water consumption. Removed exhaust fan when ERV[17] is used.

ERV: Energy Recovery Ventilation

[17] This is a limitation of EnergyPlus.

Table 6 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	Standalone 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

After completion of the scoping study (FY07 work), PNNL's research project underwent a formal Stage-Gate review by the Buildings Technology Program to determine if further work in this area was merited. DOE rendered a "go' decision in March 2008, and included stipulations for the conduct of further work. One of those stipulations was for PNNL to conduct an independent market assessment of the proposed LLCS that is, conducted not by PNNL but by a knowledgeable consultancy.

PNNL issued a request for proposal for conducting such an assessment. Navigant Consulting, Inc. (NCI) was selected. An assessment of the potential market for LLCS was performed by NCI, and presented to PNNL and to DOE. The market assessment consisted of four steps:

1. Review of the proposed technology and models,

2. an identification of potential benefits and barriers to market penetration,

3. a validation of those benefits and barriers through surveys and discussions with stakeholders, and

4. a recommendation of initiatives that DOE could take to accelerate market adoption of the proposed low-lift solutions.

NCI Summary of Market Assessment

In its review of the proposed LLCS, Navigant noted that RCP's are an emerging technology, popular in Europe, and that the combination of RCP's and a DOAS would be capable of providing zone control without wasteful reheat, eliminating 80% of fan transport energy, increasing water-side free cooling capacity, and raising the chilled water temperature to 55-60°F. Navigant found that load shifting with TES was a proven demand saving strategy, which can use either the building's own thermal mass or additional thermal energy storage media. They found that this strategy can reduce the average condensing temperature by 10-20°F, reduce the peak and median load on the chiller, and increase the chiller's load factor. Finally, Navigant found that low-lift cooling equipment was capable of reducing energy consumption via the use of efficient part load and low-lift operation characteristic of variable-speed compressors. They noted that low-lift cooling equipment is especially suited for RCP's and TES, because those two technologies enable low-lift and part-load operation, The sum of the energy savings of the full LLCS appears to be greater than the sum of its parts, indicating that the proposed technologies are synergistic.

In addition to the energy savings benefits of each individual technology, Navigant also identified potential market and technical benefits and barriers that accompany their installation. The potential benefits are listed in Table 7, and the barriers in Table 8.

Table 7 Low Lift Technology Options Benefits Characterized by Navigant

Technology	Market Benefit	Technical Benefit
Radiant cooling/heating	Ability to downsize HVAC equipment and defer first costs in new construction.	Integration possibilities with existing water/steam lines.
Thermal energy storage	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.
DOAS + enthalpy wheel	Allows for better humidity control, comfort and indoor environment quality 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.
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.
Advanced controls	Allows for occupancy based optimization of energy consumption in buildings 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.

Table 8 Low-Lift Technology Options Barriers Characterized by Navigant

Technology	Market Barriers	Technical Barriers
Radiant cooling/heating	Requires early engagement between architect and engineer for new construction because of 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.	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.
Thermal energy storage	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.
DOAS + Enthalpy wheel	Not suited for retrofits (outside of rooftop 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.
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.

To investigate the extent to which each of these benefits and barriers would influence the decision of the various stakeholders to consider each of the technologies within the LLCS, a survey was sent out to a sample of potential stakeholders. These included LEED (Leadership in Energy and Environmental Design) and other HVAC engineers, original equipment manufacturers (OEMs), building owners, building occupants, and energy service providers. A copy of the survey can be found in Appendix A (Appendix: Supporting Material for Market Assessment).

For radiant cooling panels, the only major barrier that was encountered was among the engineers, who expressed that a major hurdle in North American markets is getting the architects to talk to the engineers early on in the construction process, so that the panels can be incorporated into new construction. Otherwise, the hurdles were mostly minor. Building owners and occupants expressed some resistance to what they saw as a new and unconventional technology. OEMs were concerned that the fixation with ductwork as standard practice in U.S. markets presented a market barrier, and also voiced concerns about potential for condensation on the radiant cooling panels. This particular concern was echoed by the engineers and the energy service providers as well. The energy service providers stressed that building envelope optimization was key to mitigating this potential problem. Both building owners and occupants mentioned that this type of technology is not well suited for retrofits because of high costs.

For TES, major barriers to broad adoption of *active* TES exist because it is generally expensive, has a large footprint, and is not really seen as an energy efficiency measure. LEED and HVAC engineers stated that this technology only has practical applicability in locations with large difference between day and night electricity rates. The only group that expressed some degree of comfort with active TES systems was building owners, who saw them as a useful load management tool. In terms of the technical hurdles, in addition to the large footprint, building occupants also expressed that active TES systems were difficult to install and maintain. Engineers also mentioned that they are difficult to integrate with existing equipment. In general, however, stakeholders are much more receptive to passive TES, although there is a lack of familiarity with TES among building owners and occupants.

For DOAS systems with an enthalpy wheel, there was generally a very favorable impression of the technology, with building occupants responding that they perceived the energy savings as justifying the adoption of the technology. Engineers responded by saying that the technology was only suitable for new construction. Building owners seemed very unfamiliar with the technology and were concerned about it being unproven and possibly expensive. Energy service providers were concerned that the products made by certain manufacturers entailed high O&M costs. Building occupants had concerns about the fouling of the enthalpy wheel.

None of the stakeholders identified any major barriers to the adoption of variable-speed chillers. Engineers spoke highly of the technology, noting that more and more locations were adopting variable-speed chillers. The OEM's brought up the technical issue that there are very few large chillers available with variable speed drives/compressors. Building owners and energy service providers both echoed the fact that most building operators are very comfortable with variable-speed drives for pump and fan motors, but had little experience with variable-speed chillers. Building owners and operators expressed concerns that the energy savings might not justify the extra cost.

Finally, for advanced building controls, no major barriers were identified among the stakeholders, although there were a couple minor hurdles. The most common concern, voiced by engineers, building owners, and energy service providers was that the technology requires trained and sophisticated personnel, which can sometimes be an issue in certain installations. OEMs and energy service providers complained about poor interfaces for certain products. Building occupants appeared to be very cognizant of the potential benefits, however, and energy service providers noted that more and more people are becoming comfortable with the technology.

Based on all of the feedback about the individual technologies by each of the stakeholders, Navigant made the following recommendations and actions for PNNL to take to accelerate the adoption of the technologies in the LLCS:

Table 5: Recommendations for Broad Market Adoption of Low-Lift Technologies

Technology	Market Adoption Methods
Variable capacity chillers	Continue development of improved drives, compressors etc. and improve integration with other HVAC components in the building.
Advanced controls	Create user friendly interfaces and better training/education programs to make users aware of benefits. For example, public data on building energy savings with and without advanced controls.
DOAS + enthalpy wheel	Improve efficiency of enthalpy wheels through development of better desiccant materials. Acquire more field data for multiple building use case scenarios.
Radiant cooling/heating	Enhance training of architects and engineers on incorporation of these as part of standard high efficiency building designs.
Thermal energy storage	Develop low footprint, high energy density TES solutions (active and passive), and suitable engineering modeling tools.
All	Integrated, packaged solution with corresponding engineering modeling tools will be most attractive to customers.

Navigant concluded by saying that the LLCS package seems to be 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 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.

PNNL Perspective on NCI 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 DOE, 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 yet evaluated passive TES as an option because of simulation limitations.

Another issue identified by NCI (although cited as minor) is the need for advanced controls that can nonetheless be effectively used by building operator and maintenance personnel, who may not be highly trained. To achieve high efficiencies, the high-performance and net-zero energy buildings will use highly integrated systems, which in turn will need advanced controls and diagnostic tools. These tools will need to have an effective interface to help even an unsophisticated operator manage the buildings correctly.

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 9 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.

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 9 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: Supporting Material for Incremental Cost).

Table 9 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 Houston 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 Houston region and the national average.

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 ERV incremental cost
4. Heating system

Results

The charts in Figure 1through Figure 4 show the results of the incremental cost study, for each of the four building type: medium office, large office, supermarket and secondary schools.

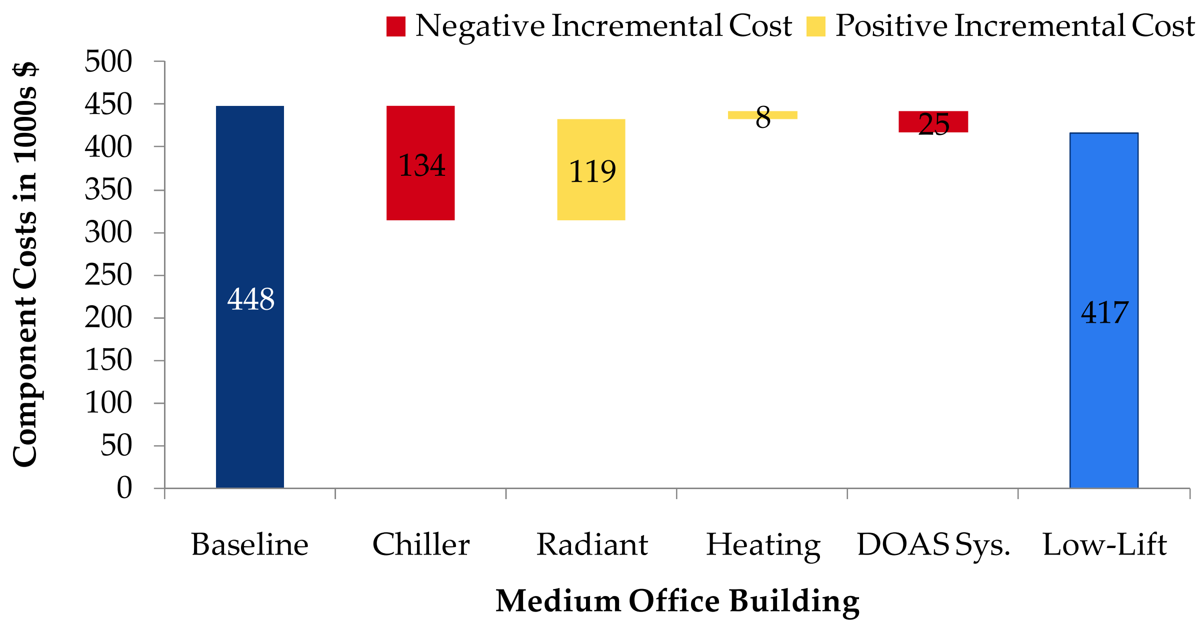


Figure 1 Incremental Cost for Medium Office Building Using Low-Lift Cooling

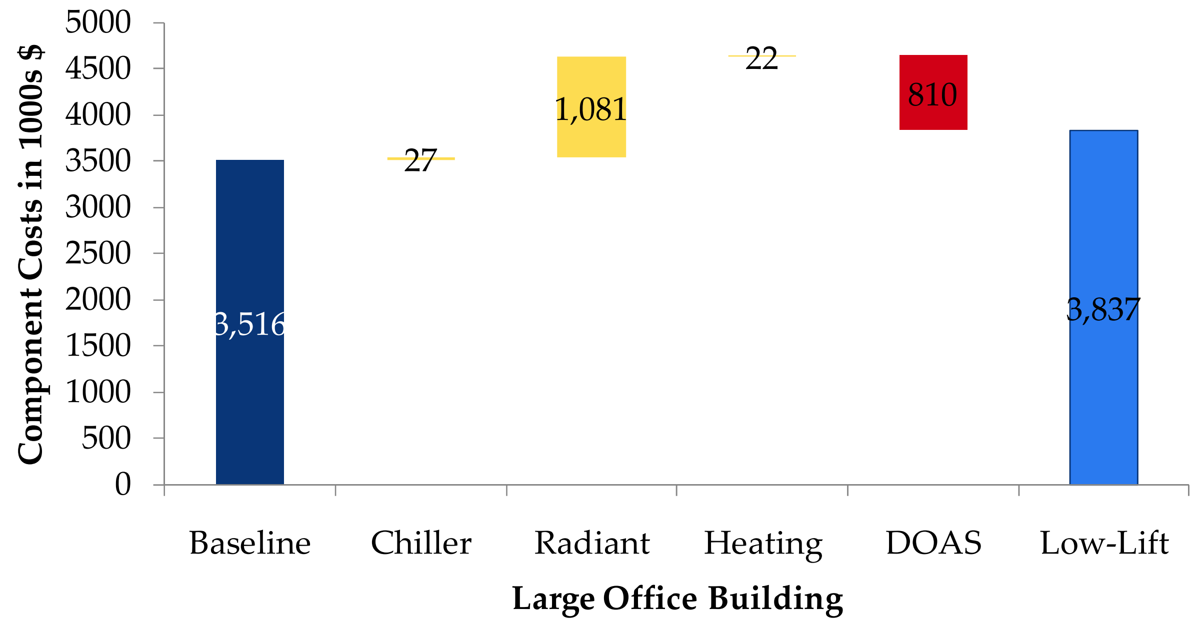


Figure 2 Incremental Cost for Large Office Building Using Low-Lift Cooling

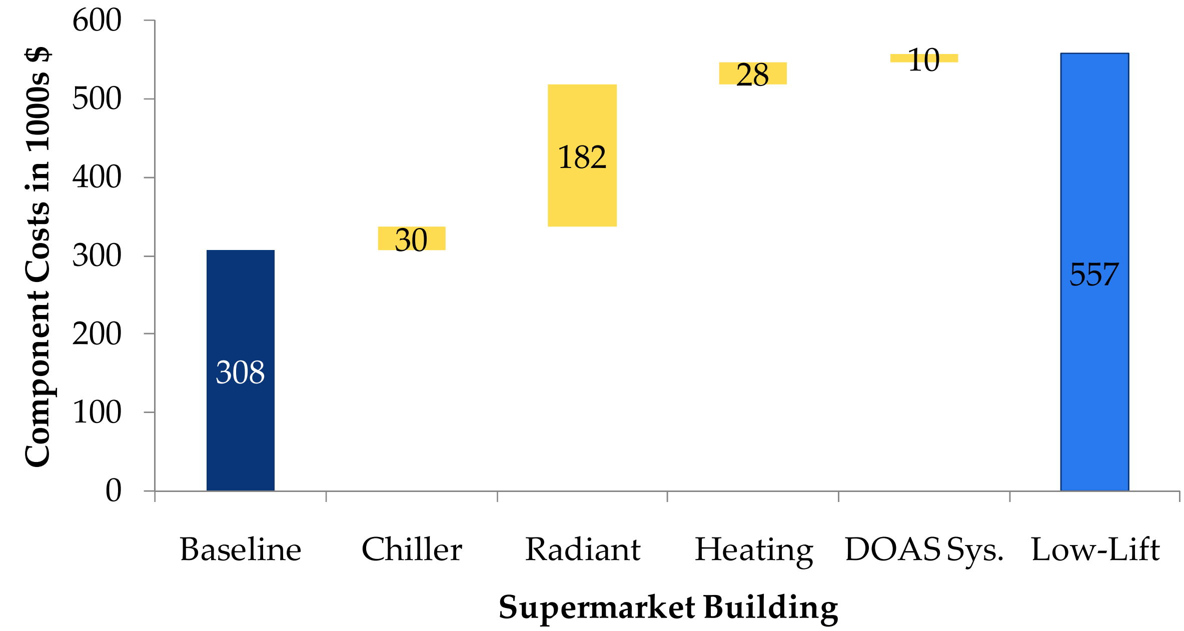


Figure 3 Incremental Cost for Supermarket Building Using Low-Lift Cooling

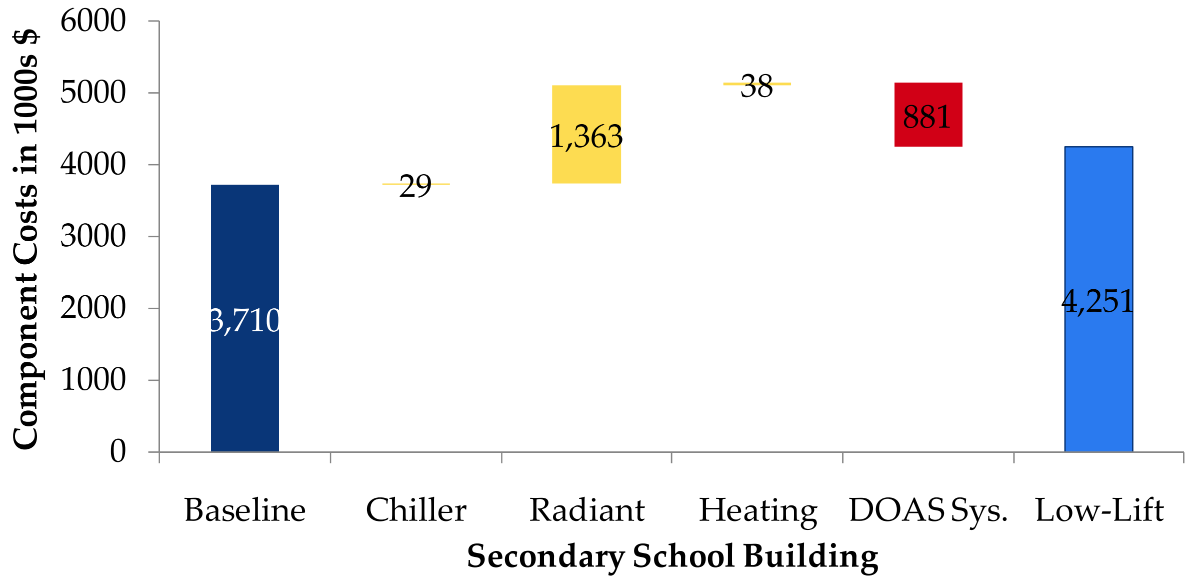


Figure 4 Incremental Cost for Secondary School Building Using Low-Lift Cooling

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 comparable 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 building type typically use inexpensive single-zone packaged units; therefore, these building will have difficultly completing 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 due to 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.

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).

- Whereas 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 and 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 20 to 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[18] and EnergyPlus[19]) 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 5 lists the changes made to the benchmark templates. There are two major differences from the previous study (Jiang et al. 2008; Armstrong et al. 2009a and 2009b): 1) use of EnergyPlus instead of DOE 2.2 for estimating the thermal loads in the buildings and 2) simulation of 12 building types in 16 climate locations instead of 1 building type in 5 climate locations.

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 16 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 developed in FY07 and enhanced this year in Matlab environment.

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 (7-20 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,

[18] http://www.doe2.com/
[19] http://apps1.eere.energy.gov/buildings/energyplus/

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 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 chiller model developed in FY07 has been enhanced for this study; refer to the Appendix C (Appendix: Enhanced Chiller Models) for details.

The 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.

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. The DOAS model has been modified from the previous year. The details of the DOAS model are presented in the next subsection.

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.

Dedicated Outdoor Air System (DOAS) Model

The changes made to the DOAS model are described in this section. The DOAS consists of an enthalpy wheel, a DX (direct expansion) dehumidifier coil, a run-around heat exchanger in the form of a heat wheel, and balanced-flow supply and return fans. These components are illustrated in the DOAS unit schematic, Figure 5.

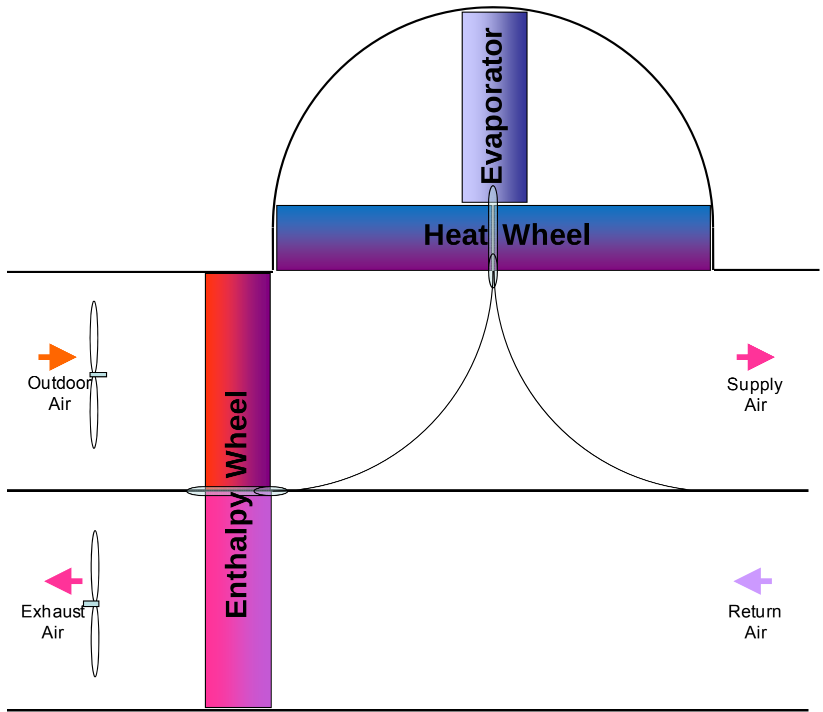


Figure 5 Schematic of DOAS that provides Dry Ventilation Air with Minimal Sensible Cooling

The enthalpy wheel is modeled in EnergyPlus as a constant-effectiveness heat transfer and constant effectiveness mass transfer device. The run-around heat wheel is modeled as a constant-effectiveness heat transfer device with $\xi = 0.75$.

The evaporator load is calculated from the building latent load minus the latent cooling provided by the enthalpy wheel as follows:

$$Q_{\mathrm{Lat,DX}} = Q_{\mathrm{Lat,Bldg}} - Q_{\mathrm{Lat,ERV}}$$

When the ventilation rate is zero or the evaporator load is zero, the evaporator leaving air conditions are set to the enthalpy wheel leaving air conditions. In this situation the run-around heat exchanger load is zero. If the ventilation rate and evaporator load are non-zero, the evaporator leaving air conditions are:

$$w_{\mathrm{DX}} = w_{\mathrm{ERV}} = Q_{\mathrm{Lat,DX}} /(\rho V_{\mathrm{OA}})$$

where V_{OA} is the outside air flow rate. The evaporator leaving air is assumed to be saturated:

$$T_{\mathrm{DX}} = \mathrm{hsat}(w_{\mathrm{DX}})$$

The supply air temperature is the run-around heat exchanger leaving air temperature given by

$$T_{\mathrm{RRHX}} = T_{\mathrm{DX}} + \xi_{\mathrm{RRHX}} *(T_{\mathrm{ERV}} - T_{\mathrm{DX}})$$

and the sensible cooling contributed by the DOAS is

$$Q_{\text{Sen,DOAS}} = (T_{\text{RRHX}} - T_{\text{RA}})\rho c_p V_{\text{OA}}$$

where T_{RA} is return air temperature and $\xi_{\text{RRHX}} = 0.75$.

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 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 10. 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), similar to what was presented in the FY07 analysis.

Table 10 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. 16 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), and
5. 8 different low-loft combinations.

These combination of simulations resulted in 1,152 EnergyPlus runs and 9,216 Matlab simulation runs. The energy savings estimates are summarized in following sub-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 16 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 6) 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 16 climate locations is calculated with 8 different combinations of the LLCS.

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 6).
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 10).

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 D (Appendix: Energy Use 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 11 and Table 12 show the annual energy consumption (chiller, fan, and pump) for the standard- and high-performance medium office building designs for various HVAC combinations across 16 climate locations. The second row (following the row of labels) represents the annual energy consumption for the base case HVAC system (for medium office, it is packaged multi-zone VAV system). The third row represents the low-lift base case (for medium office, it is two-speed chiller with a VAV AHU). The reminder of the rows 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 when 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 13 through Table 18. The tables of the rest of the building types are included in Appendix D (Appendix: Energy Use Tables and Figures).

Figure 6 through Figure 15 compare the annual energy consumption for four selected standard buildings (medium office, large office, supermarket and secondary school) for 9 different combinations of the systems (Case 0 through Case 8) in 16 climate locations. In all cases, the base case is significantly higher than the full LLCS (Case 8).

For standard medium office (Figure 6), the reduction in energy consumption between Case 0 and Case 8 ranges from 58% to 67%, with an average reduction of 63%. 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 14% to 52%, with an average reduction of 37%, 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. Although there is a significant difference between Case 0 and Case 8 in mild dry climates (Los Angeles, San Francisco and Seattle), the difference is small between Case 1 and Case 8 (a range between 14% and 26%) because of higher part-load efficiency of the 2-speed chiller in mild dry climates.

Table 11 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Medium Office Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-OfficeMedium	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	186,328	232,164	210,597	120,553	92,836	158,050	61,550	105,164	105,197	54,056	92,019	79,875	85,664	63,044	59,703	44,344
Case 1: 2-Speed Chiller, VAV	93,391	115,116	143,627	63,072	39,132	114,733	32,566	58,978	67,521	31,884	50,543	51,958	47,229	42,966	37,099	32,175
Case 2: Var-Speed Chiller, VAV	86,711	107,861	134,830	58,645	34,351	108,780	29,464	55,345	63,521	29,582	47,651	48,764	44,469	40,679	35,459	30,844
Case 3: 2-Speed Chiller, VAV, TES	83,665	104,439	121,059	57,507	37,526	95,426	30,987	53,059	59,644	30,486	46,186	46,060	43,871	38,758	35,147	31,367
Case 4: Var-Speed Chiller, VAV, TES	67,261	84,691	102,614	47,454	30,873	83,668	26,992	44,323	49,985	26,885	39,158	39,001	37,932	34,045	32,074	29,248
Case 5: 2-Speed Chiller, RCP/DOAS	83,425	101,233	107,527	56,525	44,939	84,545	36,108	50,866	52,564	31,480	43,525	41,186	40,605	34,163	31,116	25,809
Case 6: Var-Speed Chiller, RCP/DOAS	71,269	86,836	95,820	47,545	37,502	75,636	29,017	43,014	45,011	25,942	36,829	34,630	34,159	28,745	25,856	21,383
Case 7: 2-Speed Chiller, RCP/DOAS, TES	79,824	98,502	91,380	54,622	44,034	69,669	35,043	48,542	48,068	30,664	41,915	37,938	39,325	31,983	30,237	25,271
Case 8: Var-Speed Chiller, RCP/DOAS, TES	61,586	76,170	71,277	41,753	33,862	54,758	26,194	37,248	35,361	23,576	32,461	27,635	30,419	23,962	23,498	19,649

Table 12 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Medium Office Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-OfficeMedium	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	83,758	104,592	81,678	53,342	41,111	62,908	24,572	45,744	37,311	22,608	36,478	28,144	33,031	22,172	21,753	15,294
Case 1: 2-Speed Chiller, VAV	36,270	43,682	53,797	25,408	19,851	44,865	13,686	23,201	23,104	14,386	18,974	17,868	17,135	15,088	13,104	11,294
Case 2: Var-Speed Chiller, VAV	33,300	40,458	50,007	23,259	17,817	42,300	12,409	21,434	21,465	13,402	17,524	16,618	15,817	14,181	12,428	10,820
Case 3: 2-Speed Chiller, VAV, TES	32,843	40,076	45,399	23,850	19,343	37,361	13,122	21,532	20,110	13,938	17,886	15,211	16,347	13,350	12,584	11,027
Case 4: Var-Speed Chiller, VAV, TES	24,726	30,299	36,513	18,939	16,383	31,478	11,584	17,184	16,192	12,463	14,579	12,964	13,582	11,689	11,184	10,164
Case 5: 2-Speed Chiller, RCP/DOAS	39,198	48,453	43,916	25,205	18,327	34,596	14,227	22,458	20,760	12,466	18,680	16,229	17,316	13,605	12,698	9,957
Case 6: Var-Speed Chiller, RCP/DOAS	33,763	41,213	39,464	21,422	16,231	31,387	13,156	19,418	18,450	11,410	16,025	14,473	15,047	12,274	11,457	9,172
Case 7: 2-Speed Chiller, RCP/DOAS, TES	38,314	47,938	38,050	24,741	18,145	28,981	14,063	21,955	19,461	12,332	18,330	15,270	17,053	12,984	12,541	9,870
Case 8: Var-Speed Chiller, RCP/DOAS, TES	30,413	38,114	28,840	19,842	15,469	22,508	12,710	17,742	14,973	10,955	14,994	12,126	14,214	10,762	10,936	8,789

Table 13 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Large Office Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-OfficeLarge	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	1,126,714	1,445,175	1,245,158	746,333	739,022	1,128,242	430,164	657,447	1,105,175	395,989	587,181	828,722	554,239	619,572	419,583	361,331
Case 1: 2-Speed Chiller, VAV	869,057	1,089,112	1,433,528	575,700	398,263	1,244,190	288,729	526,945	1,066,898	287,702	462,725	796,670	433,695	623,105	340,146	301,512
Case 2: Var-Speed Chiller, VAV	809,859	1,017,454	1,347,228	537,982	360,456	1,199,102	263,636	495,816	1,046,894	268,482	439,235	780,970	410,644	612,064	326,763	292,756
Case 3: 2-Speed Chiller, VAV, TES	776,342	995,762	1,283,334	523,254	376,445	1,107,857	275,596	475,958	980,875	272,723	417,905	732,119	398,791	579,546	319,993	289,277
Case 4: Var-Speed Chiller, VAV, TES	639,323	805,974	1,159,893	438,178	316,565	1,037,428	242,308	407,589	943,505	244,210	361,646	700,878	349,860	556,882	295,229	272,902
Case 5: 2-Speed Chiller, RCP/DOAS	767,358	939,189	1,053,580	516,031	433,119	822,980	312,489	466,961	544,936	288,616	404,148	431,924	379,736	351,292	294,778	257,818
Case 6: Var-Speed Chiller, RCP/DOAS	648,569	795,933	939,488	430,868	366,613	752,394	247,173	389,794	500,751	235,597	335,625	390,425	313,302	314,752	237,778	211,382
Case 7: 2-Speed Chiller, RCP/DOAS, TES	737,198	919,211	941,655	499,371	420,036	718,544	300,994	447,762	485,825	278,135	389,235	386,356	367,172	321,496	285,300	249,434
Case 8: Var-Speed Chiller, RCP/DOAS, TES	564,022	701,116	783,189	374,930	316,081	612,778	210,758	338,260	414,974	204,891	292,631	320,267	274,801	265,998	210,998	187,697

Table 14 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Large Office Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-OfficeLarge	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	678,678	873,028	594,569	392,992	302,506	465,397	194,292	338,267	276,217	148,739	272,500	219,811	249,903	176,561	164,247	121,364
Case 1: 2-Speed Chiller, VAV	339,959	426,882	554,135	207,227	139,452	458,588	102,548	189,284	212,437	100,483	159,652	179,341	145,355	145,734	107,400	92,618
Case 2: Var-Speed Chiller, VAV	310,472	395,198	507,087	189,575	121,137	441,262	92,423	174,377	201,070	91,871	147,151	172,279	133,816	140,732	101,117	88,311
Case 3: 2-Speed Chiller, VAV, TES	302,512	385,561	489,018	189,824	133,846	370,360	98,168	171,674	185,384	96,470	147,707	151,229	136,660	126,234	102,190	90,006
Case 4: Var-Speed Chiller, VAV, TES	225,785	279,931	420,545	145,885	107,451	342,495	85,232	136,594	163,866	84,509	118,856	138,244	112,448	116,921	90,366	83,519
Case 5: 2-Speed Chiller, RCP/DOAS	412,939	515,283	503,248	245,937	176,926	388,466	111,850	218,160	210,286	108,486	183,144	174,790	167,828	142,422	127,694	100,566
Case 6: Var-Speed Chiller, RCP/DOAS	352,486	432,587	447,274	208,313	154,104	366,604	97,161	187,188	193,313	94,613	155,170	165,156	142,562	133,794	111,077	90,729
Case 7: 2-Speed Chiller, RCP/DOAS, TES	404,003	509,726	456,040	241,198	174,602	327,469	109,649	213,134	192,039	106,547	179,292	153,904	164,842	129,227	125,799	99,051
Case 8: Var-Speed Chiller, RCP/DOAS, TES	320,902	398,846	375,621	191,628	144,560	292,157	91,284	171,517	161,563	88,673	143,876	135,717	133,100	114,895	105,420	85,340

Table 15 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Supermarket Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-Supermarket	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	288,000	286,778	297,606	225,550	150,958	246,794	149,592	222,525	218,750	161,794	222,256	244,950	250,269	267,614	258,528	279,764
Case 1: 2-Speed Chiller, CAV	203,575	184,829	243,958	182,267	136,375	209,991	141,210	187,337	196,694	152,340	195,465	228,285	225,442	254,685	245,532	272,137
Case 2: Var-Speed Chiller, CAV	198,171	177,669	237,777	179,091	135,179	205,663	140,697	184,900	194,353	151,693	193,591	226,639	223,778	253,697	244,961	271,822
Case 3: 2-Speed Chiller, CAV, TES	197,602	180,060	222,467	179,824	135,880	198,338	140,387	184,472	193,118	151,569	193,493	225,373	224,055	252,219	244,748	271,863
Case 4: Var-Speed Chiller, CAV, TES	185,087	163,966	207,677	173,135	134,199	187,685	139,676	179,221	187,448	150,527	189,573	221,336	220,722	249,703	243,396	271,202
Case 5: 2-Speed Chiller, RCP/DOAS	91,511	94,336	123,620	71,223	58,963	96,144	56,613	69,617	69,693	56,645	65,904	65,485	65,468	63,286	61,125	61,131
Case 6: Var-Speed Chiller, RCP/DOAS	81,470	80,563	116,287	64,535	55,521	90,568	54,446	64,684	65,964	54,738	61,663	62,606	61,618	61,169	59,190	60,079
Case 7: 2-Speed Chiller, RCP/DOAS, TES	89,532	93,284	106,802	70,212	58,553	86,735	55,929	68,499	67,657	56,095	65,120	63,647	64,842	61,874	60,757	60,905
Case 8: Var-Speed Chiller, RCP/DOAS, TES	75,250	75,317	91,131	61,701	54,315	75,344	53,330	61,848	61,051	53,707	59,746	58,782	59,965	58,185	58,320	59,442

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

HP-Supermarket	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	106,239	98,444	120,639	81,619	54,058	95,283	56,161	81,458	79,894	63,722	81,536	79,525	85,639	82,261	80,172	98,556
Case 1: 2-Speed Chiller, CAV	73,380	61,269	95,232	65,402	47,946	78,362	50,964	67,185	70,514	58,087	70,553	71,853	75,398	75,647	73,792	93,003
Case 2: Var-Speed Chiller, CAV	70,933	58,612	91,889	64,162	47,797	76,228	50,923	66,265	69,961	57,993	69,954	71,502	74,852	75,469	73,719	92,971
Case 3: 2-Speed Chiller, CAV, TES	71,936	60,491	86,730	64,822	47,752	74,795	50,653	66,439	68,329	57,633	70,040	70,103	75,128	74,418	73,441	92,838
Case 4: Var-Speed Chiller, CAV, TES	67,017	54,949	79,170	62,648	47,541	69,704	50,605	64,514	67,519	57,517	68,804	69,733	74,166	74,191	73,267	92,806
Case 5: 2-Speed Chiller, RCP/DOAS	41,961	42,052	60,336	35,473	31,664	47,039	31,527	35,363	35,524	31,751	34,290	34,303	34,320	33,805	33,490	34,549
Case 6: Var-Speed Chiller, RCP/DOAS	38,010	37,059	56,946	33,520	31,431	44,890	31,443	33,893	34,910	31,613	33,221	33,895	33,418	33,570	33,317	34,484
Case 7: 2-Speed Chiller, RCP/DOAS, TES	41,313	41,733	53,599	35,166	31,563	44,238	31,313	35,026	34,669	31,535	34,074	33,481	34,175	33,190	33,406	34,465
Case 8: Var-Speed Chiller, RCP/DOAS, TES	36,057	35,736	46,132	32,745	31,211	39,232	31,169	32,942	32,941	31,221	32,647	32,494	33,051	32,557	33,049	34,335

Table 17 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Secondary School Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-SchoolSecondary	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	1,779,517	2,161,697	1,751,819	1,195,256	867,881	1,351,853	657,514	1,060,042	961,608	587,211	935,028	801,803	913,353	738,297	710,283	605,706
Case 1: 2-Speed Chiller, VAV	897,526	1,049,733	1,289,344	687,417	510,062	1,038,347	460,541	657,639	744,527	462,389	622,491	638,556	620,947	607,858	568,155	539,245
Case 2: Var-Speed Chiller, VAV	881,173	1,035,294	1,262,366	674,607	496,406	1,017,779	450,981	647,180	734,468	454,797	614,567	630,947	611,835	601,294	562,988	536,056
Case 3: 2-Speed Chiller, VAV, TES	773,183	879,862	1,089,142	615,887	490,988	904,011	446,341	596,418	670,760	449,112	571,696	583,735	586,011	569,951	550,933	529,977
Case 4: Var-Speed Chiller, VAV, TES	690,510	768,577	1,024,341	564,151	463,833	860,514	430,942	555,920	647,918	435,291	538,658	564,807	555,847	555,561	538,074	523,844
Case 5: 2-Speed Chiller, RCP/DOAS	686,421	804,655	933,206	486,515	376,746	691,524	304,441	444,489	453,145	289,543	403,094	380,424	395,886	345,943	319,692	299,371
Case 6: Var-Speed Chiller, RCP/DOAS	642,448	744,437	901,272	457,128	362,247	666,245	296,061	420,003	439,364	282,149	382,584	370,159	376,238	337,092	310,868	295,080
Case 7: 2-Speed Chiller, RCP/DOAS, TES	663,835	792,684	787,322	474,898	370,369	594,823	299,715	430,834	407,976	284,714	393,615	351,123	388,734	326,142	316,138	294,447
Case 8: Var-Speed Chiller, RCP/DOAS, TES	574,662	673,543	711,851	419,379	345,038	543,840	287,192	386,739	377,100	272,188	357,841	328,242	356,062	307,493	301,752	286,502

Table 18 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Secondary School Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-SchoolSecondary	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	924,808	1,167,794	831,219	591,189	391,214	656,156	279,294	510,269	397,631	238,694	432,850	322,700	384,614	276,500	267,722	223,100
Case 1: 2-Speed Chiller, VAV	401,909	486,780	599,019	290,479	205,756	476,583	179,084	271,876	281,792	176,844	249,843	235,658	230,289	213,206	195,752	187,041
Case 2: Var-Speed Chiller, VAV	393,925	481,569	586,088	283,800	196,604	465,976	173,440	266,115	277,305	172,788	245,199	231,952	225,794	209,949	193,256	185,474
Case 3: 2-Speed Chiller, VAV, TES	329,356	387,986	457,982	251,889	196,800	383,288	170,561	236,832	236,612	170,251	222,507	203,005	212,681	190,567	187,086	181,444
Case 4: Var-Speed Chiller, VAV, TES	279,893	318,425	418,406	220,706	181,309	353,701	162,442	213,257	221,956	162,962	202,604	191,158	196,745	181,709	180,547	178,154
Case 5: 2-Speed Chiller, RCP/DOAS	390,915	476,907	531,775	267,223	197,018	395,394	151,830	238,315	232,973	141,232	210,056	189,319	192,331	167,135	148,599	130,553
Case 6: Var-Speed Chiller, RCP/DOAS	367,962	440,269	518,206	251,987	190,840	383,553	148,610	226,410	227,755	138,540	199,273	185,461	183,940	164,137	145,445	129,102
Case 7: 2-Speed Chiller, RCP/DOAS, TES	377,799	470,324	426,610	261,016	194,450	330,311	148,375	230,016	206,882	139,026	204,975	173,183	188,586	154,751	147,111	128,048
Case 8: Var-Speed Chiller, RCP/DOAS, TES	328,357	400,073	387,804	231,124	184,587	300,439	143,884	207,182	191,302	134,398	186,072	161,714	174,091	146,903	141,693	124,901

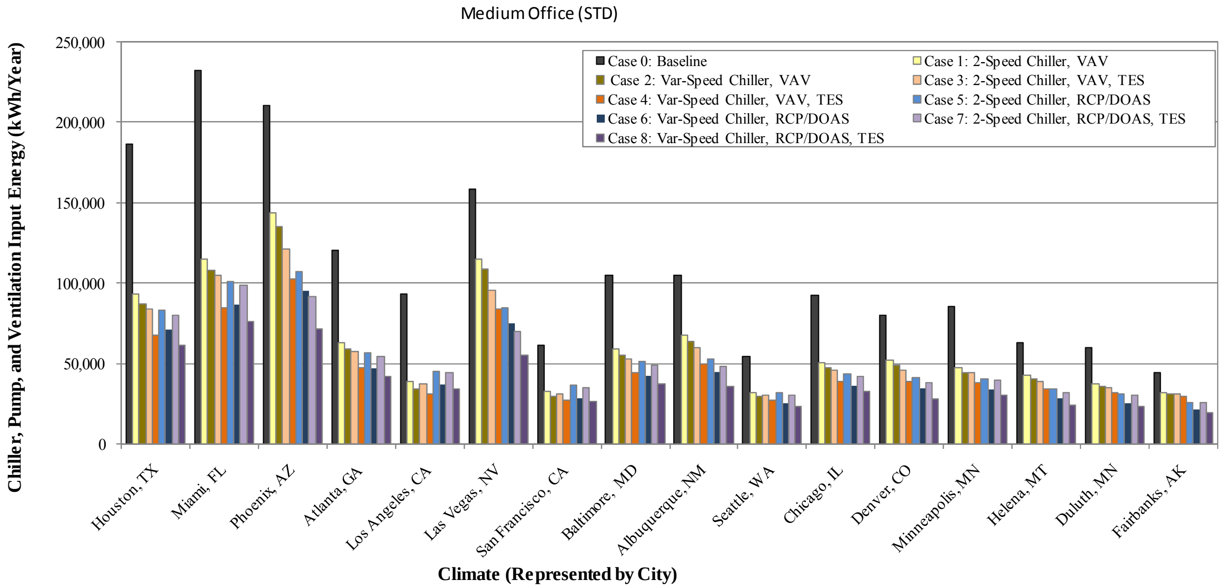


Figure 6 Comparison of Annual Chiller and Distribution Energy Consumption for Standard Medium Office Building for Various System Configurations in 16 Locations

For high-performance medium office (Figure 7), the reduction in energy consumption between Case 0 and Case 8 ranges from 53% to 65% with an average reduction of 57%. 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 7% to 50%, with an average reduction of 25%, significantly lower than the difference between Case 0 and Case 8.

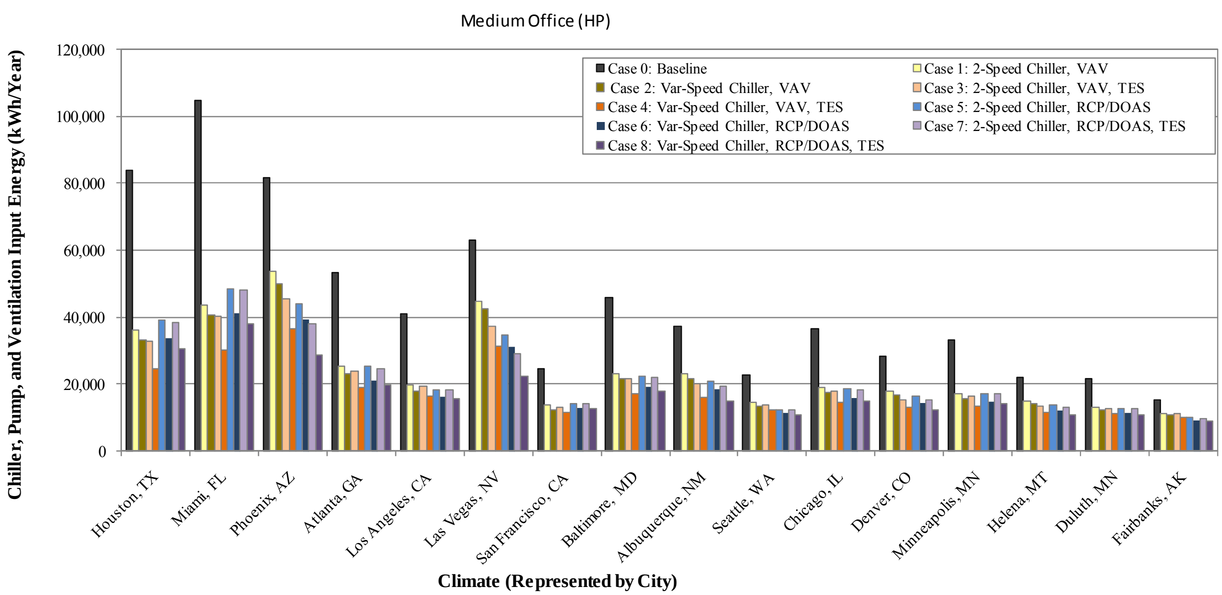


Figure 7 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Medium Office Building for Various System Configurations in 16 Locations

For standard large office (Figure 8), the reduction in energy consumption between Case 0 and Case 8 ranges from 37% (Phoenix) to 63% (Albuquerque and Denver), with an average reduction of 51%. 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 21% (Los Angeles) to 61% (Albuquerque and Denver), with an average reduction of 40%; this is slightly lower than the difference between Case 0 and Case 8. The large office buildings use a water-cooled chiller with VAV system as the base case (Case 0) and two-speed air-cooled chiller with VAV system as the low-lift base case (Case 1). Although the water-cooled chillers are generally more efficient than air-cooled chiller, in humid climates, the difference in performance between air-cooled and water-cooled is small because of high wet-bulb temperatures that limit the water-cooled chiller efficiency. With exception of humid climates (Houston and Miami), the difference between Case 0 and Case 1 is insignificant, and in some climates, Case 1 is higher than Case 0 because water-cooled chillers are generally more efficient than air-cooled chiller in mild dry climates. Like medium office building, the difference between Case 1 and Case 8 in mild dry climates (Los Angeles, San Francisco and Seattle) is lower than the difference between Case 0 and Case 8.

For high-performance large office building (Figure 9), the reduction in energy consumption between Case 0 and Case 8 ranges from 30% (Fairbanks) to 54% (Houston and Miami) with an average reduction of 44%. It is worth noting that the difference between the low-lift base case (Case 1) and the full LLCS (Case 8) is significantly lower and ranges from -4% (Los Angeles) to 36% (Las Vegas), with an average reduction of just 13%. The DOAS-DX system in Case 8 consumes significantly more energy than the low-lift chiller in most climate locations. Because high-performance buildings have significantly lower sensible gains through the building envelop, much of the gains are from the internal loads and ventilation. Furthermore, the ventilation loads are unchanged (between standard- and high-performance buildings), so they become a bigger portion of the total cooling load.

High-performance buildings using conventional HVAC systems with conventional dry-bulb control could experience zone conditions that are outside the comfort zone for a significant number of hours during the year. This is illustrated by plotting the average zone return air conditions on the psychrometric chart for the standard building (Figure 10) and high-performance building (Figure 11). As can be seen, for high-performance buildings (Figure 11), there are a number of hours that are to the right of the comfort line; although not clear from the chart, these hours most likely are occurring during the cooling period. The return conditions are not available for Case 8; however, because the DOAS-DX system is trying to maintain the humidity condition leaving the DOAS-DX, it is unlikely to have similar problems and therefore, the consumption of DOAS-DX may be higher. This also points out the DOAS-DX systems may not be optimized and can be further optimized to reduce consumption.

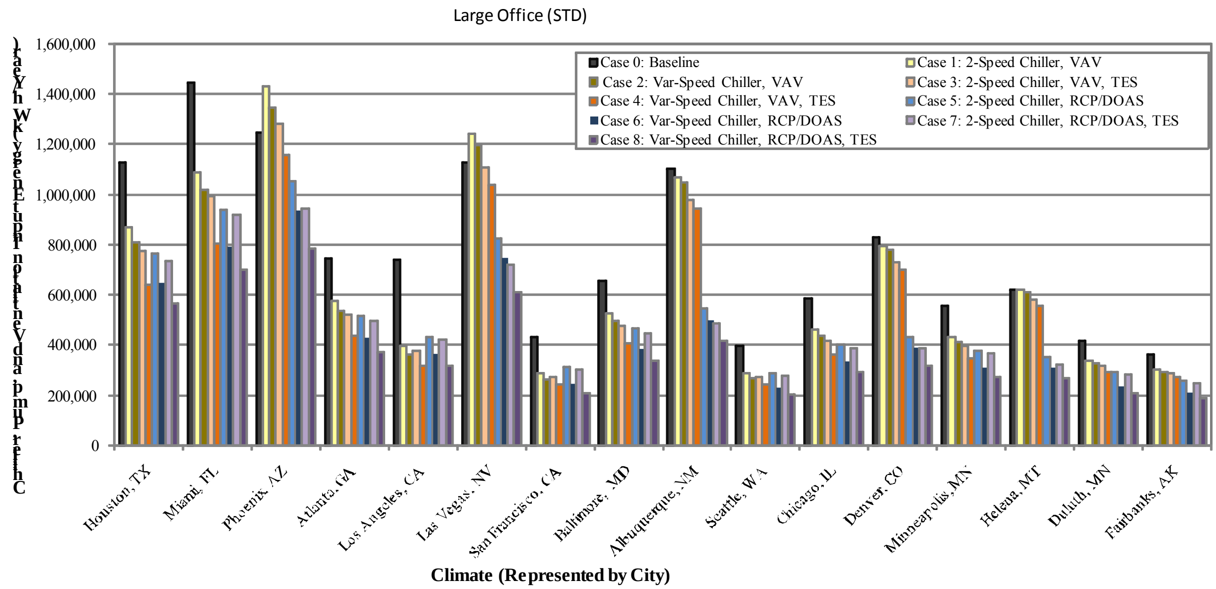


Figure 8 Comparison of Annual Chiller and Distribution Energy Consumption for Standard Large Office Building for Various System Configurations in 16 Locations

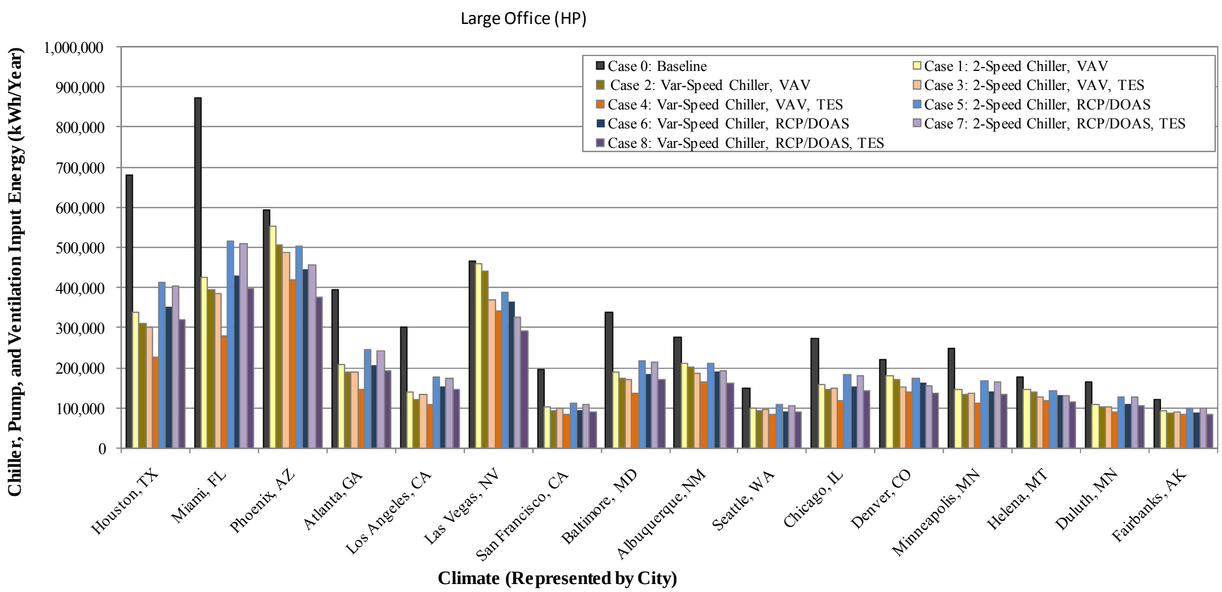


Figure 9 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Large Office Building for Various System Configurations in 16 Locations

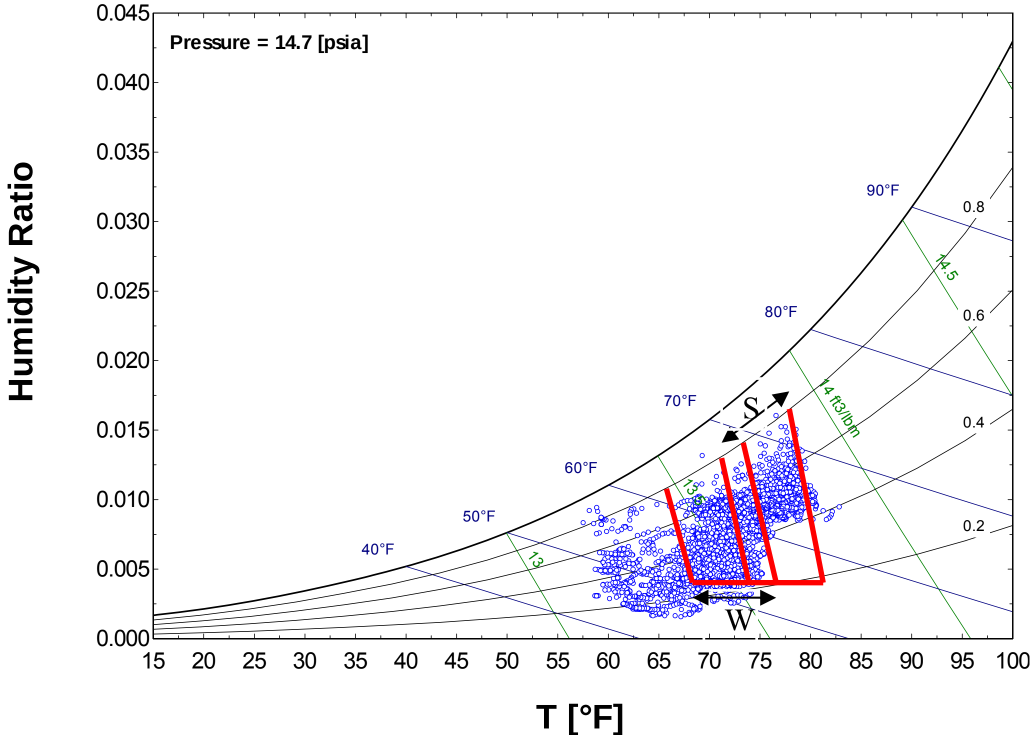


Figure 10 Return Air Condition for Standard Large Office Building (S=summer comfort condition zone, W=winter comfort condition zone)

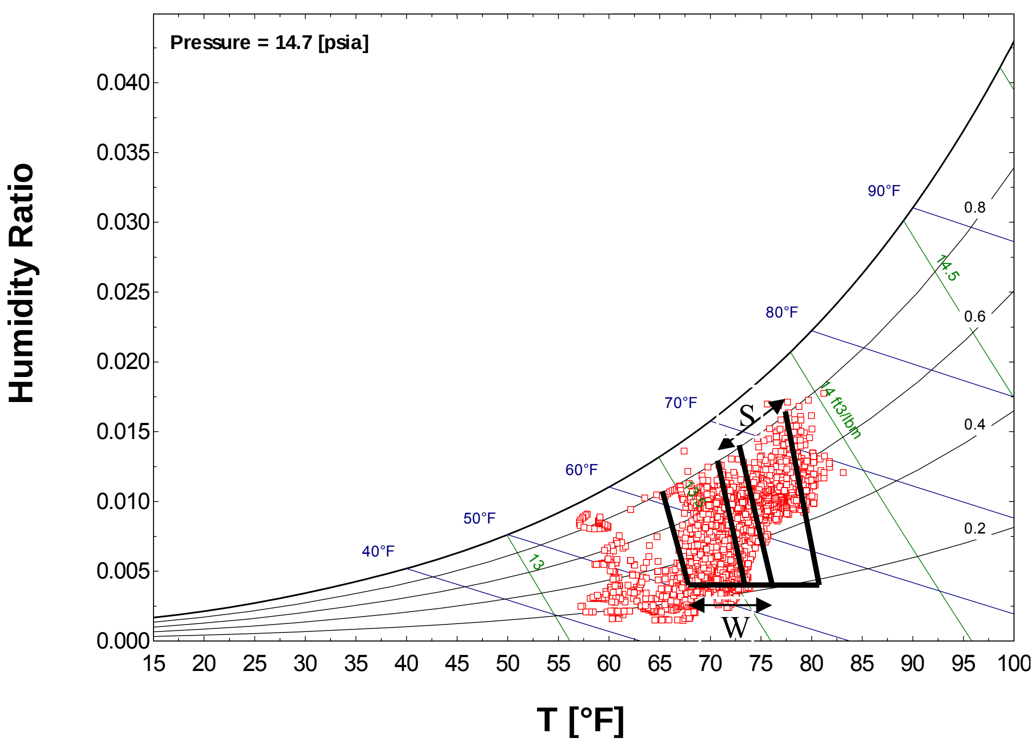


Figure 11 Return Air Condition for High-Performance Large Office Building (S=summer comfort condition zone, W=winter comfort condition zone)

For standard supermarket (Figure 12), the reduction in energy consumption between Case 0 and Case 8 ranges from 64% (Los Angeles and San Francisco) to 79% (Helena and Fairbanks), with an average reduction of 72%. 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 59% to 72%, 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. Also, there is a large difference between the two base cases, Case 0 and Case 1; this is because Case 1 uses a two-speed chiller with a constant volume system, which is more efficient than the packaged single zone constant volume system used for Case 0.

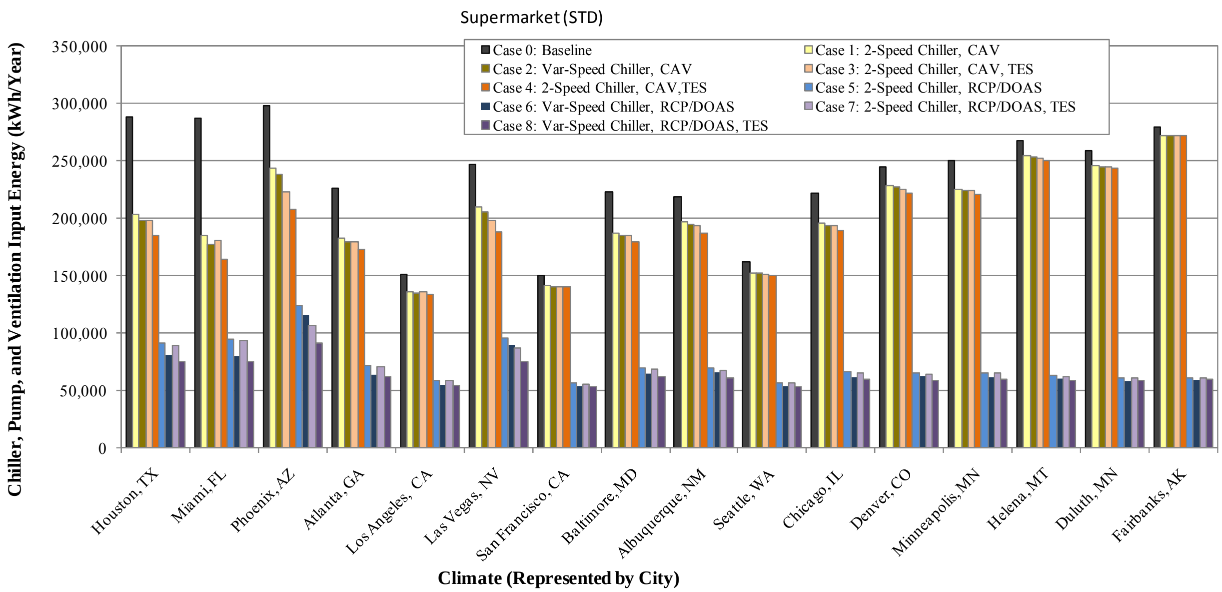


Figure 12 Comparison of Annual Chiller and Distribution Energy Consumption for Standard Supermarket Building for Various System Configurations in 16 Locations

For high-performance supermarkets (Figure 13), the reduction in energy consumption between Case 0 and Case 8 ranges from 42% (Los Angeles) to 66% (Houston), with an average reduction of 58%. 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 35% (Los Angeles and San Francisco) to 68% (Fairbanks), with an average reduction of 51%, significantly lower than the difference between Case 0 and Case 8.

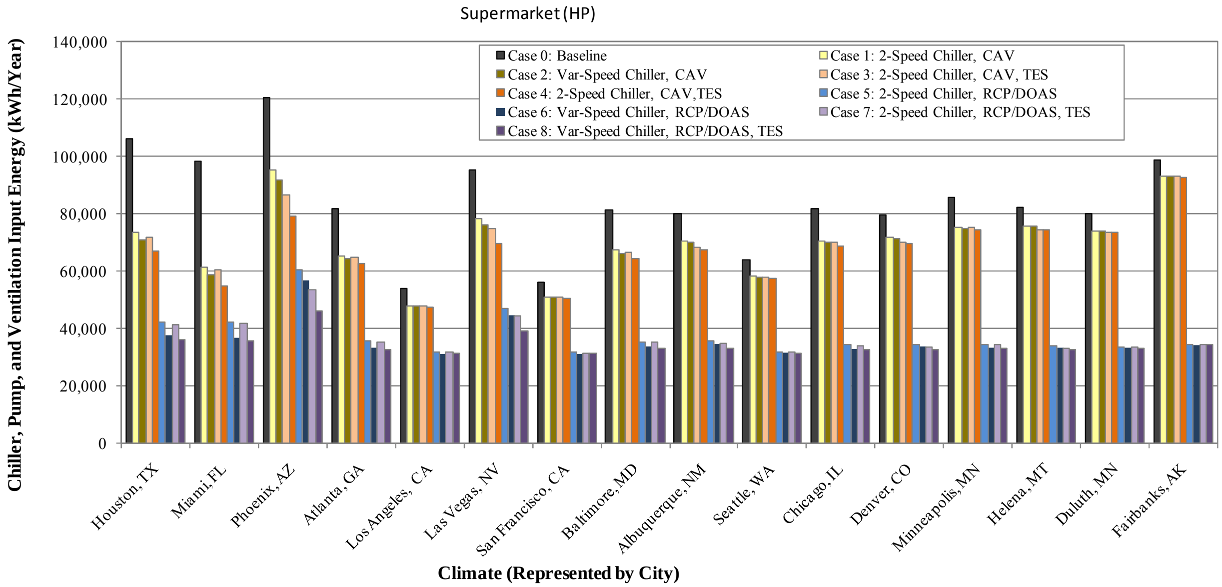


Figure 13 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Supermarket Building for Various System Configurations in 16 Locations

For the standard secondary schools (Figure 14), the reduction in energy consumption between Case 0 and Case 8 ranges from 53% (Fairbanks and Seattle) to 69% (Houston and Miami), with an average reduction of 60%. 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 32% (Los Angeles) to 49% (Helena and Denver), with an average reduction of 43%; 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 the high-performance secondary schools (Figure 15), the reduction in energy consumption between Case 0 and Case 8 ranges from 44% (Fairbanks) to 66% (Houston and Miami), with an average reduction of 53%. It is worth noting that the difference between the low-lift base case (Case 1) and the full LLCS (Case 8) is significantly lower and ranges from 10% (Los Angeles) to 37% (Las Vegas), with an average reduction of just 26%. Like high-performance large office, for Case 8, the DOAS-DX system may be consuming significantly more energy that the low-lift chiller in most climate locations.

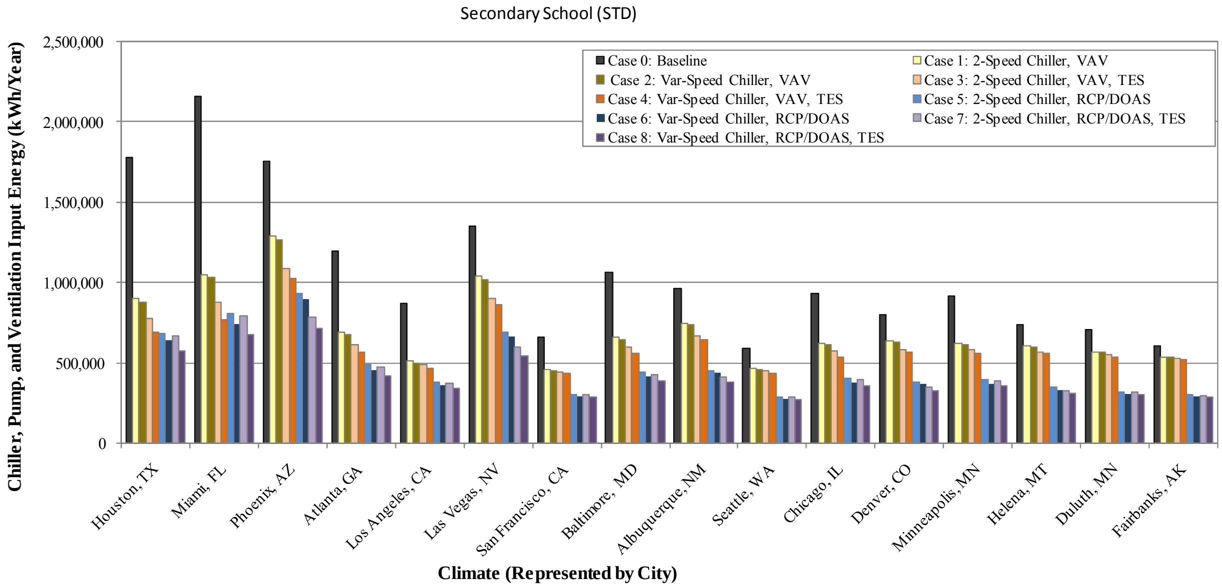


Figure 14 Comparison of Annual Chiller and Distribution Energy Consumption for Standard Secondary School Building for Various System Configurations in 16 Locations

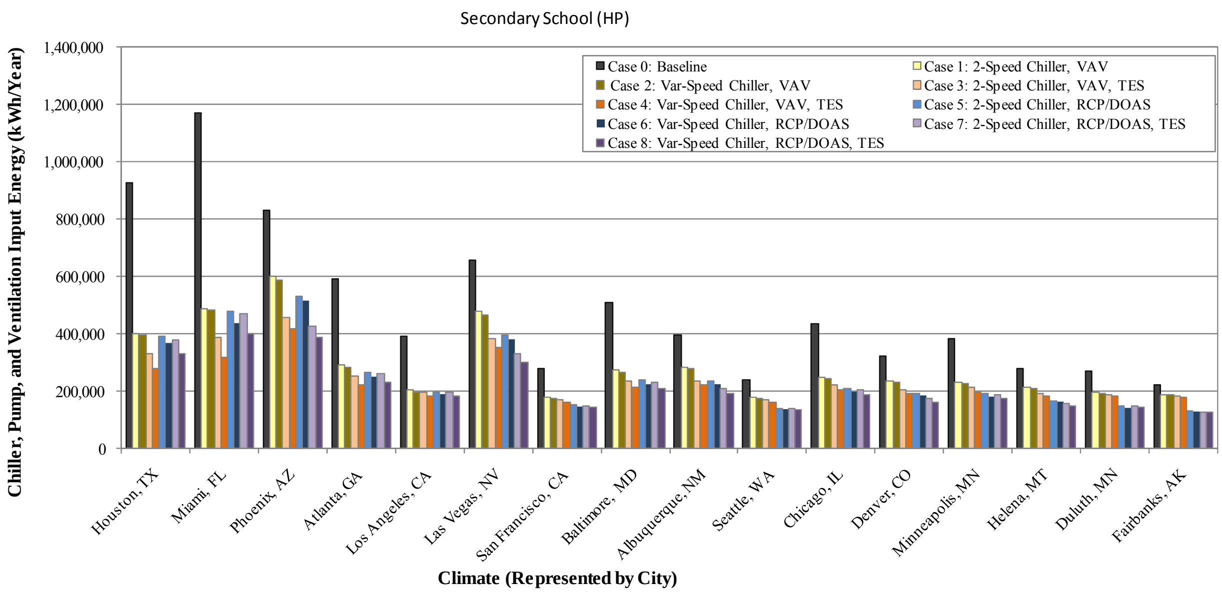


Figure 15 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Secondary School Building for Various System Configurations in 16 Locations

The comparison figures for the rest of the building (similar to Figure 6) are included in Appendix D (Appendix: Energy Use 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 19 (Case 0 as reference), and

Table 20 (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 building from use of the full LLCS, they are only from central HVAC systems used in the common areas and conference rooms and not the individual rooms. Note that for the primary and the secondary schools, the percent savings are also high, even considering that these buildings usually have high ventilation requirements. The savings for the warehouses (non-refrigerated) are of the office portion on the warehouse and not the entire warehouse.

Table 19 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 Building			High Performance Building		
Building Type	Minimum	Maximum	Average	Minimum	Maximum	Average
Office Small	68%	78%	76%	-9%	56%	40%
Office Medium	56%	67%	63%	43%	65%	57%
Office Large	37%	62%	51%	30%	54%	44%
Retail Standalone	67%	76%	72%	43%	67%	55%
Retail Strip Mall	56%	70%	65%	7%	60%	37%
Primary School	53%	69%	64%	35%	70%	56%
Secondary School	53%	69%	60%	44%	66%	53%
Hotel Large						
Supermarket	64%	79%	72%	42%	66%	58%
Warehouse	53%	81%	73%	-3%	69%	45%
Outpatient	78%	84%	81%	44%	68%	62%
Hospital	60%	78%	72%	47%	68%	61%

Table 20 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 Building			High Performance Building		
Building Type	Minimum	Maximum	Average	Minimum	Maximum	Average
Office Small	59%	77%	70%	-19%	43%	25%
Office Medium	13%	52%	37%	7%	50%	25%
Office Large	21%	61%	40%	-4%	36%	13%
Retail Standalone	56%	73%	66%	31%	50%	41%
Retail Strip Mall	45%	63%	56%	-7%	41%	16%
Primary School	46%	55%	51%	22%	46%	34%
Secondary School	32%	49%	43%	10%	37%	26%
Hotel Large	16%	57%	44%	-11%	47%	29%
Supermarket	59%	78%	68%	35%	63%	51%
Warehouse	50%	81%	69%	-5%	69%	40%
Outpatient	65%	83%	78%	34%	67%	53%
Hospital	48%	76%	64%	10%	49%	37%

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 16. 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 $T_{z,i} > Tsupply$. The reheating penalty (E_{reheat}) is estimated using the following equations:

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

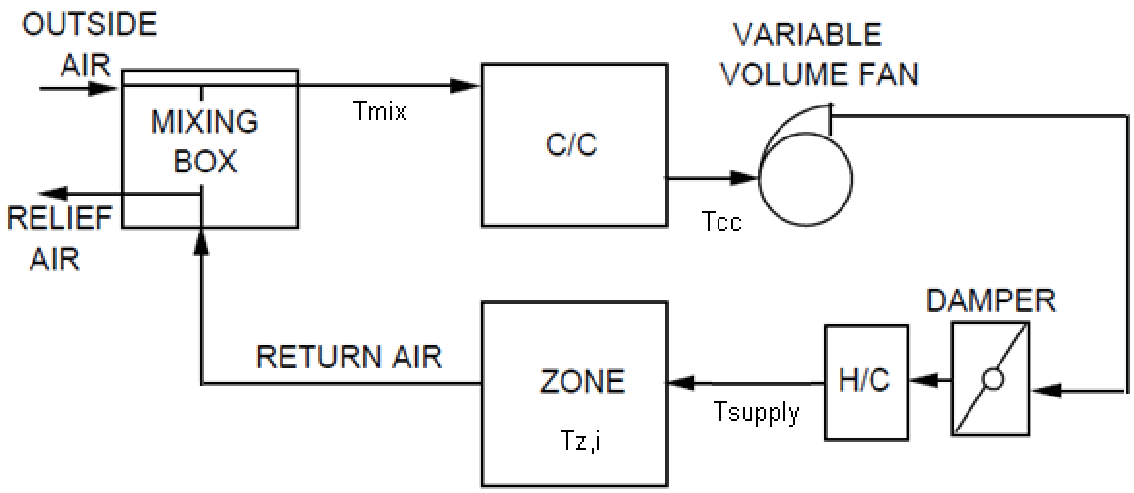


Figure 16 Variable Air Volume System with Terminal Reheat

The reheating penalty is computed for each zone and aggregated in Table 21. Although the absolute energy reheat penalty is of some size, it is a negligible fraction of the total heating energy use, as shown in Table 22. In reality, the reheating penalty is going to be significantly higher than what the simulation has estimated. This is because it is common to have *differen*t set point in different zones, which will lead to increased reheat. Also, while simulating buildings, the controls are assumed to perfect, so it is idealized.

Table 21 Reheat Savings for Selected Building Types in Different Climate Locations (million Btus)

	Hospital	Hotel Large	Office Large	Office Medium	School Primary	School Secondary
Albuquerque	1,681.3	122.5	4,475.6	83.2	71.1	307.2
Atlanta	1,386.5	230.7	716.8	79.8	70.9	187.2
Baltimore	1,240.2	199.6	804.5	81.7	54.4	140.3
Chicago	1,094.3	163.2	790.7	75.9	40.8	121.1
Denver	1,749.1	120.9	3,402.0	80.8	56.7	276.8
Duluth	993.9	100.3	1,114.3	91.0	37.0	118.3
Fairbanks	642.5	84.6	1,144.6	87.7	15.5	118.0
Helena	1,080.4	106.5	2,721.5	79.6	41.4	260.5
Houston	1,792.9	300.7	1,128.1	114.9	114.5	265.5
Las Vegas	1,994.1	253.8	1,541.0	140.5	107.0	316.9
Los Angeles	1,275.5	384.5	674.1	73.4	71.4	246.7
Miami	1,390.8	468.3	714.2	83.6	121.1	269.1
Minneapolis	904.0	147.5	834.5	80.3	36.7	129.0
Phoenix	2,019.3	300.3	1,975.4	179.9	155.1	504.7
San Francisco	1,855.6	268.0	1,309.6	121.8	62.8	316.6
Seattle	1,480.3	187.8	895.4	74.4	41.1	131.6

Table 22 Reheating Savings as a Fraction of the Total Heating

	Hospital	Hotel Large	Office Large	Office Medium	School Primary	School Secondary
Albuquerque	0.035%	0.003%	0.079%	0.008%	0.003%	0.004%
Atlanta	0.031%	0.006%	0.013%	0.008%	0.003%	0.002%
Baltimore	0.017%	0.003%	0.007%	0.005%	0.001%	0.001%
Chicago	0.011%	0.002%	0.005%	0.003%	0.001%	0.000%
Denver	0.026%	0.002%	0.035%	0.005%	0.001%	0.002%
Duluth	0.006%	0.001%	0.004%	0.002%	0.000%	0.000%
Fairbanks	0.002%	0.000%	0.002%	0.001%	0.000%	0.000%
Helena	0.013%	0.001%	0.016%	0.003%	0.000%	0.001%
Houston	0.036%	0.010%	0.017%	0.015%	0.008%	0.006%
Las Vegas	0.056%	0.011%	0.057%	0.024%	0.010%	0.011%
Los Angeles	0.051%	0.027%	0.069%	0.030%	0.016%	0.027%
Miami	0.101%	0.037%	0.114%	0.086%	0.106%	0.097%
Minneapolis	0.007%	0.001%	0.003%	0.002%	0.000%	0.000%
Phoenix	0.044%	0.013%	0.040%	0.028%	0.018%	0.023%
San Francisco	0.033%	0.009%	0.022%	0.013%	0.004%	0.008%
Seattle	0.022%	0.003%	0.009%	0.004%	0.001%	0.001%

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 a 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; significant peak demand savings are needed to make TES cost-effective. A significant portion of the discrete TES savings can be captured by using passive thermal storage (via the thermal mass of the building itself). Because this case (passive TES) was not analyzed for this study, the benefits from TES will not be used in evaluating 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[20] (cooling and fan) and gas[21] (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 if passive TES is used, 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 Mean[22] provides the city cost indices for each city as shown in Table 23. The national cost can be multiplied by the index shown in Table 23 to get an estimate of the incremental cost in each climate location (Table 24).

The energy cost savings for the four building types in the 16 climate location is shown in Table 25. Simple payback is estimated as a ratio of the incremental cost (Table 24) and cost savings (Table 25) and reported in Table 26. Because the incremental cost of the medium office is negative, the LLCS has a zero payback. Large office and secondary school buildings in cooling-dominated climate regions have between 5 to 10 year payback, which is reasonable for an emerging technology. It appears that in mild (Los Angeles, San Francisco and Seattle) and heating-dominated (Chicago, Minneapolis, Duluth and Fairbanks), climates this LLCS may not be favorable, unless other incentives are provided. As more buildings adopt LLCS, over time the incremental cost will decrease. The aggregated payback for the three building types is 9.3, 17.3 and 8.8 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 for more information on new construction volumes).

---

[20] Electricity Prices: Table 5.6.A http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html (August 2009)
[21] Natural Gas Prices: http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm (August 2009)
[22] http://rsmeans.reedconstructiondata.com/60020.aspx (December 2009)

Table 23 City Cost Index (RS Means 2009)

Houston	0.883
Miami	0.903
Phoenix	0.89
Atlanta	0.902
Los Angeles	1.022
Las Vegas	1.057
San Francisco	1.238
Baltimore	0.931
Albuquerque	0.898
Seattle	1.039
Chicago	1.149
Denver	0.95
Minneapolis	1.098
Duluth	1.024
Fairbanks	1.213

Table 24 Incremental Cost of the LLCS by Building Type in each Climate Location

	Medium Office	Large Office	Supermarket	Secondary School
Houston	$0	$ 321,000	$ 250,000	$ 550,000
Miami	$0	$ 345,849	$ 249,228	$ 563,472
Phoenix	$0	$ 340,870	$ 245,640	$ 555,360
Atlanta	$0	$ 345,466	$ 248,952	$ 562,848
Los Angeles	$0	$ 391,426	$ 282,072	$ 637,728
Las Vegas	$0	$ 404,831	$ 291,732	$ 659,568
San Francisco	$0	$ 474,154	$ 341,688	$ 772,512
Baltimore	$0	$ 356,573	$ 256,956	$ 580,944
Albuquerque	$0	$ 343,934	$ 247,848	$ 560,352
Seattle	$0	$ 397,937	$ 286,764	$ 648,336
Chicago	$0	$ 440,067	$ 317,124	$ 716,976
Denver	$0	$ 363,850	$ 262,200	$ 592,800
Minneapolis	$0	$ 420,534	$ 303,048	$ 685,152
Duluth	$0	$ 392,192	$ 282,624	$ 638,976
Fairbanks	$0	$ 464,579	$ 334,788	$ 756,912

Table 25 Energy Cost Savings by Building Type in each Climate Location

	Office Mediu	Office Large	Supermarket	Secondary School
Houston	$ 12,102	$ 54,515	$ 20,385	$ 113,952
Miami	$ 14,827	$ 68,925	$ 20,106	$ 140,302
Phoenix	$ 11,249	$ 44,571	$ 14,995	$ 75,269
Atlanta	$ 6,981	$ 35,237	$ 12,994	$ 62,120
Los Angeles	$ 7,513	$ 51,594	$ 12,235	$ 66,231
Las Vegas	$ 9,583	$ 51,822	$ 15,763	$ 72,036
San Francisco	$ 4,867	$ 30,940	$ 12,198	$ 48,146
Baltimore	$ 8,565	$ 40,335	$ 20,172	$ 82,866
Albuquerque	$ 5,079	$ 71,515	$ 11,703	$ 41,735
Seattle	$ 2,628	$ 19,976	$ 7,012	$ 21,373
Chicago	$ 5,860	$ 30,612	$ 15,112	$ 53,048
Denver	$ 3,954	$ 54,737	$ 13,895	$ 34,627
Minneapolis	$ 4,286	$ 22,529	$ 14,111	$ 40,873
Duluth	$ 3,023	$ 19,617	$ 14,910	$ 30,515
Fairbanks	$ 3,370	$ 25,725	$ 26,780	$ 38,633

Table 26 Simple Pay Back by Building Type for each Climate Location

	Office Medium	Office Large	Supermarket	Secondary School
Houston	0	5.9	12.3	4.8
Miami	0	5.0	12.4	4.0
Phoenix	0	7.6	16.4	7.4
Atlanta	0	9.8	19.2	9.1
Los Angeles	0	7.6	23.1	9.6
Las Vegas	0	7.8	18.5	9.2
San Francisco	0	15.3	28.0	16.0
Baltimore	0	8.8	12.7	7.0
Albuquerque	0	4.8	21.2	13.4
Seattle	0	19.9	40.9	30.3
Chicago	0	14.4	21.0	13.5
Denver	0	6.6	18.9	17.1
Minneapolis	0	18.7	21.5	16.8
Duluth	0	20.0	19.0	20.9
Fairbanks	0	18.1	12.5	19.6
Aggregate Payback	0	**9.3**	**17.3**	**8.8**

National Energy Savings Estimation Methodology

In the previous section, the potential energy savings for the LLCS for 12 building prototypes in 16 climate locations was summarized. To estimate the national energy savings potential, however, requires the "translation" from savings per *building* to savings across the commercial buildings sector in the nation. 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 for assessing the savings from the proposed ASHRAE 90.1-2010 work were used to estimate the national energy savings.

The new construction weights for the ASHRAE work were developed from the McGraw-Hill Construction (MHC) Projects Starts Database. The MHC data set 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 a draft PNNL report.[23] This dataset covers construction data for most new buildings, as well as additions to existing facilities over a 5 year period (2003-2007) and represents a set of 254,158 individual records of construction of commercial buildings across the U.S. covering a total of 8.2 billion square feet.

To estimate the number of equivalent prototype buildings (Table 27), weights (based on square footage) were assigned by 16 climate locations and by building prototype or category of building type (i.e. large office, supermarket), as shown in Table 28. The 12 building types for which the LLCS is relevant represents about 58% of the all new construction. The data presented in Table 28 can be converted to number of equivalent prototype buildings by dividing by the area of the each representative prototype (Table 27). The number of equivalent buildings built each year for each building type and climate location are shown in Table 29.

Table 27 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

[23] Jarnagin and Bandyopadhyay (2009).

Table 28 New Construction Weights by Building Type and Climate Location (1000s of square feet) between 2003 and 2007

	Miami	Phoenix	Houston	Los Angeles	Las Vegas	San Francisco	Atlanta	Albuquerque	Seattle	Baltimore	Denver	Chicago	Helena	Minneapolis	Duluth	Fairbanks	Total
Supermarket	730	3,117	10,919	6,268	1,832	1,111	13,098	369	2,439	21,101	3,511	25,512	632	5,556	672	123	96,990
Hospital	2,669	6,336	31,675	15,057	2,975	2,584	30,950	1,473	7,005	40,719	14,448	53,727	1,567	14,631	2,230	87	228,131
Hotel Large	7,193	8,264	41,074	18,880	33,574	6,986	42,021	2,449	8,106	63,408	13,212	60,813	3,817	14,994	2,534	237	327,562
Office Large	6,733	4,019	21,549	17,648	1,185	7,718	29,439		10,170	74,887	8,006	29,259		8,808	714		220,134
Office Medium	8,564	19,319	53,760	37,673	9,639	8,987	50,661	2,409	12,956	78,714	22,628	70,100	2,304	19,744	2,182	452	400,091
Outpatient Health Care	2,464	8,877	37,541	13,225	4,956	4,050	38,451	1,538	11,967	54,105	14,407	70,020	2,202	22,655	2,578	136	289,171
School Primary	4,213	10,870	61,754	22,337	7,182	3,149	62,485	1,990	6,195	59,208	14,795	60,881	2,479	11,120	1,541	219	330,418
Retail Stand-Alone	14,839	33,515	146,887	58,451	24,272	12,648	157,835	7,882	28,338	168,410	52,421	226,899	6,033	62,737	7,181	900	1,009,246
School Secondary	10,600	15,188	100,737	41,590	12,604	7,244	125,250	4,185	16,049	133,185	28,960	150,955	5,687	27,474	4,984	817	685,508
Office Small	5,553	19,132	70,387	20,752	10,659	5,142	63,693	3,131	8,106	61,903	21,289	60,858	1,999	15,956	2,139	310	371,009
Retail Strip Mall	9,094	16,772	65,543	32,496	8,889	6,838	67,525	1,490	7,061	66,706	13,316	67,664	1,057	10,099	454	89	375,093
Warehouse	22,016	37,910	164,361	132,005	18,505	9,847	191,596	4,162	27,844	154,913	43,572	223,201	2,578	27,741	2,799	137	1,063,186
Total																	4,743,854

Table 29 Annual New Construction Weights (number of buildings per year) by Building Type and Climate Location

	Miami	Phoenix	Houston	Los Angeles	Las Vegas	San Francisco	Atlanta	Albuquerque	Seattle	Baltimore	Denver	Chicago	Helena	Minneapolis	Duluth	Fairbanks	Total
Supermarket	3.2	13.9	48.5	27.9	8.1	4.9	58.2	1.6	10.8	93.8	15.6	113.4	2.8	24.7	3.0	0.5	431
Hospital	2.2	5.2	26.2	12.5	2.5	2.1	25.6	1.2	5.8	33.7	12.0	44.5	1.3	12.1	1.8	0.1	189
Hotel Large	14.3	16.4	81.5	37.5	66.6	13.9	83.4	4.9	16.1	125.8	26.2	120.6	7.6	29.7	5.0	0.5	650
Office Large	2.7	1.6	8.6	7.1	0.5	3.1	11.8	0.0	4.1	30.0	3.2	11.7	0.0	3.5	0.3	0.0	88
Office Medium	31.9	72.0	200.5	140.5	35.9	33.5	188.9	9.0	48.3	293.6	84.4	261.4	8.6	73.6	8.1	1.7	1,492
Outpatient Health Care	49.3	177.5	750.4	264.4	99.1	80.9	768.6	30.7	239.2	1,081.6	288.0	1,399.7	44.0	452.9	51.5	2.7	5,780.5
School Primary	11.4	29.4	167.0	60.4	19.4	8.5	169.0	5.4	16.8	160.1	40.0	164.6	6.7	30.1	4.2	0.6	894
Retail Stand-Alone	120.2	271.5	1,189.8	473.4	196.6	102.4	1,278.4	63.8	229.5	1,364.1	424.6	1,837.8	48.9	508.2	58.2	7.3	8,175
School Secondary	10.1	14.4	95.5	39.4	12.0	6.9	118.8	4.0	15.2	126.3	27.5	143.2	5.4	26.1	4.7	0.8	650
Office Small	201.9	695.7	2,559.5	754.6	387.6	187.0	2,316.1	113.9	294.8	2,251.0	774.1	2,213.0	72.7	580.2	77.8	11.3	13,491
Retail Strip Mall	80.8	149.1	582.6	288.9	79.0	60.8	600.2	13.2	62.8	592.9	118.4	601.5	9.4	89.8	4.0	0.8	3,334
Warehouse	84.6	145.7	631.6	507.3	71.1	37.8	736.3	16.0	107.0	595.3	167.4	857.7	9.9	106.6	10.8	0.5	4,086
Total																	39,260

National Technical Energy Savings Potential

The annual national 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 16 climate locations. Table 30 summarizes the national 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 30 Summary of National 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	National Cooling and Fan and Pump Electricity Savings	
	Quad	Percentage
Standard	0.011	72.1%
High Performance	0.004	62.9%

For baseline buildings that are compliant with ASHRAE 90.1-2004, the full LLCS saves about 0.011 quads of site electricity use *in 1 year of new construction* with the full LLCS being applied to approximately 60% of floor area of total U.S. new commercial building stock (assuming 100% penetration); the annual site electricity savings are about 0.004 quads for high-performance buildings. The national energy saving for the *full* LLCS (Case 8) compared to the conventional VAV system with two-speed chiller (Case 1) are shown in Table 31.

Table 31 - Summary of National *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	National Cooling and Fan and Pump Electricity Savings	
	Quad	Percentage
Standard	0.005	56.7%
High Performance	0.001	31.7%

The annual national technical energy savings for different system configurations compared to the baseline building (Case 0) are shown in Figure 17. For baseline buildings, the savings range from 0.005 Quads/year for conventional system to 0.011 quads for the full LLCS.

The annual national technical energy savings for different system configurations compared to the conventional VAV system with two-speed chiller (Case 1) are shown in Figure 18. For baseline buildings, the savings range from 0.0003 Quads/year for variable-speed chiller system configured with conventional VAV distribution to 0.0061 Quads/year for the full LLCS.

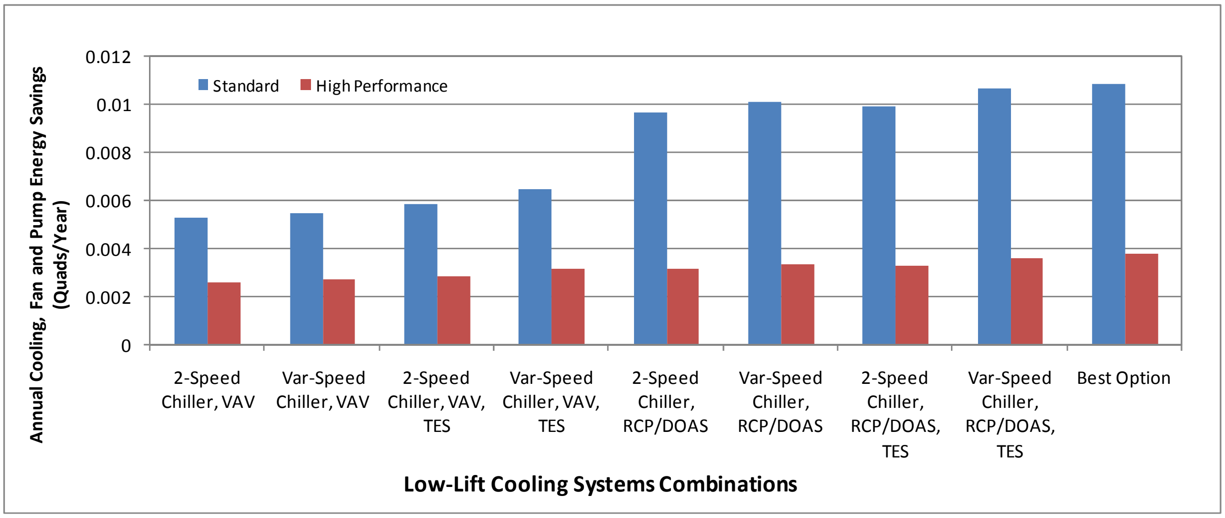


Figure 17 Comparison of National Technical Site Electricity Savings Potential for the Year 2010 for Various Low-Lift Cooling Design Option Sets (assuming 100% Penetration) in Comparison to Case 0

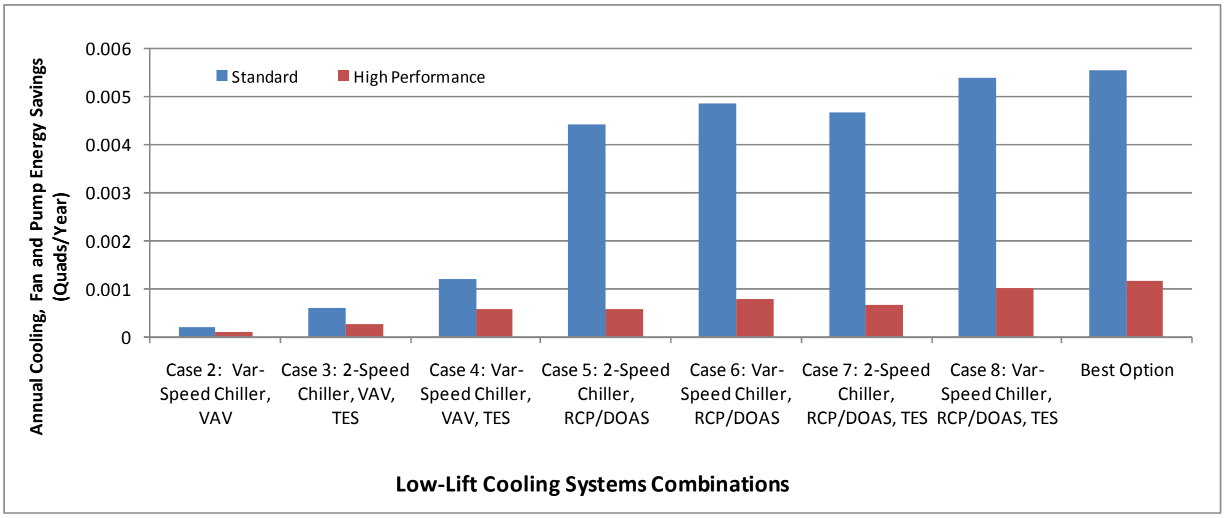


Figure 18 Comparison of National Technical Site Electricity Savings Potential for the Year 2010 for Various Low-Lift Cooling Design Option Sets (assuming 100% Penetration) in Comparison to Case 1

Assuming a new construction growth rates (1%) remain the same for the next decade (through the year 2020), the total national technical site energy savings potential (again assuming 100% penetration) for the baseline building would be 0.12 Quads/year (Figure 19 and Figure 20). To reiterate, all of these savings are in site energy terms; to calculate source energy savings at the power plant, using average fossil-steam heat rates, the previous estimates should be multiplied by 3.[24] The total savings potential – relative to the baseline building – is therefore 0.36 quads. [25]

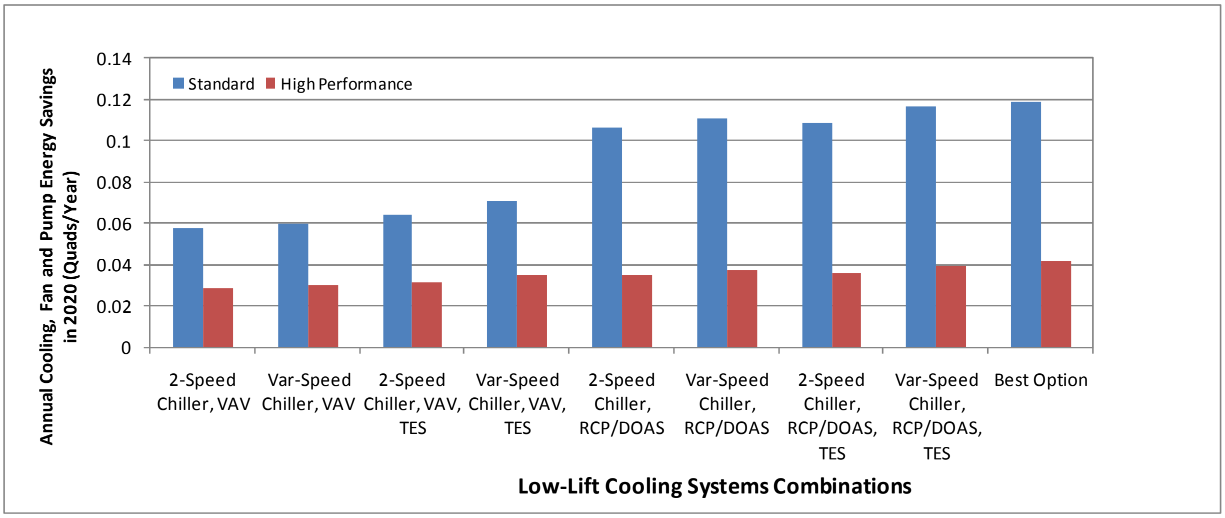


Figure 19 National Technical Site Electricity Savings in 2020 over the Standard HVAC System (Case 0) for Different System Configurations for 2020 Assuming 100% Penetration

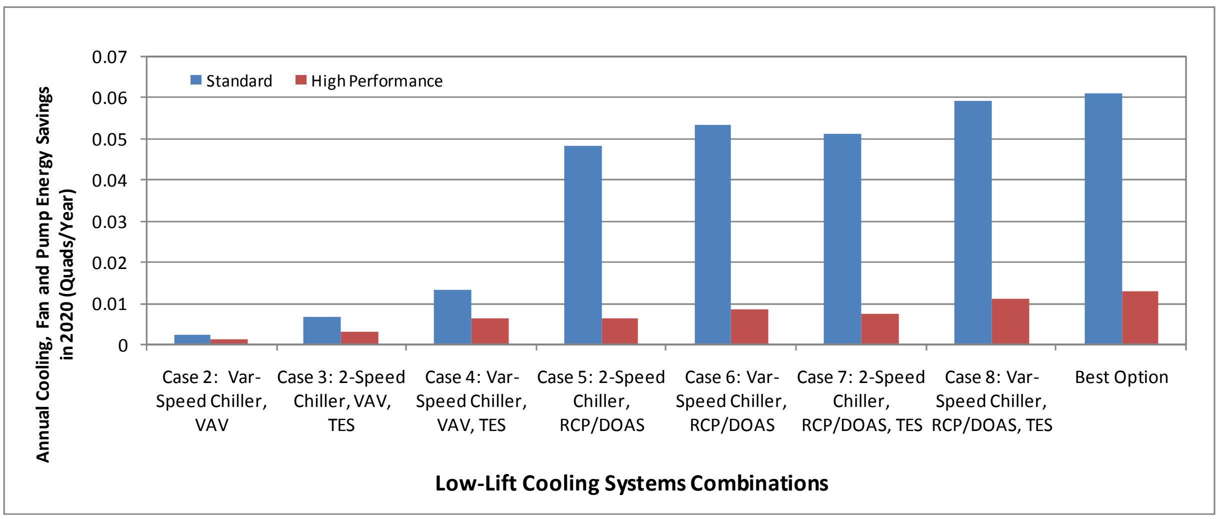


Figure 20 National Technical Site Electricity Savings in 2020 over Case 1 for Different System Configurations for 2020 Assuming 100% Penetration

[24] Per the *2007 Buildings Energy Databook,* the stock average fossil fuel steam heat rate (Btu/kWh) will be 10,098 in 2020 - see http://buildingsdatabook.eren.doe.gov/docs/6.2.5.pdf This compares to the electricity consumption heat rate of 3412 Btu/kWh, about a factor of three difference.
[25] For reference, 1 quadrillion Btu is equivalent to the output of 47 gigawatts of coal-fired capacity at current heat rates and capacity factors.

Discussion, Recommendations and Future Work

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 37% to 84% and, for a very high-performance building, from -9% to 70%.

For baseline buildings that are compliant with ASHRAE 90.1-2004, the full LLCS saves about 0.011 Quads of site electricity use *in 1 year* with the full LLCS being applied to approximately 58% of floor area (assuming 100% penetration) of total new construction in 2010 U.S. new commercial building stock. The annual site electricity savings are about 0.004 for high-performance buildings. Assuming the new construction growth rates remain the same for the next 10 years (through the year 2020), the total national technical site energy savings potential (again assuming 100% penetration) for the baseline building would be 0.12 Quads in 2020. To reiterate, these savings are in site energy terms; to calculate source energy savings at the power plant, using average fossil-steam heat rates, the previous estimates should be multiplied by 3. The total savings potential – relative to the baseline building – is therefore 0.36 Quads 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 form 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.

There are significant savings from use of two-speed or 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 16 climate locations) of between 13 and 71%. A significant portion of savings attributed to RCP/DOAS is from fan energy savings. The VS chiller alone results in savings of only 1 to 7% but when a VS chiller is added to HVAC configurations that already include RCP/DOAS and/or TES, the average incremental savings range from 2 to 25%.

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 permits 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 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 due to use of 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. 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 chiller, that can be integrated with RCP/DOAS. Work next year, will include identifying both alternate low-lift cooling technologies and high-efficiency heating technologies that can be integrated with RCP/DOAS.

References

Armstrong, P.R., W. Jiang, D. Winiarski, et al. 2009. Efficient Low-Lift Cooling with Radiant Distribution, Thermal Storage and Variable-Speed Chiller Controls – Part I: Component and Subsystem Models. ASHRAE HVAC&R Research, 15(2):366-401.

Armstrong, P.R., W. Jiang, D. Winiarski, et al. 2009. Efficient Low-Lift Cooling with Radiant Distribution, Thermal Storage and Variable-Speed Chiller Controls – Part II: Component and Subsystem Models. ASHRAE HVAC&R Research, 15(2):402432.

Conry, R., L. Whelan and J. Ostman. 2002. Magnetic bearings, centrifugal compressor and digital controls applied in a small tonnage refrigeration compressor design. ICEC at Purdue: West Lafayette, IN.

Jiang W, D.W Winiarski, S. Katipamula, and P.R Armstrong. 2008. Cost-Effective Integration of Efficient Low-Lift Base Load Cooling Equipment . PNNL-17157, Pacific Northwest National Laboratory, Richland, WA.
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-17157.pdf

Torcellini, P. et al., 2008, "DOE Commercial Building Benchmark Models." ACEEE 2008 summer study on energy efficiency in buildings, NREL Conference Paper NREL/CP-550-43291. Available at: http://www.nrel.gov/docs/fy08osti/43291.pdf

U.S. Department of Energy. 2009 Buildings Energy Data Book. Available at http://buildingsdatabook.eere.energy.gov/Default.aspx

A Appendix: Supporting Material for Market Assessment

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 technologies 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 VC 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 technologies 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. US 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)

<u>Introduction</u>
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?

<u>LOW LIFT COOLING TECHNOLOGIES SURVEY</u>

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 is 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

Overview of Market Status, Barriers to Adoption, and Options for Overcoming Barriers

Final Presentation to:

Pacific Northwest National Laboratory

June 11, 2008

Navigant Consulting, Inc.
77 South Bedford Street, Suite 400
Burlington, MA 01803
(781) 270-8351
www.navigantconsulting.com

NAVIGANT CONSULTING

Table of Contents

NAVIGANT CONSULTING

Overview Approach

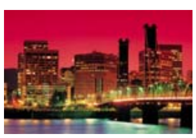
The DOE has requested a market assessment of Low Lift Base-Load Cooling Equipment being developed at Pacific Northwest National Laboratory (PNNL), focusing on future new construction markets.

1. **Review Technology and Models** — Review available literature and discuss benefits/barriers with PNNL
2. **Identify Benefits and Barriers** — Review energy savings potential estimates and identify other potential benefits and barriers
3. **Validate Benefits and Barriers** — Conduct interviews with key stakeholders to validate benefits and barriers
4. **Recommend Initiatives** — Recommend initiatives that can be implemented or facilitated by the DOE to accelerate market adoption

NAVIGANT CONSULTING

Overview Low Lift Cooling

Start with



Peak-Shifting (PS) by Cooling at Night

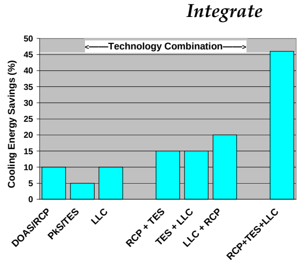
- Proven demand savings technology
- Use Building Mass or Thermal Energy Storage (TES)
- Improves chiller load factor; milder conditions

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

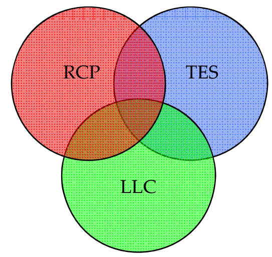
Objective Sum of Energy Savings Greater than its Parts …Plus Comfort and Control Benefits

NAVIGANT CONSULTING

Overview Low Lift Cooling Application

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

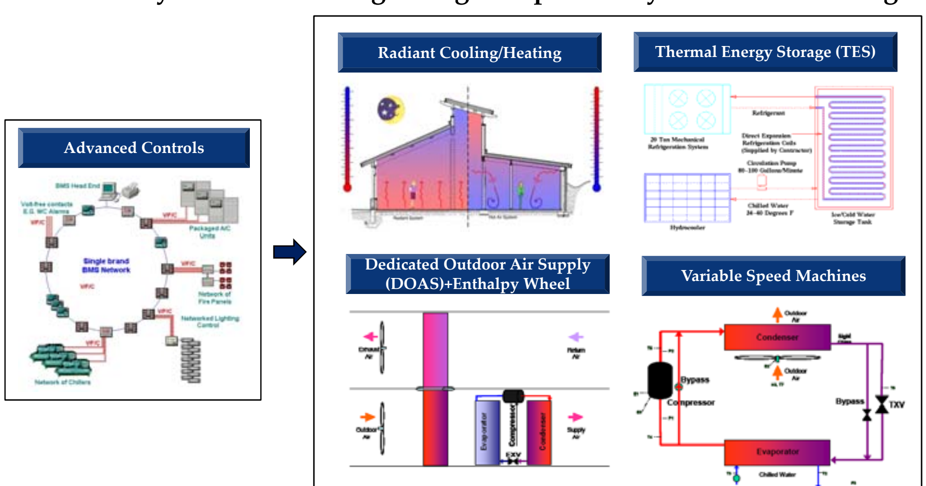
- **Radiant Cooling Panels (RCP)**
  - Zone control without wasteful reheat
  - 55-60°F chilled water temperature
  - Eliminate 80% of fan transport energy
  - Increase water-side free-cooling capacity & hrs/yr
- **Peak-Shifting/TES**
  - Reduce condensing temperature 10-20F
  - Reduce peak and median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



4

Overview Low Lift Cooling Technology and Components

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.



5

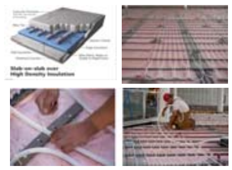
Overview Radiant Cooling/Heating

Several component suppliers currently provide various ground mount and ceiling mount designs of radiant cooling/heating.

Viega

Dadanco

Uponor



Radiant cooling/heating solutions come in floor and ceiling mounted versions and leverage the radiative heating and/or cooling process to provide comfort to the space with minimal moving parts.

6

NAVIGANT CONSULTING

Overview Thermal Energy Storage (TES)

Several TES system suppliers provide tanks and/or heat exchanger configurations to facilitate thermal storage, but the LLC concept may also use passive thermal storage.

JUSTINSULATION

CALMAC

FAFCO

TES components store thermal energy for heating and/or cooling during peak operation, thus reducing peak loads, but TES often does not substantially reduce overall energy consumption.

7

NAVIGANT CONSULTING

Overview Dedicated Outdoor Air Supply (DOAS) + Enthalpy Wheel

Several major manufacturers now offer DOAS+Enthalpy Wheel products or are integrating enthalpy wheels into Air Handling Units (AHUs) and/or Rooftop Units (RTUs)

Carrier – 62 D

York - Solution

Trane - CDQ

McQuay - Roofpack

DOAS + Enthalpy Wheel units takes outdoor air and treats it prior to mixing with indoor air to optimize comfort and indoor environmental quality (IEQ). The enthalpy wheel is configured to recover energy from the exhaust and/or for humidity control.

Overview Variable Capacity Chillers

Several leading manufacturers offer variable speed/capacity chillers as packaged units that includes advanced controls.

Carrier – Weathermaker

York – Series 100

Trane - IntelliPak

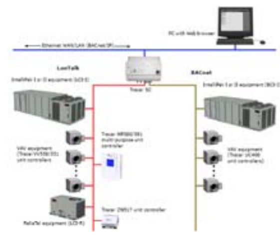
McQuay - Maverick

Variable speed chillers combine variable speed components such as compressors, pumps, fans etc. to optimize refrigerant flow and overall performance of the vapor compression cycle at part load conditions. Alternatively, variable capacity can be accomplished using multiple compressors.

Overview Advanced Controls

Several systems have incorporated advanced controls/drives into new equipment, and the major players are also offering high performance building solutions that incorporate advanced supervisory controls.

Carrier – ComfortView	JCI – Comfort Systems	Trane – Tracer



Advanced controls looks at integrating all of the building HVAC equipment on a single network that can help manage the demands within the building based upon variable load requirements that are created by changes in occupancy levels, lighting levels etc. and consequently improve overall energy efficiency of the building.

Identify Benefits & Barriers Benefits Summary

All the options being considered offer energy-related benefits. Some other market and technical benefits are summarized below.

Low Lift Technology Options Benefits

Technology	Market Benefit	Technical Benefit
Radiant cooling/heating	Ability to downsize HVAC equipment and defer first costs in new construction.	Integration possibilities with existing water/steam lines.
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.
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.
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.
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.

Identify Benefits & Barriers Barriers Summary

Perceived technical and market barriers that are specific to each technology are summarized below.

Low Lift Technology Options Barriers		
Technology	**Market Barriers**	**Technical Barriers**
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.	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.
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.
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.
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.

12

NAVIGANT CONSULTING

Validate Benefits & Barriers Relevant stakeholder groups

A cross section of stakeholders was identified and profiles were created to understand some of the key motivations, concerns and barriers for the group that was then used to craft the questionnaires.

Stakeholder Profiles	
Stakeholder	**Motivations/Concerns/Barriers**
LEED Engineers	LEED engineers are mostly concerned with achieving the highest energy efficiency and energy credits for a particular building. They are likely to adopt cost effective technologies first to achieve LEED certified or bronze before migrating to premium products to achieve silver, gold or platinum, although that adoption is also dictated by the building owner.
OEMs	Primary concern for product line managers in OEMs is the ability to integrate technology improvements into existing product lines without disrupting their existing business activity. This group is likely to want a phased approach for new technology insertion into their product lines and is cautious about pursuing high risk technology development.
Building Owners	Owners are concerned with energy efficiency and utility bills only if they actually have to pay those for the facility. Otherwise, they are willing to pass these costs down to building occupants. In cases where they do not occupy the space, they are more likely to be first cost sensitive.
Building Occupant	Occupants are only concerned with energy efficiency when they have to pay the utility bills directly. This group generally tends to be less technology savvy and will follow standard adoption profiles for all new technologies (innovators – early adopters – early majority – late majority). Their primary concerns include comfort but more importantly may be highly payback sensitive.
Energy Service Provider	Energy service providers look at providing building owners or facilities with energy contracting options and equipment upgrades that lower their energy footprint. They tend to focus more on lifecycle costing and provide long term service contracts with fixed rates that they would then manage through equipment upgrades. They would be somewhat sensitive to equipment first and O&M costs because their value proposition is based on the ability to achieve a NPV positive on a project faster.

13

NAVIGANT CONSULTING

Validate Benefits & Barriers Interview Questionnaires

Two types of questionnaires were crafted, one for a general audience comprised of multiple stakeholders such as retail stores, LEED designers, building owners etc. and another for manufacturers.

Questionaire A - General
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)
5. Advanced controls at the HVAC equipment and HVAC system (supervisory) levels

There are five main areas I am reviewing:

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?

Questionaire B – OEM Specific
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.

NAVIGANT CONSULTING

Validate Benefits & Barriers Interview List

Fifteen interviews were completed with a broad group of stakeholders, including both early adopters and more typical industry participants.

Interviewee List

Stakeholder	Organization/Position
LEED and Other HVAC Engineers	Carrier, LEED Projects Manager
	Independent Consultant
	Centerpoint Engineering, Senior Design Engineer, HVAC
	Taitem Engineering, HVAC
	Hines, Chief Engineer
OEMs	Carrier, Research Fellow, OEM Equipment
	Independent Consultant, OEM Equipment (former Trane executive)
	Chief Engineer, McQuay
Building Owners	Commercial Buildings Owner in CA
	Real Estate Firm, Hines, Commercial Buildings
	Real Estate Organization, Commercial Buildings, General Manager
Building Occupant	UTRC, Strategic Business Analyst, Educated Occupant
	UC Merced, Campus Buildings, Assistant Project Manager
Energy Service Provider	Carrier, Project Manager, Energy Contracting Business (NORESCO)
	North East Utilities, Senior Program Planner

Though the discussion focus was future trends, interviewees commented on both current and likely future environment when evaluating attractiveness of the low-lift concept .

NAVIGANT CONSULTING

The primary barrier to RCPs is the footprint and need to incorporate components early in the design process, issues which could be addressed well in the ZEB or high performance building sector.

Radiant Cooling/Heating Barriers		
Stakeholder	**Market Barriers**	**Technical Barrier**
LEED and other Engineers	Major hurdle in NA markets is having architect talk to engineer early on in construction process to incorporate these features into new construction.	Careful engineering required to prevent condensation problems.
OEMs	Fixation with ductwork in U.S. market prevents adoption of this type of technology. Need large retail e.g., a WalMart to adopt this as standard practice in new construction.	Better controls and integration needed with other building HVAC equipment to prevent condensation problems.
Building Owners	Less familiarity with this technology compared to other options. High costs in retrofits.	Not aware of specific issues.
Building Occupant	Not suited for retrofits but suited for new construction. Customer resistance to new concepts.	IAQ could be a concern (insufficient mixing in air).
Energy Service Provider	Some negative perceptions exist in the market because condensation issues arise when building envelope not optimized.	Need to understand and factor in building operating conditions and external envelope before designing system.

Major Barrier | Minor Barrier | No Barrier

Major barriers to broad adoption of *active* TES exist because it is not seen as an energy efficiency measure, has a large footprint, and unpredictable future electricity rate structures will impact economics.

TES Barriers		
Stakeholder	**Market Barriers**	**Technical Barrier**
LEED and other Engineers	Technology does not have broad applicability, only suitable for places where there is a large difference between day time and night time rates	Difficulty in integration with other systems and also difficult to add due to large footprint requirements (active storage). Passive systems may be attractive but still need to draw in some air for ventilation/IAQ purposes so system needs to be optimized.
OEMs	Only adopted if engineer truly believes in the technology. It is not a net energy reducer.	TES sometimes hurts chiller efficiencies because it may force the chiller to run at a part load condition where its COP is non optimal.
Building Owners	Some building owners using active storage widely for load management.	Lack of visibility and awareness of the technology options and benefits. Other energy efficiency features may be easier to implement.
Building Occupant	Expensive technology and does not provide sufficient energy savings.	Difficulty in installing and maintaining systems (active). Less familiar with technical issues related to passive systems
Energy Service Provider	Even in places where rate advantage exists, change in building usage (e.g., going to 24 hour operation) could limit economic benefits.	Requires large footprint (active). Passive storage may be attractive but need to understand building load profiles better before implementation.

Major Barrier | Minor Barrier | No Barrier

Consequently, *passive* TES is a key topic for future RD&D and modeling tool development.

No major barriers exist for DOAS+Enthalpy Wheel configurations in new construction applications.

DOAS+Enthalpy Wheel Barriers		
Stakeholder	**Market Barriers**	**Technical Barrier**
LEED and other Engineers	Modification of ductwork to facilitate energy significant issue in retrofit and only suited for new construction. Not as many options exist for this technology in the market place.	No major technical barriers for incorporation into new construction.
OEMs	No major barriers observed.	None observed. Pressure drop considerations being built into design.
Building Owners	Some owners were familiar with DOAS systems but perceived technology to be expensive. Some owners also mentioned using these in newer buildings. Some information barrier exists.	Some perception exists that this is an unproven product.
Building Occupant	No concerns seen. Provides sufficient energy benefits to warrant adoption.	Fouling of wheels is a concern.
Energy Service Provider	Need to understand usage scenario for equipment for energy benefits to be realized. Pressure drop issues could be a problem (observed in some previous installations).	Could have high O&M costs depending on manufacturer.

Major Barrier Minor Barrier No Barrier

No major barriers have been identified for variable capacity chillers and variable speed drives.

Variable Speed Chillers Barriers		
Stakeholder	**Market Barriers**	**Technical Barrier**
LEED and other Engineers	No major barriers preventing adoption. More and more places are adopting this type of technology.	No major technical issues seen as more installers/operators are comfortable with the technology.
OEMs	None observed.	Not enough large chillers exist that use variable speed drives/compressors. Systems operate at slightly worse efficiencies at full load and better at part loads.
Building Owners	Several building owners and their facility managers are specifying variable speed drives for pumps, fans etc. Less familiar with the variable speed chillers. High costs for some options.	Not aware of specific issues.
Building Occupant	Does not provide sufficient energy savings for the additional costs.	Need better drive technologies for larger sized chillers.
Energy Service Provider	People not as comfortable with variable speed chillers compared to drives for pumps and motors but that should change over time.	None observed.

Major Barrier Minor Barrier No Barrier

Major barrier identified for advanced controls is lack of user friendly interfaces and lack of educated operators, although that trend seems to be shifting.

Advanced Controls Barriers		
Stakeholder	**Market Barriers**	**Technical Barrier**
LEED and other Engineers	Primarily being used by early adopters interested in monitoring the energy consumption of their facilities. Undereducated operators in several places still a problem.	Interfaces still require some operator sophistication for implementation and use. Training of personnel for use is an issue.
OEMs	Need better interfaces with the operator/consumer (analogy to iPhone) and this may get past potential cost issues.	Need to think of controls + ductwork simultaneously.
Building Owners	Some building owners were found to be more proactive about understanding the benefits of advanced controls. Limited understanding exists among others on how technology can be beneficial and payback sensitivity is a barrier.	Not aware of specific issues.
Building Occupant	No major issues exist and good understanding exists in the market about potential benefits.	Lack of wireless controls and interface options for different HVAC brands.
Energy Service Provider	None observed, more people now comfortable with technology and work force now more computer savvy.	Training personnel to understand benefits is an issue.

Major Barrier Minor Barrier No Barrier

A system that includes a VCC with a DOAS+Enthalpy wheel and advanced controls as a packaged product could be of most value to the new construction, green building market.

Low Lift Technology Options – Customer Acceptance Level	
Technology	**Customer Acceptance Level and Comment**
Variable Capacity Chillers	High – Industry is aggressively 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/High – More product offerings of this type entering the marketplace but there is limited awareness and field data on the units.
Radiant cooling/heating	Medium – Requires significant improvement in implementer and consumer awareness.
Thermal energy storage (TES)	Low – 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.

Additional opportunities for improving adoption have been captured below.

Low Lift Technology Options Market Adoption Recommendations	
Technology	**Market Adoption Methods**
Variable Capacity Chillers	Continue development of improved drives, compressors etc. and improve integration with other HVAC components in the building.
Advanced Controls	Create user friendly interfaces and better training/education programs to make users aware of benefits. For example, public data on building energy savings with an without advanced controls.
Dedicated Outdoor Air System (DOAS) + Enthalpy Wheel	Improve efficiency of enthalpy wheels through development of better desiccant materials. Acquire more field data for multiple building use case scenarios.
Radiant cooling/heating	Enhance training of architects and engineers on incorporation of these as part of standard high efficiency building designs.
Thermal energy storage (TES)	Develop low footprint, high energy density TES solutions (active and passive), and suitable engineering modeling tools.
All	Integrated, packaged solution with corresponding engineering modeling tools will be most attractive to customers.

Educational information and customized training programs could further enhance market acceptance of low lift cooling technologies.

Conclusions

- Stakeholder groups were receptive to low lift cooling technologies because of broader awareness of energy efficiency and climate change issues.
- Enablers such as LEED, ASHRAE Standard 189, utility rebates and ARRA focus on energy efficiency in institutional buildings provide a prime demonstration opportunity for integrated low lift cooling solutions.
- Clear need to create training programs and educational materials specific to various stakeholder groups to broaden awareness of the technology options that comprise the low lift cooling solution. Information should also include case studies with data on energy savings, paybacks etc.

The low lift cooling solution appears to be an attractive option worthy of further RD&D investment.

In Summary
• Technically feasible- does not violate laws of physics or thermodynamics!
• Stakeholders receptive- no dealbreakers
• Packaged solutions most attractive.
• Timing is good due to increasing interest in green buildings
• Need case studies and demonstrations of benefits, including costs and energy savings
• Only technical option meeting substantial resistance is active thermal energy storage- passive approaches and corresponding engineering modeling tools are needed
• Education and training will be critical.

The information contained in this report contains content that was extracted from the websites listed below.

1. http://www.commercial.carrier.com/
2. http://www.trane.com/Commercial/
3. http://www.daikin.com/global_ac/products/commercial/
4. http://www.activechilledbeam.com/index.asp
5. http://www.johnsoncontrols.com/
6. http://products.construction.com/Manufacturer/Uponor-Inc-Uponor-Wirsbo-NST3210/
7. http://www.calmac.com/
8. http://www.mcquay.com/mcquay/IntlPortal/index
9. http://www.dadanco.com/
10. http://www.viega.net/
11. http://www.fafco.com/
12. http://www.just-insulation.com/gyprocduplex.html

Contacts

William Goetzler
Director
phone: 781-270-8351
wgoetzler@navigantconsulting.com
77 South Bedford Street
Burlington, MA 01803

Aris Marantan
Associate Director
phone: 202-973-4501
amarantan@navigantconsulting.com

Rakesh Radhakrishnan
Managing Consultant
phone: 781.270.8373
rakesh.radhakrishnan@navigantconsulting.com

Chris Ahlfeldt
Consultant
phone: 415.356.7106
cahlfeldt@navigantconsulting.com

B Appendix: Supporting Material for Incremental Cost

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

Navigant Consulting, Inc.
77 South Bedford Street, Suite 400
Burlington, MA 01803
(781) 270-8351
www.navigantconsulting.com

NAVIGANT CONSULTING

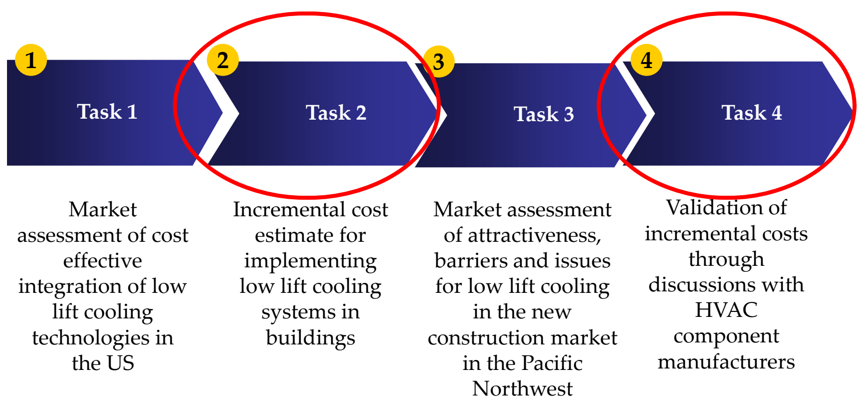
Table of Contents

Table of Contents

NAVIGANT CONSULTING

Overview » Introduction

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



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

NAVIGANT CONSULTING

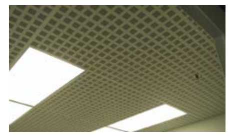
Low Lift Cooling Cost Estimation » Low-Lift System Description

Start with

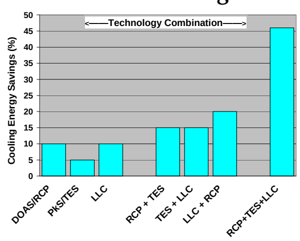
Peak-Shifting (PS) by Cooling at Night
- Proven demand savings technology
- Use Building Mass or Thermal Energy Storage (TES)
- Improves chiller load factor; milder conditions

Add

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

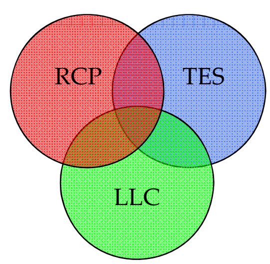
4

NAVIGANT CONSULTING

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
- **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

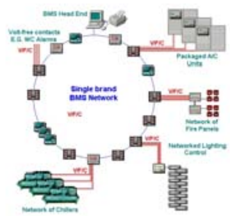


5

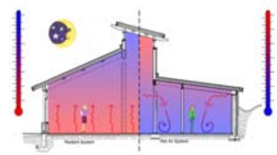
NAVIGANT CONSULTING

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.

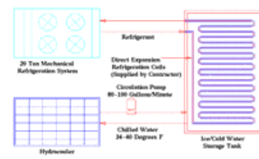
Advanced Controls



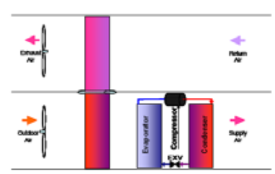
Radiant Cooling/Heating



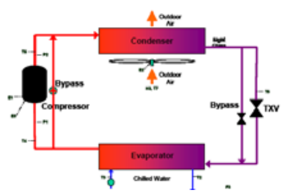
Thermal Energy Storage (TES)



Dedicated Outdoor Air Supply (DOAS)+Enthalpy Wheel



Variable Speed Machines



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

Low Lift Cooling Cost Estimation » Overall Methodology

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

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

8

NAVIGANT CONSULTING

Low Lift Cooling Cost Estimation » Location of Analysis

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/*

9

NAVIGANT CONSULTING

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.

NAVIGANT CONSULTING

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

Energy Plus Output Files

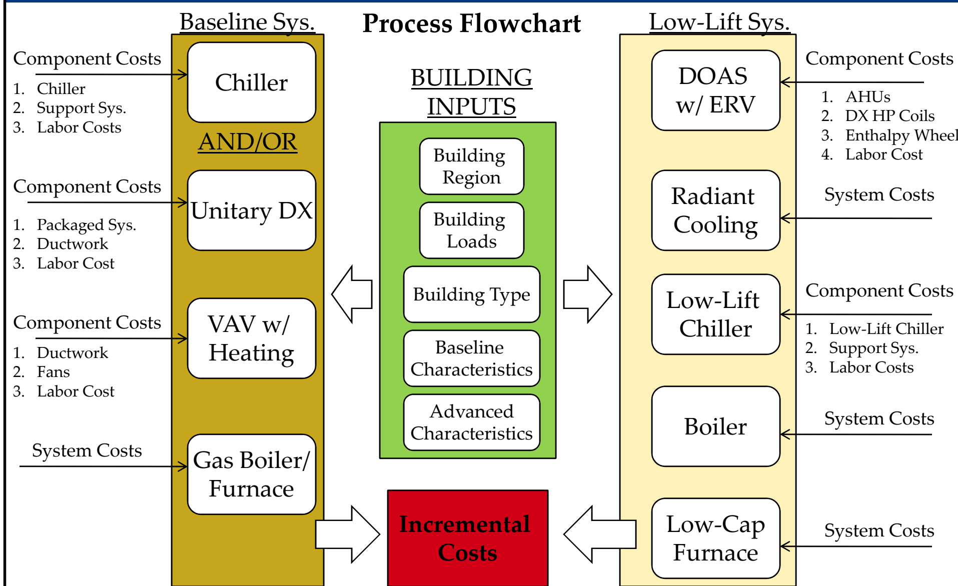
- **Equipment Types**
- **Equipment Sizes**
- **Component Efficiencies**
- **Monthly Thermal Loads**
- **Monthly Ventilation Loads**

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.

NAVIGANT CONSULTING

Low Lift Cooling Cost Estimation » Cost Flowchart



NAVIGANT CONSULTING

Low Lift Cooling Cost Estimation » Proposed Sources for Costs

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

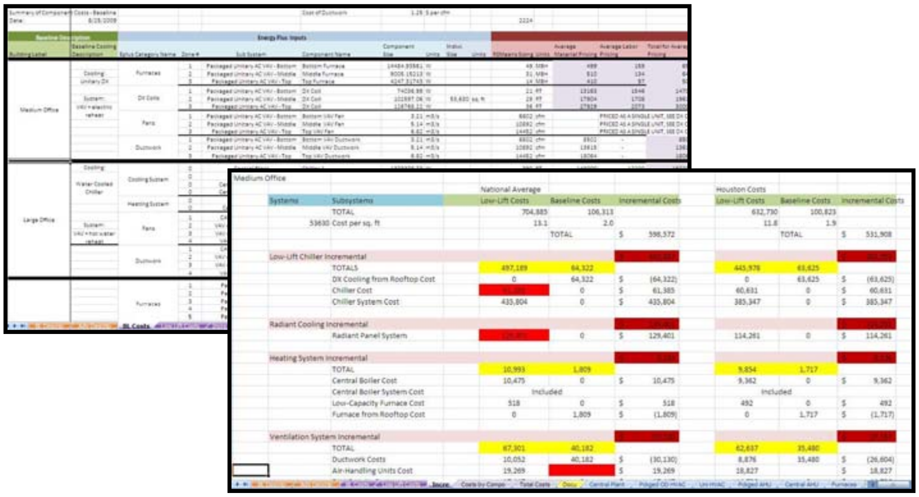
Component Cost Sources		
Component	Baseline Costs	Low-Lift Costs
Chiller, Rooftop Units	RS Means 2007	Suppliers, RS Means 2007
Boiler	RS Means 2007	RS Means 2007
Furnaces	RS Means 2007	RS Means 2007
Control System	Assumed no incremental	
Ductwork	Suppliers, RS Means 2007	Suppliers, RS Means 2007
Air-Handlers	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.

NAVIGANT CONSULTING

Low Lift Cooling Cost Estimation » Spreadsheet Tool for Cost Modeling

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



NAVIGANT CONSULTING

Table of Contents

NAVIGANT CONSULTING

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

Low Lift Cooling Cost Estimation » Calculation of Costs Methodology

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

Steps for calculating baseline costs using RS Means:

1.1 **Receive component and sizing information**

1.2 **Identify appropriate component and size in RS Means**

1.3 **Determine average material and labor costs from RS Means**

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

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

18

NAVIGANT CONSULTING

Low Lift Cooling Cost Estimation » Sizing and Descriptions Provided

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

1.1 **Receive component and sizing information**

	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.

19

NAVIGANT CONSULTING

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

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

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

NAVIGANT CONSULTING

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
	1.2			
0010	**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.

NAVIGANT CONSULTING

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

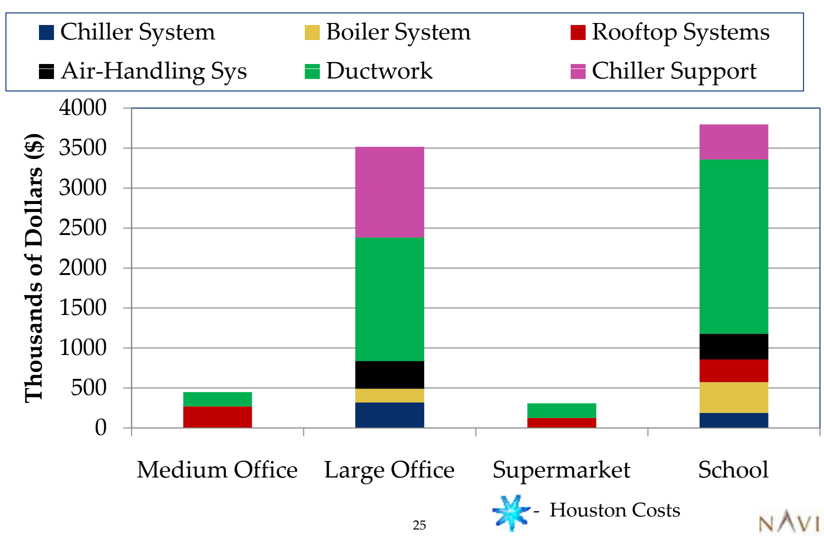
RSMeans City Cost = RSMeans National Average Cost × City Cost Index / 100

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.

NAVIGANT CONSULTING

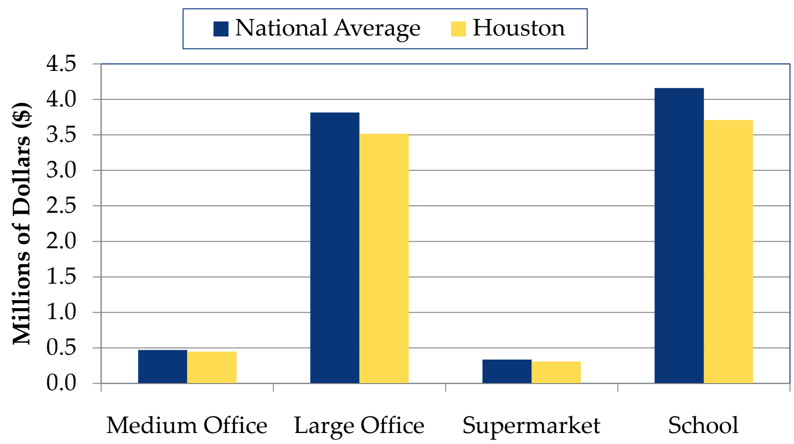
The baseline component costs show that larger buildings are significantly more expensive, because of supporting costs.



NAVIGANT CONSULTING

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

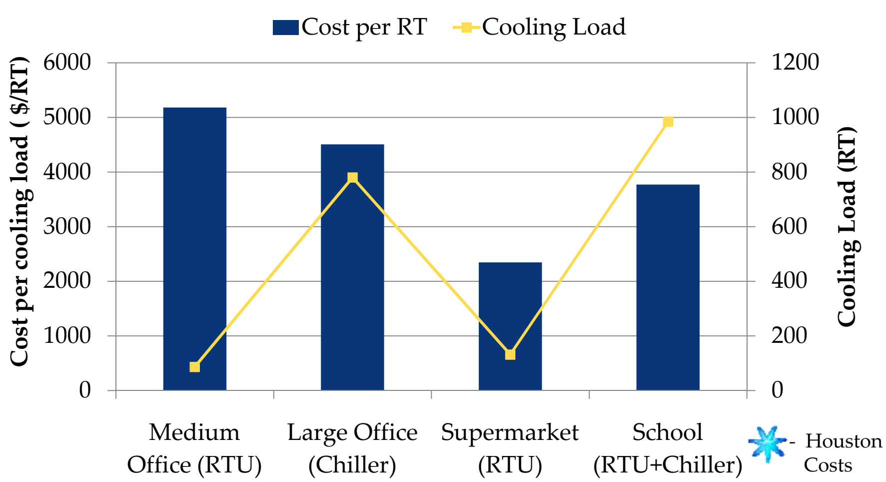
The Houston costs were slightly lower than the national average, with savings in labor costs driving the difference.



26

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.



27

Table of Contents

NAVIGANT CONSULTING

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.

NAVIGANT CONSULTING

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.

NAVIGANT CONSULTING

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.

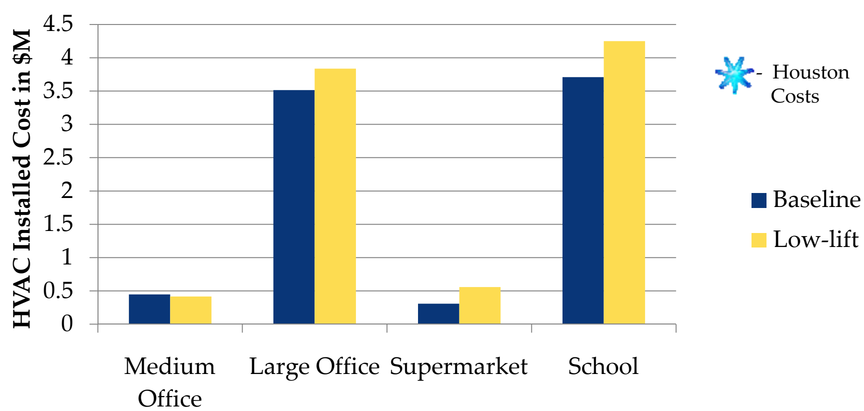
1. Determine baseline system costs
2. Size advanced cooling systems using baseline system inputs
3. Determine advanced system costs
4. Calculate incremental costs

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.

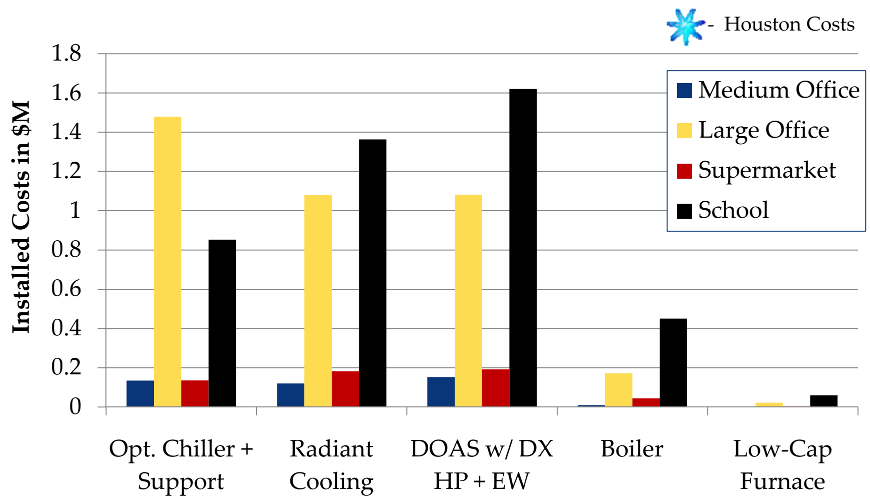
NAVIGANT CONSULTING

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).

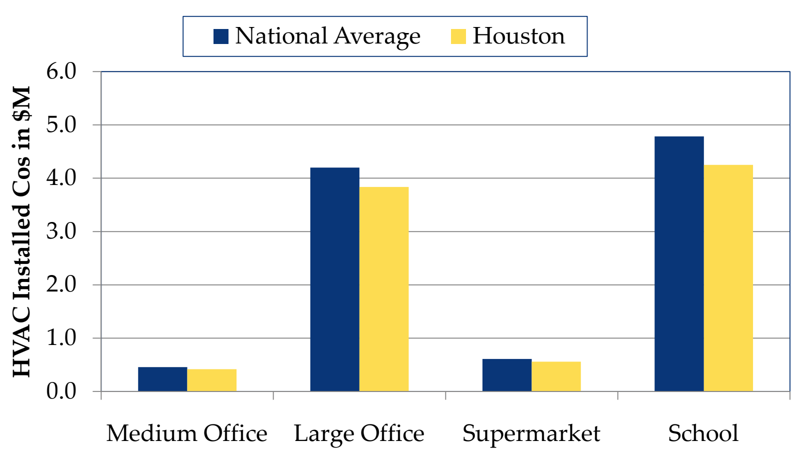


NAVIGANT CONSULTING

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



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



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.

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.

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.

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**

NAVIGANT CONSULTING

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

NAVIGANT CONSULTING

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

NAVIGANT CONSULTING

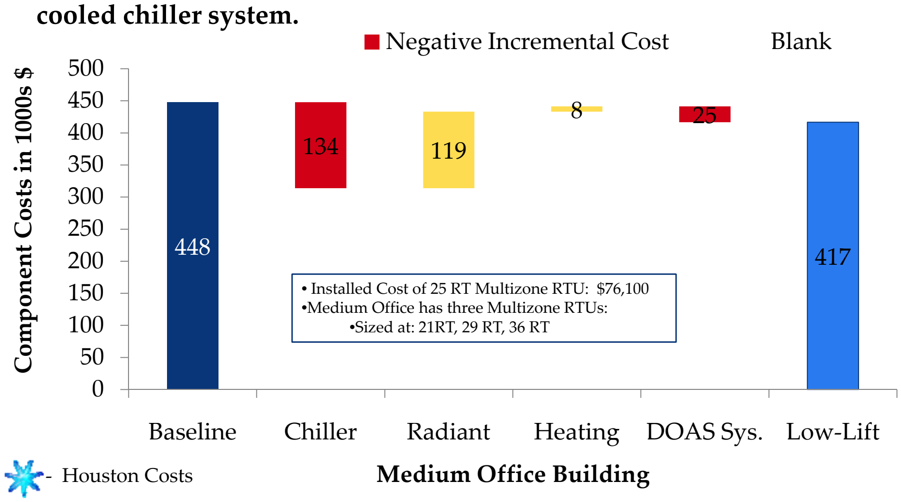
The incremental costs were calculated by comparing similar components within the baseline and low-lift systems.

	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

NAVIGANT CONSULTING

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.

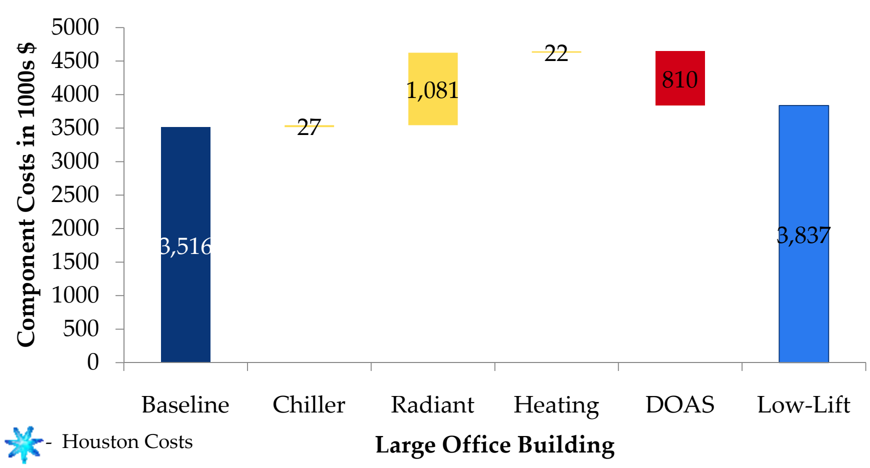


44

NAVIGANT CONSULTING

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

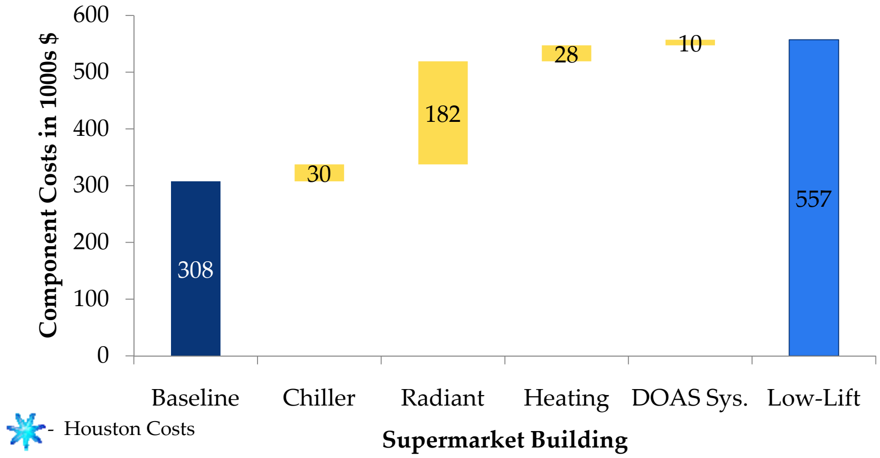
The large office chiller was resized to meet the sensible cooling load, offsetting the additional cost of the advanced chiller system. The radiant cooling and ductwork resizing drove the incremental costs.



45

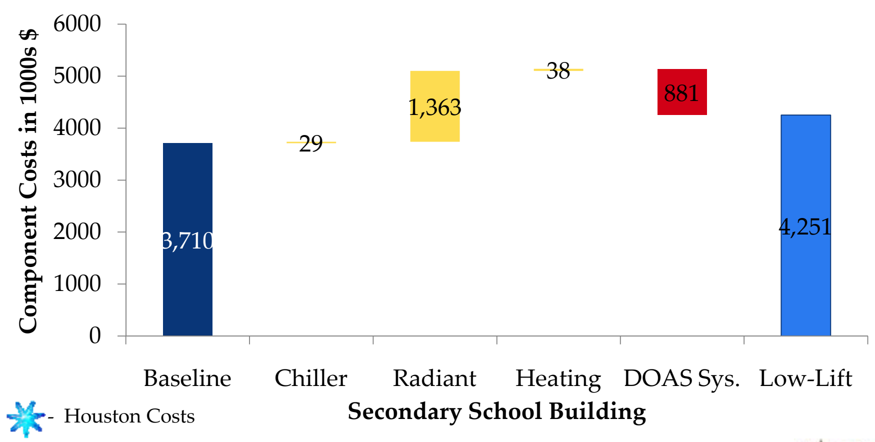
NAVIGANT CONSULTING

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.



NAVIGANT CONSULTING

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.



NAVIGANT CONSULTING

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%

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

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.

NAVIGANT CONSULTING

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.

NAVIGANT CONSULTING

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.

NAVIGANT CONSULTING

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.

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.

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 (29th 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

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

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

Low Lift Cooling Cost Estimation » Incremental Costs – Table - School

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

76

NAVIGANT CONSULTING

Low Lift Cooling Cost Estimation » Incremental Costs – Table - Houston

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.

77

NAVIGANT CONSULTING

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.

NAVIGANT CONSULTING

C Appendix: Enhanced Chiller Models

A new compressor model was developed to better reflect low speed compressor performance. The static chiller optimizer was run with the new model to produce new chiller performance maps. These new results are documented in this appendix.

Compressor and Chiller Models

The compressor model is a key and problematic element of the variable-speed, low lift chiller. It is problematic because of the lack of published compressor performance data for the wide speed range and low pressure ratios of interest in the low-lift application. A purely empirical model may not reliably extrapolate performance to the low speed and low pressure ratio regions. Efforts were therefore made to develop a compressor model that is "more physical" than the model used in the FY07 final report. The new compressor model and the resulting new chiller performance maps are described in this appendix. Efforts are currently underway to measure performance of the 5F60 compressor over the wider speed range, lower condensing temperatures and higher evaporating temperatures of interest. After these measurements are made, the parameters of the compressor model described here will be recalculated.

New Compressor Model

In FY07 a dataset was generated by a publicly available sizing tool[26] for shaft speeds of 900, 1100, 1300, 1525, and 1750 rpm; condensing temperatures of 80, 90, 100, 110 and 130°F (26.67, 32.22, 37.78, 43.33 and 54.44°C); evaporating temperatures of 30, 35, 40, 45, and 50°F (-1.11, 1.67, 4.44, 7.22, and 10.0°C); and evaporator superheat temperatures of 0, 5, 10, and 20°F (0, 2.78, 5.56, and 11.1 K). The resulting hypergrid involves 5x5x5x4 = 500 performance evaluations used to characterize the compressor. A subset of points returned by the sizing tool is presented in Table: C-1. The lowest speed accepted by the sizing tool is 900 rpm, the highest evaporating temperature is 50°F (10°C) and the lowest condensing temperature is 80°F (26.67°C).

The range of saturation temperature difference of interest for low-lift cooling is 0-50 R (0-28 K), while the published range of saturation temperature difference is typically 30-90 R (17-50 K). Published performance data for variable-speed compressors typically cover a range of 2:1 to 3:1 but for efficient cooling with peak shifting controls, a speed range of at least 5:1 is needed. Simple approximate models involving, for example, a constant compression exponent or mass-flow and input power proportional to shaft speed, do not fit the published data very well even over the limited range of pressure ratio and shaft speed presented in Table: C-1. Compressor flow rate and input power models designed to extrapolate reliably to lift conditions and compressor speeds well below the ranges covered by published data have therefore been developed.

Compression is frequently modeled as a polytropic process, Pv^n = constant, in which the polytropic exponent, n, is a function of refrigerant properties, pressure ratio, (P_o/P_i), and compressor design (Gosling 1980; Moran and Shapiro 1995; Popovic and Shapiro 1995; Stoecker 1982; Threlkeld 1970). The fact that internal heat transfer per unit mass is roughly proportional to the duration of the suction-compression-discharge-reexpansion cycle (Boeswirth and Milovanova 1998) means that n will also be a function of shaft speed.

[26] http://www.carlylecompressor.com/corp/details/0,2938,CLI1_DIV24_ETI1240,00.html

Table: C-1 Subset of Sizing Tool Data Used to Estimate Compressor Model Parameters

Spee Rpm	SST °F	SDT °F	SS °F	ρV lbm/	Q Btuh	W Btuh	T_o °F	ρV kg/h	Q W	W W	T_o °C	P_o/P (-)	COP (-)
900	30	80	0	2114	15678	20360	11	961	45951	5967.	43.	2.27	7.70
900	30	10	0	2007	13648	25998	13	912	40001	7619.	59.	3.02	5.25
900	30	13	0	1774	10326	30328	17	806	30264	8888.	81.	4.47	3.40
900	40	80	0	2584	19385	19553	10	117	56816	5730.	40	1.90	9.91
900	40	10	0	2476	17047	26859	13	112	49964	7871.	56.	2.53	6.35
900	40	13	0	2233	13186	32870	17	101	38646	9633.	77.	3.74	4.01
900	50	80	0	3118	23639	17797	98	141	69285	5216	36.	1.60	13.28
900	50	10	0	3011	20975	26953	12	136	61476	7899.	52.	2.13	7.78
900	50	13	0	2764	16545	34920	16	125	48491	10234	75	3.15	4.74
1330	30	80	0	3061	22702	34204	11	139	66537	10025	47.	2.27	6.64
1330	30	10	0	2906	19762	43675	14	132	57922	12800	65	3.02	4.52
1330	30	13	0	2569	14952	50950	19	116	43822	14933	88.	4.47	2.93
1330	40	80	0	3742	28070	32848	11	170	82270	9627.	43.	1.90	8.55
1330	40	10	0	3585	24685	45121	14	163	72348	13224	60.	2.53	5.47
1330	40	13	0	3233	19093	55219	18	147	55960	16184	83.	3.74	3.46
1330	50	80	0	4515	34230	29898	10	205	10032	8762.	39.	1.60	11.45
1330	50	10	0	4360	30372	45280	13	198	89017	13271	56.	2.13	6.71
1330	50	13	0	4003	23957	58664	17	182	70215	17193	80	3.15	4.08
1750	30	80	0	3986	29562	47726	12	181	86644	13988	50	2.27	6.19
1750	30	10	0	3784	25735	60941	15	172	75426	17861	67.	3.02	4.22
1750	30	13	0	3345	19470	71091	19	152	57065	20836	91.	4.47	2.74
1750	40	80	0	4873	36553	45834	11	221	10713	13433	45	1.90	7.98
1750	40	10	0	4668	32145	62958	14	212	94212	18452	62.	2.53	5.11
1750	40	13	0	4210	24863	77049	18	191	72871	22582	86.	3.74	3.23
1750	50	80	0	5880	44575	41717	10	267	13064	12227	40.	1.60	10.69
1750	50	10	0	5678	39551	63181	13	258	11591	18517	58.	2.13	6.26
1750	50	13	0	5212	31197	81855	18	236	91434	23990	82.	3.15	3.81

Input Power. The compressor sizing tool gives mass flow rate, ρV, to four digits and compressor input power, W, to five or six digits, for a specified inlet temperature and pressure, pressure ratio and rpm. The compressor inlet state (P_i, T_i, v_i, h_i, s_i) is therefore known to the precision of the state equations and the outlet-inlet enthalpy difference may be evaluated, to the accuracy of the sizing tool, by:

$$h_o - h_i = W/(\rho V) \tag{3}$$

With (P_o, h_o) in hand, we can evaluate the remaining outlet state variables (T_o, v_o, s_o) to reasonable precision, and a polytropic model can be obtained by nonlinear least squares. The polytropic model, as mentioned above, is based on the idea that there is some n such that Pv^n = constant. This model can be applied even though the actual compression path is unknown[27]. Thus, for a given compressor, refrigerant, shaft speed, inlet condition and pressure ratio (P_o/P_i), there is some n such that:

$$P_o v_o^n = P_i v_i^n \tag{4}$$

[27] i.e., unknown distribution of irreversibilities and unknown variation of refrigerant state along the path

There are three special processes, deviations from which can give a sense for how a real process might be represented by a polytropic model:

$n_{IG} = c_p/c_v$ for an ideal gas[28] in isentropic (adiabatic, reversible) compression;
$n_T = 1$ for ideal gas in isothermal compression (heat removed during compression);
n_s for real gas undergoing isentropic compression.

The last process is of particular interest because it accounts for real gas properties as well as the pressure ratio of the process. It is also of interest because reversible compression is efficient compression. Note that the polytropic exponent of a real process can be higher (because of internal dissipation) or lower (because of heat transfer) than the isentropic exponent. In reality, both forms of entropy generation (flow loss and heat transfer) are at play, and one can only determine n from detailed modeling or careful experiment (Boeswirth and Milovanova 1998). When n is greater than n_s, outlet temperature, pressure, enthalpy, and compression work are also greater and conversely when n is less than n_s.

The isentropic exponent for a real process with a dry[29], pure, real gas is defined in terms of the process end states. A simplification commonly used in compressor models is to define the process in terms of compressor inlet and outlet states, thus

$$n_s = \ln(P_o/P_i)/\ln(v_i/v(P_o,s_i)) \quad (5)$$

A model, in which the ratio of polytropic to isentropic exponent is a function of pressure ratio and shaft speed, f, in seconds per rotation, is postulated:

$$n \sim n_s(C_{0000} + C_{01}f + (C_{1000} + C_{11}f)(P_o/P_i)^x) \quad (6)$$

We seek the model parameters, C_{ij} and x, that minimize the coefficient of variation (CoV) of the energy balance[30]:

$$W = \rho V(h_o - h_i) \quad (7)$$

where

W = shaft work rate returned by compressor sizing tool,
ρV = refrigerant mass flow rate returned by sizing tool,
h_i = inlet enthalpy corresponding to inlet pressure and temperature,

and the outlet enthalpy, $h_o = h(P_o,v_o)$, is evaluated by the refrigerant state equations (NIST 2007) using the polytropic model (Eqns. 4 and 6) to estimate the compressed vapor's specific volume:

---

[28] Also approximately true for real gas in a well superheated state or for any dry low-pressure-ratio process

[29] The polytropic model is commonly used for dry compression and expansion processes but has also been applied (Singh et al.1986) to two-phase (wet) compression. Eqns. 4 through 6 are intended only for dry compression.

[30] A more rigorous treatment of jacket loss is not possible because the sizing tool doesn't indicate ambient conditions.

$$h_o \sim h(P_o, v_i(P_o/P_i)^{-1/n}) \quad (8)$$

The values of the Eqn. 6 model parameters that minimize the CoV of eqn. 8 are given below:

$$n \sim n_s\{0.9508_{00} + 0.002311f + (0.03226_{00} + 0.002391f)(P_o/P_i)^{-0.7217}\} \quad (9)$$

The resulting polytropic exponent is plotted against pressure ratio and shaft speed in Figure: C-1 and the isentropic compression efficiency is plotted against pressure ratio and shaft speed in Figure: C-2. The model estimates of enthalpy rise, $h_o - h_i$, are plotted against the sizing tool's values of shaft input work per unit refrigerant mass in Figure: C-3. The polytropic exponent curves are in good agreement with the semi-empirical results presented in Figures A9-A11 of Popovic and Shapiro (1995), and the isentropic efficiency curves are in general agreement with the experimental results given in Figures A5 and A6 of Villadsen and Boldvig (1981).

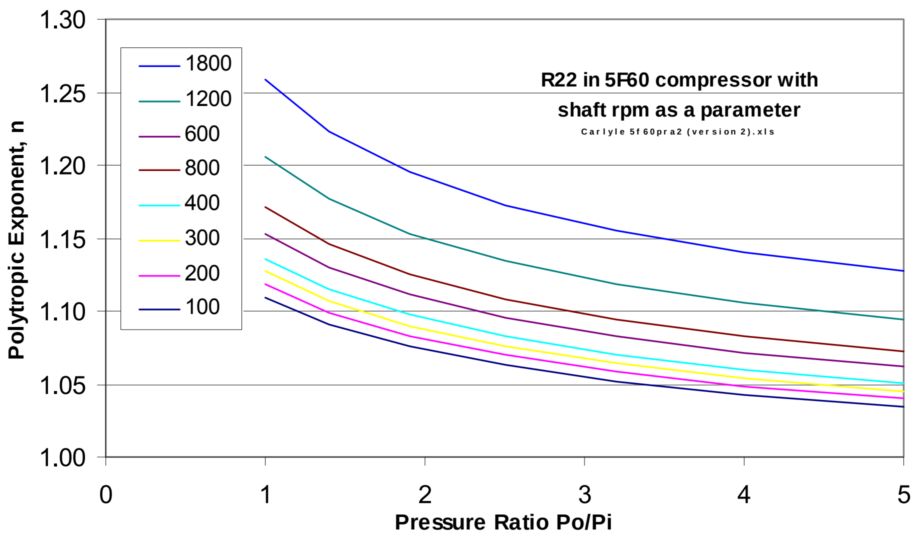


Figure: C-1 Polytropic exponent estimates, n = ns(C00 + C01f + (C10 + C11f)(Po/Pi)x), for compressor 5F60 with R22, 50°F (10°C) saturated suction temperature and zero superheat

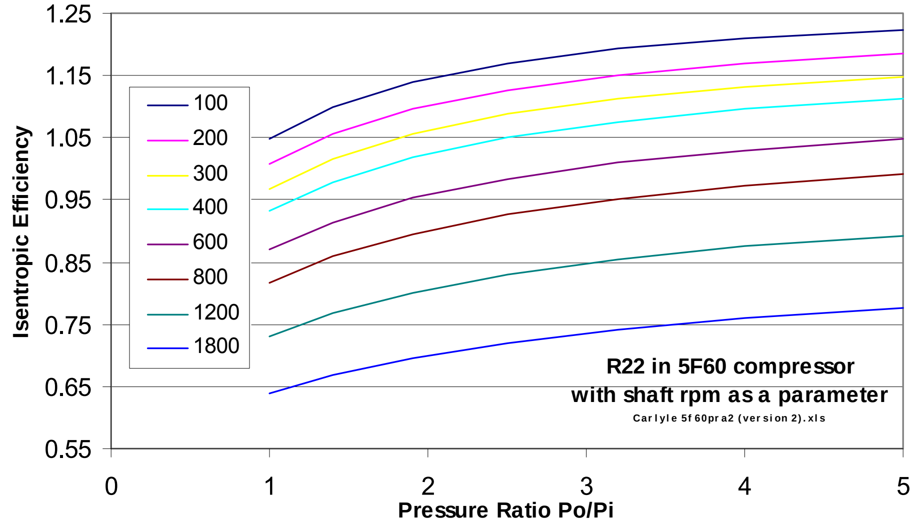


Figure: C-2 Compression efficiency for compressor 5F60 with refrigerant R22 at 50°F (10°C) saturated suction temperature and zero superheat. The 800, 1200 and 1800 rpm curves correspond to sizing tool data; curves for lower shaft speed are based on the polytropic exponent model

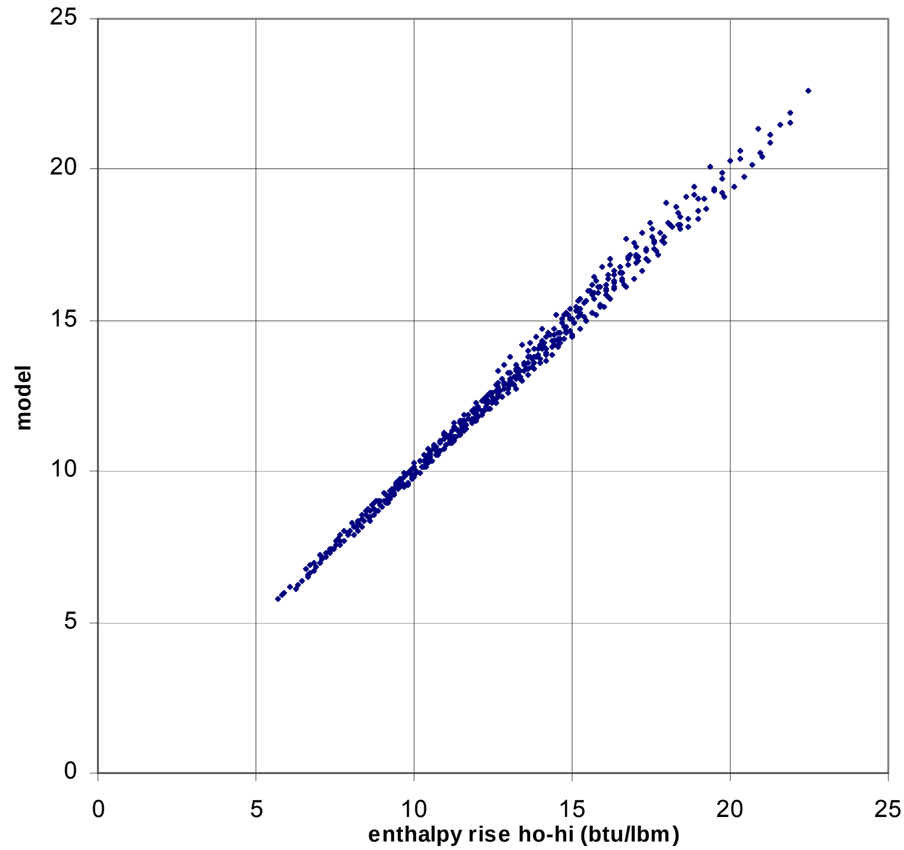


Figure: C-3 Enthalpy rise, ho – hi, across the compressor: model versus sizing-tool data

Volumetric Efficiency. At a given internal pressure ratio, P_d/P_s, a reciprocating compressor develops a suction volume flow rate, V, that is approximately linear in displacement rate, i.e., swept volume times shaft rotation frequency. However, the internal pressure ratio is greater than the external pressure ratio because of pressure drops across the suction and discharge valves, both of which are functions of flow rate. For purposes of estimating compressor performance for applications, an adjustment to the denominator of the pressure ratio has been found to adequately account for both suction and discharge flow loss (Gosling 1980, Jahnig 2000, Popovic and Shapiro, Stoecker 1982 , Threlkeld 1970). Clearance volume re-expansion and pressure drop effects are reflected in a volumetric efficiency model of the form:

$$\eta_{CV} = \left[1 + C - C\left(\frac{P_o}{P_s}\right)^{1/n} \right] \qquad (10)$$

where

$$P_s = P_i - C_{flow}\rho_i f^2 \qquad (11)$$

and

C = ratio of effective clearance volume to displacement,
P_s = discharge pressure assumed equal to outlet pressure,
n = polytropic exponent based on the compression work model,
C_{flow} = constant proportional to effective valve free area,
ρ_i = inlet density, and
f = shaft speed in rotations per second,

Other effects, such as leakage and heating, the latter of which reduces the suction gas density at the bottom of the suction stroke, have been treated empirically using a power law in shaft speed. The mass flow rate is thus modeled as:

$$\rho V = f^x D \rho_i \eta_{CV} \qquad (12)$$

where

x = empirical shaft speed exponent and
D = effective or actual displacement.

Because the sizing tool returns mass (not volumetric) flow rate, the parameters of Eqns. 9 and 11 must be solved together by substituting Eqn. 9 into Eqn. 11 and using the residual norm of Eqn. 11 as the least-squares objective function. Several variants of the model were tested. The result with constraint x=1 appears in Table: C-2, column a, and with constraint $C_{flow} = 0$, in column b. The results with effective displacement constrained to actual displacement, D_{actual} = 0.03409 ft^3, appear in columns c and d and column d again reflects the x=1 constraint.

Table: C-2 Volumetric efficiency models

model	(a)	(b)	(c)	(d)
D	0.033335	0.039796	0.03409	0.03409
C	0.074928	0.086	0.075879	0.083298
C_{flow}	0.014189	0	0.012659	0.014911
f^x	0	-0.0607	-0.00779	0
CoV	0.005147	0.002842	0.004512	0.010827

Model (b) was discarded because the inferred displacement parameter is at odds with the actual displacement by almost 20%. Model (c), which has the next best CoV, will be used instead.

RCS-Chiller Performance Map

A map of chiller system input power was produced for an indoor temperature, T_z, of 72°F (22.22°C) 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 bicubic was fit to the surface. The bicubic accurately represents the chiller performance surface and is compatible with most simulation programs. The bicubic 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: C-4 shows the optimal chiller system performance map for T_z =72°F (22.2°C) with T_x ranging from 110°F to 50°F in 10°F increments (43.33°C to 10°C in 5.56 Kelvin increments). Note the inflections at low capacity fraction on the 50°F and 60°F (10.0°C and 15.56°C) outdoor temperature lines; the compressor is bypassed below these inflection points (see refrigerant-side economizer model). Table: C-3 documents the bicubic coefficients, and Figure: C-5 shows the model regression error for the seven curves covering the region of compressor operation. The economizer region performance map is addressed later.

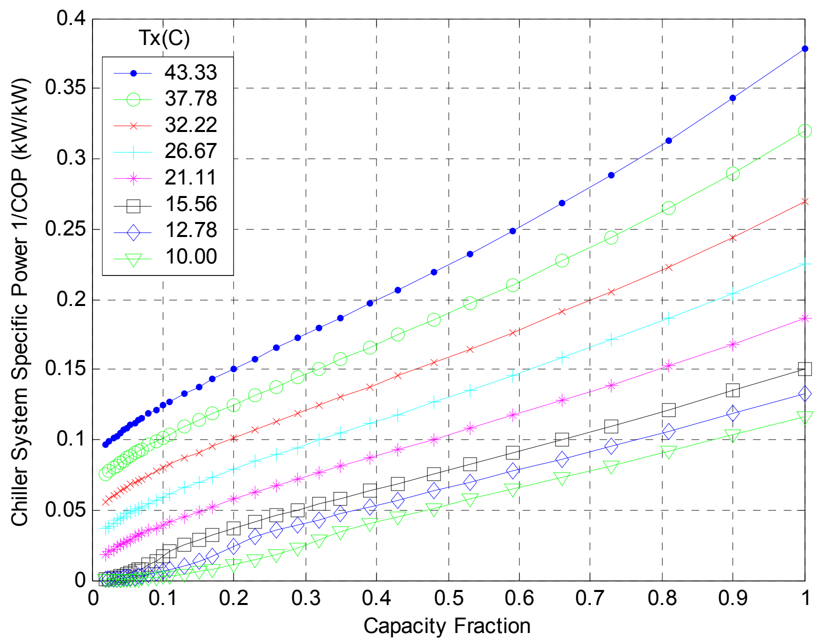


Figure: C-4 Chiller-RCP system performance map at Tz =22.2°C (72°F) with Tx ranging from 43.33°C (110°F; topmost curve) to 10°C (50°F) in 5.56 K (10 R) increments

Table: C-3 Bicubic Chiller Performance Map, x=Tx, y=Capacity Fraction; r2=0.9998

Term	Bicubic Coefficients (x in °F)	(x in °C)
const	7.457e-02	-1.990E-01
x	5.442e-03	4.905E-03
y	2.532e-01	3.190E-01
x^2	7.268e-05	-3.637E-05
xy	2.285e-03	-2.845E-03
y^2	2.337e-01	-2.729E-01
x^3	8.468e-07	1.452E-07
x^2y	7.974e-05	2.461E-05
xy^2	2.205e-03	1.225E-03
y^3	1.183e-01	1.183E-01

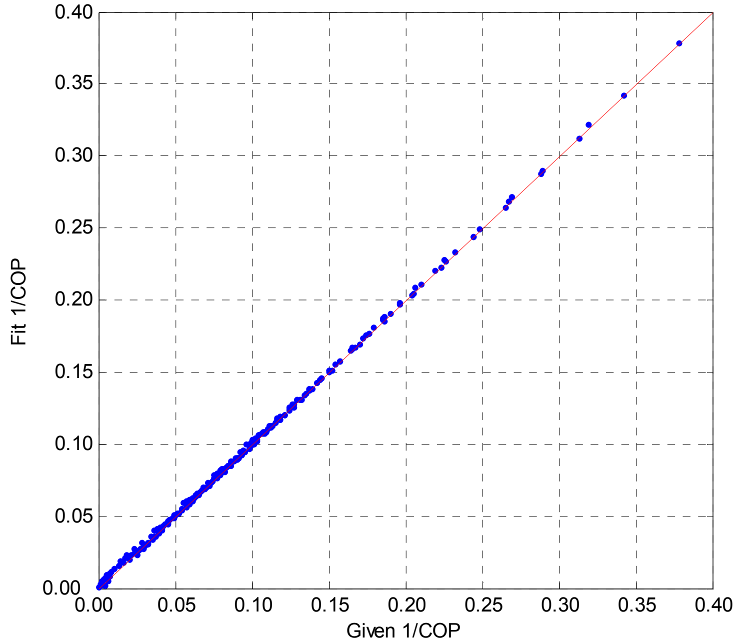


Figure: C-5 Chiller performance response surface error

VAV-Chiller Performance Map

The chiller performance model for all-air (Constant Volume [CV] and Variable Air Volume [VAV]) applications differs from an RCP-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: C-6. 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 Q and T_x. This function is shown in Figure: C-7. 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: C-6, capacity is constrained by chilled water flow rate rather than coil conductance, and 2) for the all-air system, supply fan power is not included in the chiller COP numbers represented in Figure: C-7. A separate model that relates fan power to hourly cooling and ventilation loads is used to compute annual fan energy. The cross plots, Figure: C-8, show clearly the effect of the three outdoor temperature ranges defined by the chilled-water reset schedule.

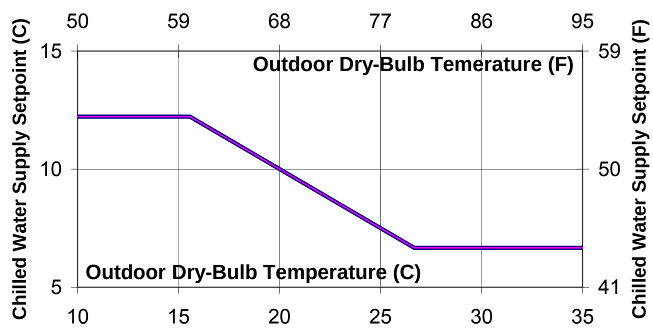


Figure: C-6 Chiller water reset schedule (Appendix G, ASHRAE 90.1-2000)

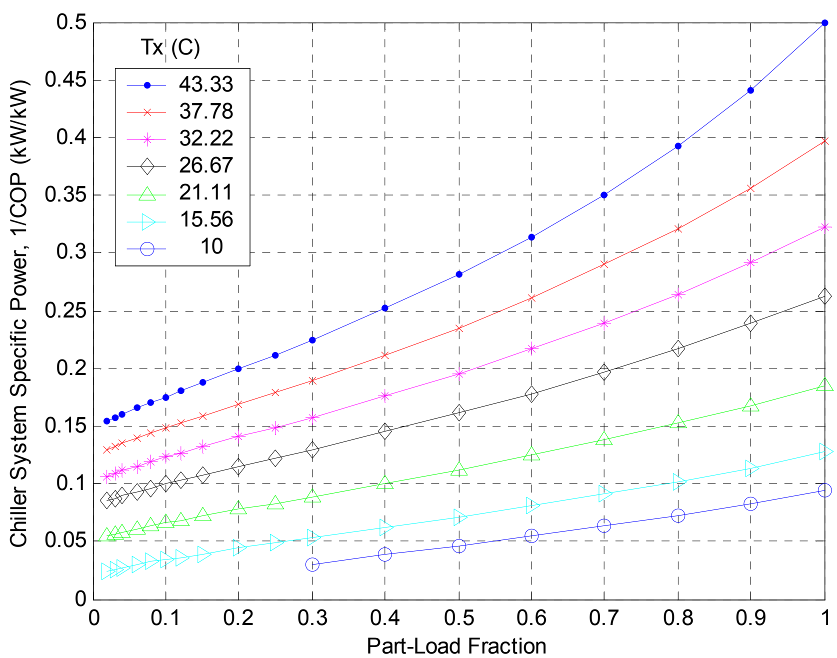


Figure: C-7 Chiller performance map for the chilled water reset schedule shown in Figure: C-6

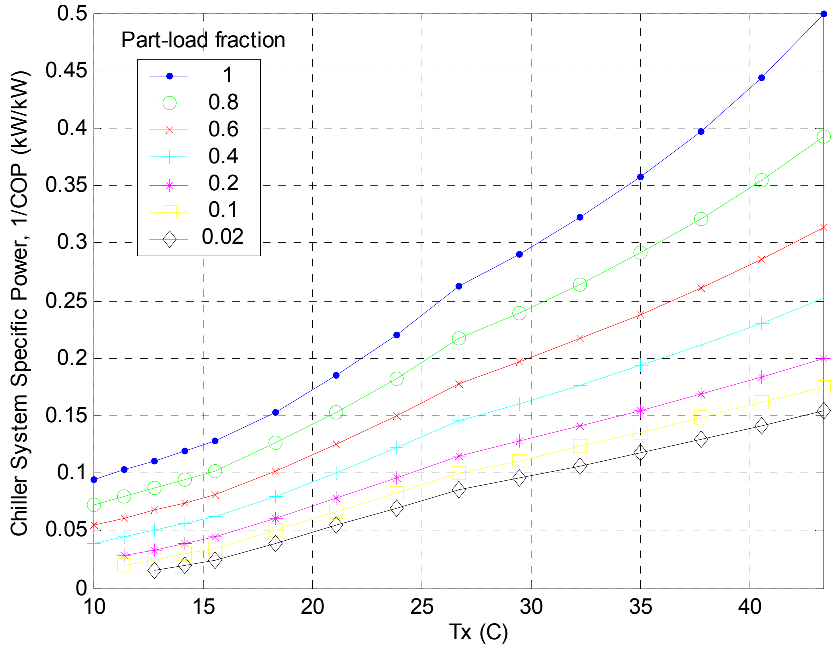


Figure: C-8 Chiller map cross-plot for the chilled water reset schedule shown in

Bivariate polynomials, fit over each of the three reset schedule ranges, are described in terms of their coefficients and regression statistics in Table: C-4. The regression coefficient is greater than 0.9998 for all three bicubics. All bicubic terms are retained because removing the least significant term was found to about double the residual norm. The fact that the bicubics do not intersect exactly at the intended 60 and 80°F (10.0 and 15.56°C) boundaries does not affect performance of the 24-hour peak-shifting algorithm.

Table: C-4 VAV-Chiller Performance Map Coefficients; x = Tx, y = Capacity Fraction

	$10 < T_x < 15.56$°C		$15.56 < T_x < 26.67$°C		$26.67 < T_x < 43.33$°C	
	$50 < T_x < 60$°F		$60 < T_x < 80$°F		$80 < T_x < 110$°F	
	$r^2 = 0.9999$		$r^2 = 0.9999$		$R^2 = 0.9998$	
Term	*x* in °C	*x* in °F	*x* in °C	*x* in °F	*x* in °C	*x* in °F
const	-4.24E-02	-2.50E-01	-7.67E-02	-2.64E-01	-1.25E-01	-4.33E-01
x	6.31E-03	1.04E-02	7.78E-03	7.72E-03	1.24E-02	1.27E-02
y	9.24E-02	1.06E-01	1.69E-01	3.96E-01	4.36E-01	8.02E-01
x^2	-2.13E-04	-1.49E-04	-1.20E-04	-6.93E-05	-2.36E-04	-1.10E-04
xy	3.17E-04	-1.00E-03	-7.76E-03	-9.87E-03	-1.59E-02	-1.40E-02
y^2	-6.82E-02	-8.10E-02	-1.03E-01	-1.48E-01	-3.05E-01	-4.32E-01
x^3	5.04E-06	8.65E-07	1.97E-06	3.37E-07	2.23E-06	3.82E-07
x^2y	5.97E-05	1.84E-05	2.82E-04	8.69E-05	2.62E-04	8.07E-05
xy^2	7.17E-04	3.98E-04	2.52E-03	1.40E-03	7.15E-03	3.97E-03
y^3	4.98E-02	4.98E-02	5.18E-02	5.18E-02	1.00E-01	1.00E-01

References

ASHRAE. 2004. *ANSI/ASHRAE/IESNA Standard 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings*, ASHRAE, Atlanta, GA.

Boeswirth, L. and V. Milovanova, 1998. Simple but efficient methods for estimation of valve loss, capacity loss due to suction valve throttling and heat transfer in cylinder. *Int'l Compressor Engrg. Conf. at Purdue*, West Lafayette, IN.

Gosling, C.T. 1980. *Applied Air Conditioning and Refrigeration*, Applied Science Publishers, Barking, Essex, England.

Jahnig, D.I., D.T. Reindl, and S.A. Klein. 2000. A semi-empirical method for representing domestic refrigerator/freezer compressor calorimeter test data. *ASHRAE Trans*. 101(2); see also http://minds.wisconsin.edu/handle/1793/7683

Moran, M.J. and H.N. Shapiro. 1995. *Fundamentals of Engineering Thermodynamics*, Wiley, Hoboken, NJ.

NIST, 2007. *Standard Reference Database 23 - NIST Reference Fluid Thermodynamic and Transport Properties Database* (REFPROP 7.0). National Institute of Standards and Technology: http://www.nist.gov/srd/nist23.htm.

Popovic, P. and H. N. Shapiro. 1995. A semi-empirical method for modeling a reciprocating compressor in refrigeration system. *ASHRAE Trans*., 101(2), pp. 367-382.

Singh, R., J.J. Nieter, and G. Prater Jr. 1986. An investigation of the compressor slugging phenomenon. *ASHRAE Trans*., 92(4):250–258.

Stoecker, W.F. 1982. *Refrigeration and Air-Conditioning*, McGraw-Hill, New York, NY.

Threlkeld, J.L. 1970. *Thermal Environmental Engineering*. 2nd ed. Prentice-Hall, Englewood Cliffs, NJ.

Villadsen, V. and F.V. Boldvig. 1981. Reciprocating compressor design for high efficiency. *ASHRAE Trans*., 87(1), pp. 819-825.

D Appendix: Energy Use Tables and Figures

Table: D-1 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Small Office Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-OfficeSmall	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	14,403	17,017	12,203	9,964	5,547	10,264	6,331	9,400	8,306	6,047	8,617	7,439	8,025	6,742	7,619	6,753
Case 1: 2-Speed Chiller, CAV	9,494	10,090	9,636	7,176	4,355	8,578	5,666	7,125	6,868	5,448	6,628	6,403	6,452	6,074	6,879	6,433
Case 2: Var-Speed Chiller, CAV	9,345	9,905	9,481	7,104	4,291	8,471	5,618	7,063	6,812	5,416	6,573	6,359	6,409	6,046	6,856	6,417
Case 3: 2-Speed Chiller, CAV, TES	8,280	9,215	7,803	6,416	4,183	7,125	5,476	6,367	6,017	5,242	6,023	5,745	6,009	5,638	6,630	6,321
Case 4: Var-Speed Chiller, CAV, TES	7,465	7,778	7,278	6,057	4,046	6,717	5,402	6,064	5,846	5,173	5,791	5,637	5,838	5,569	6,559	6,292
Case 5: 2-Speed Chiller, RCP/DOAS	4,784	5,778	4,997	3,195	2,104	4,164	2,142	2,973	2,741	1,845	2,613	2,285	2,383	1,986	1,964	1,687
Case 6: Var-Speed Chiller, RCP/DOAS	4,423	5,249	4,788	2,964	1,990	3,992	2,010	2,788	2,624	1,758	2,443	2,194	2,243	1,918	1,870	1,628
Case 7: 2-Speed Chiller, RCP/DOAS, TES	4,466	5,591	3,679	3,059	2,044	3,066	2,029	2,739	2,220	1,753	2,453	1,870	2,283	1,717	1,866	1,612
Case 8: Var-Speed Chiller, RCP/DOAS, TES	3,296	4,070	2,920	2,347	1,765	2,468	1,714	2,182	1,861	1,523	1,983	1,629	1,881	1,535	1,639	1,466

Table: D-2 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Small Office Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-OfficeSmall	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	3,269	3,714	1,653	2,300	625	1,900	914	2,206	1,372	958	1,992	1,256	1,819	1,219	1,567	978
Case 1: 2-Speed Chiller, CAV	1,769	1,834	1,361	1,395	576	1,560	847	1,415	1,194	877	1,413	1,146	1,372	1,127	1,379	956
Case 2: Var-Speed Chiller, CAV	1,731	1,782	1,333	1,367	572	1,539	840	1,390	1,180	869	1,394	1,134	1,356	1,119	1,372	953
Case 3: 2-Speed Chiller, CAV, TES	1,391	1,560	1,042	1,208	568	1,185	811	1,197	1,076	843	1,270	1,063	1,277	1,059	1,333	943
Case 4: Var-Speed Chiller, CAV, TES	1,210	1,250	936	1,108	563	1,077	801	1,110	1,046	832	1,212	1,048	1,233	1,047	1,317	939
Case 5: 2-Speed Chiller, RCP/DOAS	1,799	1,978	1,398	1,279	690	1,436	782	1,252	904	752	1,074	806	982	787	816	706
Case 6: Var-Speed Chiller, RCP/DOAS	1,705	1,845	1,372	1,204	688	1,414	777	1,194	891	745	1,025	797	946	780	803	703
Case 7: 2-Speed Chiller, RCP/DOAS, TES	1,695	1,957	1,116	1,227	687	1,133	763	1,177	835	740	1,027	759	951	750	801	701
Case 8: Var-Speed Chiller, RCP/DOAS, TES	1,438	1,617	991	1,081	684	1,006	753	1,056	790	727	944	735	890	733	780	696

Table: D-3 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Retail Standalone Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-RetailStandAlone	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	213,597	250,636	236,953	148,931	98,742	174,053	88,536	133,583	137,575	90,881	124,103	124,556	120,364	110,714	100,103	86,228
Case 1: 2-Speed Chiller, CAV	140,366	149,215	183,879	108,603	82,261	143,686	82,599	102,844	116,673	84,131	99,721	109,838	98,955	101,388	91,692	82,733
Case 2: Var-Speed Chiller, CAV	137,500	145,751	180,476	107,049	81,137	141,767	82,035	101,521	115,557	83,640	98,708	108,913	98,046	100,821	91,315	82,500
Case 3: 2-Speed Chiller, CAV, TES	132,461	141,279	162,668	104,561	81,177	129,250	81,513	99,097	110,565	82,983	96,903	104,826	96,801	98,099	90,596	82,281
Case 4: Var-Speed Chiller, CAV, TES	119,978	125,000	147,924	97,584	78,514	119,851	80,256	93,115	103,530	81,343	92,404	100,217	93,086	95,011	89,002	81,396
Case 5: 2-Speed Chiller, RCP/DOAS	70,617	84,233	95,133	49,257	37,460	68,839	32,148	43,989	44,848	30,155	39,796	38,410	38,141	33,566	30,210	26,722
Case 6: Var-Speed Chiller, RCP/DOAS	63,736	73,547	90,533	44,290	34,707	65,739	30,625	40,291	42,471	28,975	36,388	36,494	35,221	32,214	28,810	25,989
Case 7: 2-Speed Chiller, RCP/DOAS, TES	68,357	82,921	79,035	48,140	36,934	57,406	31,466	42,900	41,249	29,617	38,959	35,288	37,451	31,570	29,812	26,466
Case 8: Var-Speed Chiller, RCP/DOAS, TES	55,694	65,520	64,012	40,198	32,756	46,980	28,988	36,726	33,567	27,486	33,775	29,573	32,922	27,771	27,644	25,119

Table: D-4 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Retail Standalone Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-RetailStandAlone	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	95,914	117,058	102,167	58,111	30,350	72,572	26,847	51,347	46,033	28,206	44,328	38,628	41,361	32,753	30,119	26,786
Case 1: 2-Speed Chiller, CAV	51,450	55,733	71,915	35,933	25,564	54,235	25,553	34,482	35,435	25,806	31,771	31,919	30,315	28,646	26,371	25,685
Case 2: Var-Speed Chiller, CAV	49,612	53,240	69,583	34,922	25,194	52,835	25,423	33,697	34,641	25,607	31,135	31,360	29,744	28,327	26,202	25,593
Case 3: 2-Speed Chiller, CAV, TES	47,903	52,548	61,674	34,408	25,297	47,312	25,114	32,829	32,803	25,373	30,614	29,157	29,521	26,766	25,997	25,473
Case 4: Var-Speed Chiller, CAV, TES	40,672	42,823	51,164	30,668	24,507	41,356	24,831	29,697	29,661	24,764	28,354	27,812	27,692	25,920	25,315	25,234
Case 5: 2-Speed Chiller, RCP/DOAS	40,884	48,736	52,027	27,134	17,523	38,319	15,720	24,541	23,398	15,867	21,745	19,926	20,552	17,738	15,980	14,295
Case 6: Var-Speed Chiller, RCP/DOAS	35,996	41,378	48,799	24,435	16,956	36,806	15,598	22,598	22,364	15,594	20,180	19,271	19,279	17,361	15,616	14,196
Case 7: 2-Speed Chiller, RCP/DOAS, TES	40,009	48,160	45,868	26,678	17,440	32,884	15,531	24,116	22,370	15,726	21,430	19,113	20,310	17,173	15,886	14,258
Case 8: Var-Speed Chiller, RCP/DOAS, TES	32,833	38,508	36,146	22,985	16,704	27,184	15,257	21,220	19,220	15,261	19,285	17,047	18,562	15,968	15,288	14,059

Table: D-5 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Retail Strip Mall Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-RetailStripMall	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	142,633	168,131	150,039	105,597	61,322	126,856	56,194	94,553	91,786	58,619	85,983	82,233	84,564	73,681	66,506	59,003
Case 1: 2-Speed Chiller, CAV	86,373	93,134	113,077	72,099	49,680	104,392	51,814	69,092	75,296	53,592	66,242	70,517	66,809	66,311	60,038	56,523
Case 2: Var-Speed Chiller, CAV	83,546	89,666	109,390	70,399	48,868	102,171	51,395	67,730	74,105	53,159	65,251	69,648	65,890	65,733	59,694	56,298
Case 3: 2-Speed Chiller, CAV, TES	79,998	86,652	96,418	68,447	48,709	88,945	50,726	65,648	69,626	52,526	63,752	65,834	64,936	63,240	59,128	56,135
Case 4: Var-Speed Chiller, CAV, TES	69,604	73,454	83,986	62,285	46,761	81,400	49,767	60,194	63,902	51,094	59,755	62,176	61,571	60,772	57,798	55,354
Case 5: 2-Speed Chiller, RCP/DOAS	56,262	65,941	73,196	41,866	29,463	61,458	27,165	37,993	38,629	26,000	34,456	33,371	33,660	29,784	27,316	25,252
Case 6: Var-Speed Chiller, RCP/DOAS	50,189	56,881	68,914	37,624	27,532	58,538	26,259	34,969	36,789	25,069	31,710	31,911	31,251	28,660	26,263	24,713
Case 7: 2-Speed Chiller, RCP/DOAS, TES	54,555	64,905	60,253	40,857	28,972	49,050	26,382	36,930	34,959	25,427	33,693	30,327	33,044	27,736	26,978	24,960
Case 8: Var-Speed Chiller, RCP/DOAS, TES	44,075	50,968	47,758	34,045	25,978	40,844	24,694	31,489	28,676	23,598	29,362	25,847	29,226	24,545	25,251	23,823

Table: D-6 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Retail Strip Mall Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-RetailStripMall	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	58,083	71,211	58,058	37,653	14,411	50,550	13,631	32,644	28,194	14,864	27,497	23,633	25,853	20,022	18,078	14,100
Case 1: 2-Speed Chiller, CAV	29,393	31,926	42,630	21,369	12,100	37,893	12,968	20,605	21,005	13,384	18,528	19,070	17,765	17,187	15,567	13,492
Case 2: Var-Speed Chiller, CAV	27,881	29,861	40,604	20,434	11,883	36,426	12,888	19,912	20,308	13,237	17,981	18,611	17,254	16,907	15,431	13,419
Case 3: 2-Speed Chiller, CAV, TES	26,715	29,623	32,158	20,113	11,848	31,049	12,527	19,171	18,276	12,962	17,524	16,663	17,112	15,452	15,238	13,304
Case 4: Var-Speed Chiller, CAV, TES	21,101	23,217	27,148	17,066	11,483	26,257	12,397	16,472	16,465	12,564	15,627	15,846	15,572	14,992	14,747	13,174
Case 5: 2-Speed Chiller, RCP/DOAS	30,887	35,179	39,597	22,068	13,427	32,620	13,154	20,362	19,252	13,618	18,100	16,528	17,318	15,054	13,949	12,768
Case 6: Var-Speed Chiller, RCP/DOAS	27,995	30,598	37,597	20,224	13,214	31,142	13,095	19,086	18,531	13,489	17,063	16,042	16,480	14,769	13,704	12,702
Case 7: 2-Speed Chiller, RCP/DOAS, TES	30,151	34,756	31,961	21,673	13,325	27,166	12,902	19,933	18,099	13,449	17,829	15,529	17,116	14,315	13,873	12,726
Case 8: Var-Speed Chiller, RCP/DOAS, TES	24,684	28,382	26,239	18,784	13,001	22,469	12,741	17,523	15,690	13,148	16,148	13,945	15,741	13,270	13,431	12,547

Table: D-7 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Primary School Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-SchoolPrimary	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	529,439	639,297	560,967	359,814	271,317	434,644	206,756	314,547	311,203	184,606	275,139	255,744	265,169	215,403	212,436	178,031
Case 1: 2-Speed Chiller, VAV	338,966	405,401	434,469	235,919	180,354	322,946	145,715	217,759	242,398	138,642	196,276	195,274	183,195	176,425	169,763	155,123
Case 2: Var-Speed Chiller, VAV	332,022	398,693	422,308	229,450	173,683	315,199	140,985	212,900	237,840	134,569	192,360	191,518	179,355	173,424	167,287	153,555
Case 3: 2-Speed Chiller, VAV, TES	285,429	340,050	364,615	211,427	165,766	273,471	138,962	193,287	209,247	133,674	177,424	178,105	174,417	162,346	163,059	151,672
Case 4: Var-Speed Chiller, VAV, TES	264,722	317,132	339,562	195,429	152,662	258,915	132,781	181,776	199,204	127,715	167,926	170,460	166,714	156,591	158,193	149,186
Case 5: 2-Speed Chiller, RCP/DOAS	233,973	278,081	316,704	157,222	132,468	230,725	94,077	142,268	159,215	87,825	124,708	121,493	110,081	107,170	97,945	91,925
Case 6: Var-Speed Chiller, RCP/DOAS	225,835	270,369	305,887	148,861	126,134	222,738	88,450	135,808	154,094	83,199	119,160	116,935	104,460	103,522	93,910	89,782
Case 7: 2-Speed Chiller, RCP/DOAS, TES	185,409	225,712	235,614	136,310	113,401	170,934	84,365	120,690	121,480	81,577	109,480	101,095	101,959	92,112	92,088	87,256
Case 8: Var-Speed Chiller, RCP/DOAS, TES	163,798	201,331	209,493	117,562	97,348	153,539	73,672	106,592	108,656	72,621	97,159	90,137	90,759	83,548	84,748	83,149

Table: D-8 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Primary School Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-SchoolPrimary	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	197,556	250,386	188,881	123,533	87,200	150,883	57,344	106,439	87,847	51,419	88,306	69,022	77,303	55,856	53,014	41,122
Case 1: 2-Speed Chiller, VAV	110,053	137,955	141,593	71,001	52,766	100,884	38,936	65,327	64,259	36,158	55,634	48,994	46,138	43,593	38,765	34,262
Case 2: Var-Speed Chiller, VAV	106,316	134,858	135,940	68,092	49,959	96,646	37,239	63,016	62,606	34,679	53,782	47,671	44,375	42,521	37,910	33,800
Case 3: 2-Speed Chiller, VAV, TES	88,212	110,446	109,841	61,135	47,781	80,683	35,991	54,443	50,218	34,287	47,982	41,654	42,690	37,548	36,310	32,847
Case 4: Var-Speed Chiller, VAV, TES	75,620	94,647	94,772	52,285	41,891	70,452	33,634	48,198	46,392	32,026	42,800	38,740	38,891	35,408	34,369	31,973
Case 5: 2-Speed Chiller, RCP/DOAS	91,388	108,788	125,358	60,200	48,498	90,470	35,094	54,962	58,659	31,919	46,806	44,710	40,282	39,001	33,626	29,406
Case 6: Var-Speed Chiller, RCP/DOAS	86,347	103,661	120,121	56,115	45,439	86,136	32,923	51,595	56,762	30,119	43,852	43,199	37,596	37,660	32,287	28,742
Case 7: 2-Speed Chiller, RCP/DOAS, TES	75,654	92,763	92,629	54,132	44,349	69,557	32,029	47,517	45,111	30,379	41,971	37,111	38,137	33,309	31,707	27,995
Case 8: Var-Speed Chiller, RCP/DOAS, TES	61,546	75,838	77,024	44,474	37,468	58,363	28,356	39,912	39,723	27,126	35,582	33,167	33,402	30,175	29,172	26,586

Table: D-9 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Large Hotel Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-HotelLarge	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	1,297,033	1,430,586	1,391,047	933,606	778,844	1,111,256	733,594	883,822	880,425	674,758	788,894	808,797	783,222	744,136	701,942	658,150
Case 1: 2-Speed Chiller, VAV	252,030	261,517	373,338	199,878	181,270	279,766	158,080	190,318	209,161	164,081	181,318	191,963	177,641	184,911	171,967	173,719
Case 2: Var-Speed Chiller, VAV	233,000	242,441	353,138	185,899	167,785	269,003	152,628	180,205	202,295	159,003	173,469	186,794	170,898	180,965	168,514	171,410
Case 3: 2-Speed Chiller, VAV, TES	248,281	260,011	347,989	198,643	180,184	266,203	156,657	188,535	204,514	162,992	179,728	189,296	176,862	181,967	171,051	172,969
Case 4: Var-Speed Chiller, VAV, TES	213,357	215,740	328,569	177,064	165,444	254,848	150,477	172,044	194,964	157,099	166,772	181,664	166,667	175,799	165,789	169,939
Case 5: 2-Speed Chiller, RCP/DOAS	237,211	264,144	264,377	152,543	129,766	167,866	82,799	134,299	117,819	82,448	116,664	95,933	99,500	89,150	89,942	79,654
Case 6: Var-Speed Chiller, RCP/DOAS	204,554	221,526	240,885	131,749	114,503	154,245	76,647	118,374	109,192	76,446	104,154	89,458	88,630	83,931	84,764	76,850
Case 7: 2-Speed Chiller, RCP/DOAS, TES	235,379	263,390	244,483	151,687	128,902	157,422	81,906	133,184	114,495	81,673	115,665	94,062	98,942	87,267	89,392	79,112
Case 8: Var-Speed Chiller, RCP/DOAS, TES	201,555	220,282	223,064	130,215	112,681	145,194	74,791	116,636	104,029	74,865	102,683	85,550	87,543	80,560	83,855	75,501

Table: D-10 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Large Hotel Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-HotelLarge																
Case 0: Baseline	613,100	727,622	569,181	426,683	337,644	454,944	284,361	377,903	332,344	242,217	317,528	290,856	302,122	255,694	232,731	214,539
Case 1: 2-Speed Chiller, VAV	109,398	132,790	147,491	84,360	74,196	102,805	57,119	77,024	76,155	57,411	70,112	66,322	63,660	61,875	56,907	53,613
Case 2: Var-Speed Chiller, VAV	101,948	129,271	134,356	80,214	69,348	92,150	54,993	73,876	71,666	55,611	67,748	63,613	61,374	60,048	55,812	52,848
Case 3: 2-Speed Chiller, VAV, TES	106,415	126,008	139,885	82,125	72,311	100,884	55,865	74,350	74,251	55,462	67,891	64,677	62,638	59,710	55,872	52,648
Case 4: Var-Speed Chiller, VAV, TES	87,501	103,092	124,712	71,275	65,943	89,312	52,905	66,387	66,822	53,117	61,503	59,633	57,735	56,252	53,455	51,367
Case 5: 2-Speed Chiller, RCP/DOAS	139,300	171,559	118,391	87,935	65,266	74,226	36,841	74,242	52,389	36,875	60,734	42,845	50,159	38,145	39,533	31,779
Case 6: Var-Speed Chiller, RCP/DOAS	121,233	148,114	103,496	77,146	59,227	61,653	33,993	66,351	46,932	34,662	54,359	39,497	44,852	35,716	37,287	30,783
Case 7: 2-Speed Chiller, RCP/DOAS, TES	138,176	171,040	112,446	87,352	64,292	72,923	35,975	73,502	51,093	36,073	60,066	41,687	49,798	36,707	39,196	31,132
Case 8: Var-Speed Chiller, RCP/DOAS, TES	119,216	147,048	96,761	75,743	56,732	59,233	32,150	64,798	44,048	32,639	53,043	36,484	43,923	32,876	36,532	29,434

Table: D-11 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Warehouse Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-Warehouse	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	9,336	11,675	11,408	9,314	4,369	10,919	4,892	9,933	9,583	6,728	11,847	10,608	12,531	10,633	11,978	7,719
Case 1: 2-Speed Chiller, CAV	7,194	6,142	8,409	8,329	4,073	8,679	4,789	9,038	9,139	6,542	11,037	10,178	11,784	10,414	11,666	7,642
Case 2: Var-Speed Chiller, CAV	7,051	5,995	8,212	8,235	4,034	8,553	4,773	8,953	9,071	6,518	10,959	10,121	11,720	10,377	11,650	7,638
Case 3: 2-Speed Chiller, CAV, TES	6,716	5,881	7,286	8,044	3,985	7,440	4,736	8,597	8,614	6,462	10,734	9,844	11,635	10,117	11,565	7,611
Case 4: Var-Speed Chiller, CAV, TES	6,348	5,448	6,904	7,838	3,937	7,191	4,720	8,430	8,511	6,438	10,606	9,781	11,533	10,074	11,536	7,604
Case 5: 2-Speed Chiller, RCP/DOAS	3,497	3,241	4,390	2,811	2,172	3,939	2,382	3,031	2,620	2,373	2,733	2,504	2,638	2,329	2,339	2,439
Case 6: Var-Speed Chiller, RCP/DOAS	3,297	3,036	4,203	2,668	2,118	3,811	2,342	2,914	2,548	2,323	2,617	2,433	2,538	2,273	2,294	2,428
Case 7: 2-Speed Chiller, RCP/DOAS, TES	3,399	3,203	3,545	2,756	2,112	2,974	2,349	2,904	2,287	2,316	2,653	2,270	2,603	2,131	2,293	2,418
Case 8: Var-Speed Chiller, RCP/DOAS, TES	2,926	2,779	3,112	2,461	2,030	2,641	2,293	2,650	2,125	2,256	2,446	2,153	2,439	2,036	2,225	2,393

Table: D-12 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Warehouse Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-Warehouse	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	2,019	3,564	1,850	2,750	1,231	2,367	1,250	2,936	2,611	2,031	3,761	2,875	3,922	2,911	4,144	2,164
Case 1: 2-Speed Chiller, CAV	1,738	1,298	2,249	2,516	1,178	2,729	1,226	2,748	2,513	1,992	3,593	2,787	3,764	2,886	4,104	2,174
Case 2: Var-Speed Chiller, CAV	1,711	1,284	1,697	2,508	1,175	2,197	1,225	2,697	2,510	1,990	3,584	2,784	3,761	2,884	4,103	2,174
Case 3: 2-Speed Chiller, CAV, TES	1,583	1,200	1,478	2,445	1,161	1,909	1,217	2,604	2,434	1,974	3,523	2,731	3,726	2,836	4,081	2,169
Case 4: Var-Speed Chiller, CAV, TES	1,543	1,148	1,451	2,417	1,154	1,891	1,215	2,580	2,420	1,971	3,505	2,722	3,712	2,830	4,077	2,168
Case 5: 2-Speed Chiller, RCP/DOAS	1,473	1,367	2,088	1,345	1,168	2,081	1,293	1,475	1,192	1,325	1,361	1,254	1,406	1,195	1,292	1,393
Case 6: Var-Speed Chiller, RCP/DOAS	1,462	1,352	2,082	1,329	1,163	2,076	1,291	1,464	1,186	1,321	1,350	1,250	1,397	1,191	1,287	1,392
Case 7: 2-Speed Chiller, RCP/DOAS, TES	1,400	1,341	1,493	1,318	1,160	1,389	1,289	1,417	1,164	1,317	1,338	1,220	1,398	1,171	1,284	1,392
Case 8: Var-Speed Chiller, RCP/DOAS, TES	1,351	1,281	1,464	1,282	1,151	1,370	1,285	1,388	1,146	1,312	1,316	1,206	1,382	1,161	1,276	1,390

Table: D-13 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Outpatient Healthcare Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-OutpatientHealthCare	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	66,464	77,039	72,219	49,778	30,564	61,433	30,650	46,100	48,339	32,236	39,569	40,939	38,419	36,422	32,628	31,028
Case 1: 2-Speed Chiller, CAV	46,022	49,261	56,640	39,074	27,819	50,700	29,894	38,038	42,446	31,016	34,241	37,659	33,703	34,413	30,922	30,335
Case 2: Var-Speed Chiller, CAV	44,682	47,368	55,175	38,346	27,606	49,663	29,810	37,490	42,065	30,904	33,931	37,402	33,426	34,260	30,833	30,274
Case 3: 2-Speed Chiller, CAV, TES	44,128	47,766	51,695	37,980	27,502	47,439	29,605	36,671	40,013	30,569	33,117	35,892	32,922	33,253	30,460	30,057
Case 4: Var-Speed Chiller, CAV, TES	40,919	43,132	50,178	35,970	27,000	46,207	29,458	35,426	39,367	30,350	32,246	35,534	32,080	33,023	30,234	29,965
Case 5: 2-Speed Chiller, RCP/DOAS	17,752	22,460	21,886	12,375	8,432	17,280	6,959	10,962	11,136	6,756	9,358	8,775	8,862	7,480	6,706	5,910
Case 6: Var-Speed Chiller, RCP/DOAS	15,169	18,678	19,890	10,664	7,585	15,645	6,444	9,646	10,147	6,273	8,313	8,078	7,903	6,976	6,225	5,610
Case 7: 2-Speed Chiller, RCP/DOAS, TES	17,307	22,174	19,050	12,105	8,263	15,271	6,736	10,646	10,000	6,577	9,118	7,826	8,682	6,853	6,571	5,780
Case 8: Var-Speed Chiller, RCP/DOAS, TES	13,407	17,224	15,931	9,514	6,806	12,911	5,802	8,570	8,155	5,667	7,449	6,537	7,172	5,927	5,747	5,187

Table: D-14 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Outpatient Healthcare Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-OutpatientHealthCare	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	19,314	23,875	19,331	12,589	5,328	16,614	5,925	11,400	10,511	6,208	9,647	9,003	9,578	8,472	7,683	8,500
Case 1: 2-Speed Chiller, CAV	10,916	11,658	13,682	8,525	4,977	12,669	5,793	8,242	8,746	6,023	7,692	8,151	7,750	7,983	7,157	8,388
Case 2: Var-Speed Chiller, CAV	10,364	10,832	12,904	8,231	4,929	12,102	5,778	8,021	8,523	5,990	7,541	8,023	7,622	7,906	7,122	8,370
Case 3: 2-Speed Chiller, CAV, TES	10,152	11,259	11,994	7,997	4,924	11,395	5,738	7,747	8,125	5,936	7,363	7,778	7,497	7,728	7,057	8,350
Case 4: Var-Speed Chiller, CAV, TES	9,033	9,398	11,256	7,485	4,874	10,820	5,724	7,364	7,928	5,907	7,121	7,682	7,306	7,671	7,006	8,337
Case 5: 2-Speed Chiller, RCP/DOAS	7,755	9,665	8,844	5,279	3,099	7,147	2,900	4,803	4,247	2,984	4,079	3,492	3,847	3,226	3,072	2,826
Case 6: Var-Speed Chiller, RCP/DOAS	6,746	8,124	8,050	4,727	3,037	6,547	2,884	4,407	3,996	2,947	3,798	3,355	3,616	3,141	3,005	2,801
Case 7: 2-Speed Chiller, RCP/DOAS, TES	7,626	9,587	7,692	5,204	3,081	6,300	2,869	4,693	3,897	2,948	4,018	3,265	3,805	3,070	3,044	2,802
Case 8: Var-Speed Chiller, RCP/DOAS, TES	6,197	7,729	6,693	4,406	3,000	5,490	2,845	4,110	3,545	2,896	3,617	3,092	3,468	2,961	2,949	2,775

Table: D-15 Annual Energy Consumption (Chiller, Fan, and Pump) for the Standard-Performance Hospital Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

STD-Hospital	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	2,253,336	2,640,611	2,095,494	1,739,150	1,615,692	1,675,547	1,275,511	1,544,517	1,540,742	1,168,686	1,438,447	1,416,708	1,398,075	1,271,775	1,203,914	1,049,875
Case 1: 2-Speed Chiller, VAV	1,524,405	1,727,209	1,878,220	1,275,080	1,133,075	1,551,351	982,840	1,161,717	1,378,435	956,445	1,097,924	1,239,311	1,043,836	1,186,798	998,111	924,612
Case 2: Var-Speed Chiller, VAV	1,481,565	1,684,990	1,827,104	1,241,148	1,076,028	1,517,973	956,317	1,135,894	1,353,469	935,634	1,076,057	1,219,021	1,023,708	1,169,359	985,153	914,560
Case 3: 2-Speed Chiller, VAV, TES	1,465,770	1,655,577	1,815,656	1,240,104	1,115,676	1,504,156	970,895	1,129,351	1,337,640	945,308	1,070,128	1,213,163	1,026,957	1,172,426	985,629	918,222
Case 4: Var-Speed Chiller, VAV, TES	1,373,187	1,536,326	1,758,838	1,172,168	1,046,772	1,469,326	936,672	1,079,662	1,308,353	917,779	1,027,223	1,185,735	992,341	1,148,656	965,130	904,892
Case 5: 2-Speed Chiller, RCP/DOAS	864,543	1,056,711	974,582	618,728	580,470	732,783	418,883	539,116	557,451	383,304	463,120	455,723	407,519	354,624	337,947	286,169
Case 6: Var-Speed Chiller, RCP/DOAS	743,021	917,667	890,587	515,654	497,097	665,503	345,653	453,046	496,522	313,631	387,548	396,995	341,137	298,011	284,849	252,964
Case 7: 2-Speed Chiller, RCP/DOAS, TES	850,238	1,048,025	928,261	609,971	568,579	695,275	411,022	529,506	529,275	375,719	455,371	437,012	402,561	346,318	333,191	281,313
Case 8: Var-Speed Chiller, RCP/DOAS, TES	716,168	897,461	843,221	494,909	472,129	626,310	327,215	433,229	463,024	296,641	370,034	370,664	327,590	281,445	272,833	242,788

Table: D-16 Annual Energy Consumption (Chiller, Fan, and Pump) for the High-Performance Hospital Building Design for Various HVAC Combinations across 16 Climate Locations (units in kWh)

HP-Hospital	Houston	Miami	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Case 0: Baseline	907,797	1,139,872	754,269	634,644	487,822	576,036	351,317	539,050	437,892	309,889	446,028	379,881	427,189	340,608	317,069	261,625
Case 1: 2-Speed Chiller, VAV	427,616	513,532	595,159	320,849	273,862	448,932	212,137	287,640	321,712	209,790	261,567	270,392	236,811	243,214	212,771	194,656
Case 2: Var-Speed Chiller, VAV	401,649	487,206	566,002	301,657	250,418	432,610	202,876	273,296	310,225	201,754	250,646	261,699	227,102	236,766	207,613	191,153
Case 3: 2-Speed Chiller, VAV, TES	403,322	487,092	555,167	310,046	268,868	419,229	207,640	275,272	301,764	206,203	252,040	258,646	231,740	232,417	208,724	192,537
Case 4: Var-Speed Chiller, VAV, TES	343,344	403,179	528,125	269,680	240,255	406,922	195,803	246,381	289,453	195,939	228,319	246,483	213,728	223,011	199,721	187,877
Case 5: 2-Speed Chiller, RCP/DOAS	436,896	552,235	466,110	266,848	222,063	324,161	130,889	234,148	216,807	129,636	194,076	168,345	169,177	146,831	132,443	107,335
Case 6: Var-Speed Chiller, RCP/DOAS	380,665	468,292	430,749	227,418	193,414	302,935	118,710	206,853	201,476	119,844	171,804	156,745	150,234	137,778	123,723	102,912
Case 7: 2-Speed Chiller, RCP/DOAS, TES	431,482	549,389	437,668	263,938	219,030	303,393	128,419	230,556	203,566	127,418	191,080	160,329	167,551	139,556	130,925	105,788
Case 8: Var-Speed Chiller, RCP/DOAS, TES	367,446	459,876	399,425	219,442	185,267	281,707	113,698	198,631	184,580	114,721	165,002	143,933	145,651	127,826	120,199	99,530

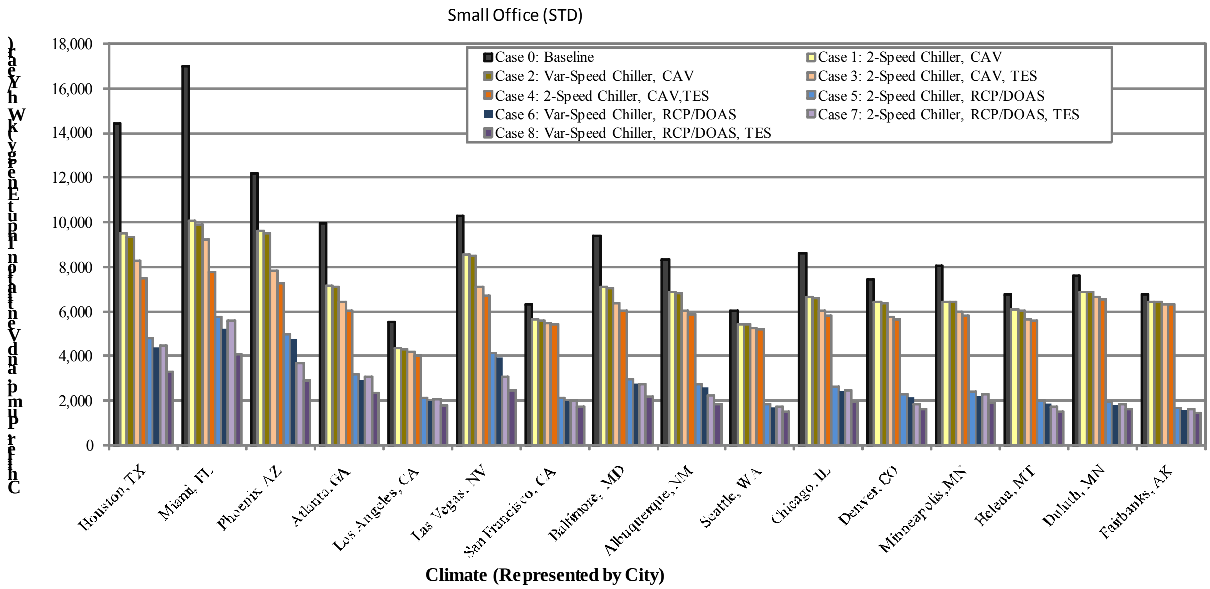


Figure: D-1 Comparison of Annual Chiller and Distribution Energy Consumption for Standard Small Office Building for Various System Configurations in 16 Locations

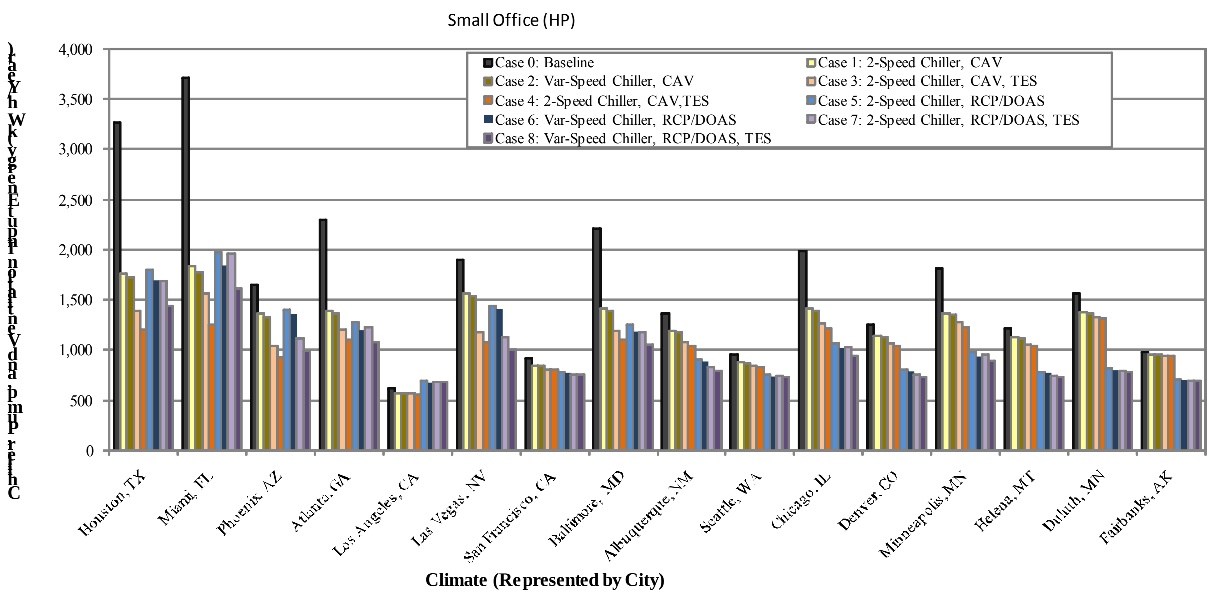


Figure: D-2 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Small Office Building for Various System Configurations in 16 Locations

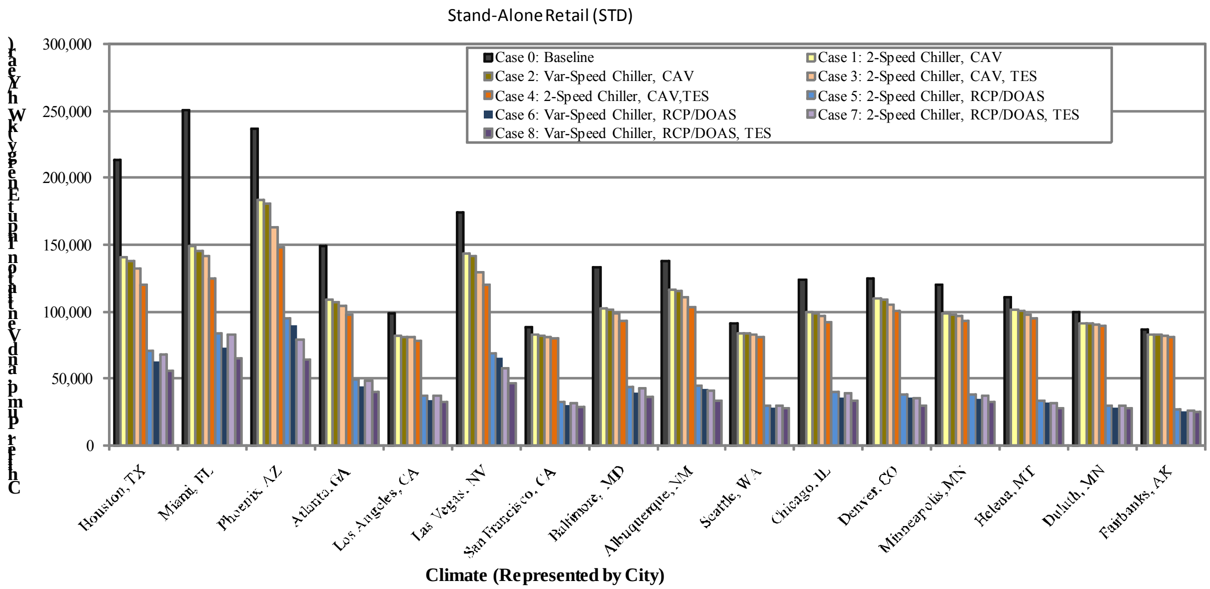


Figure: D-3 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Stand Alone Retail Building for Various System Configurations in 16 Locations

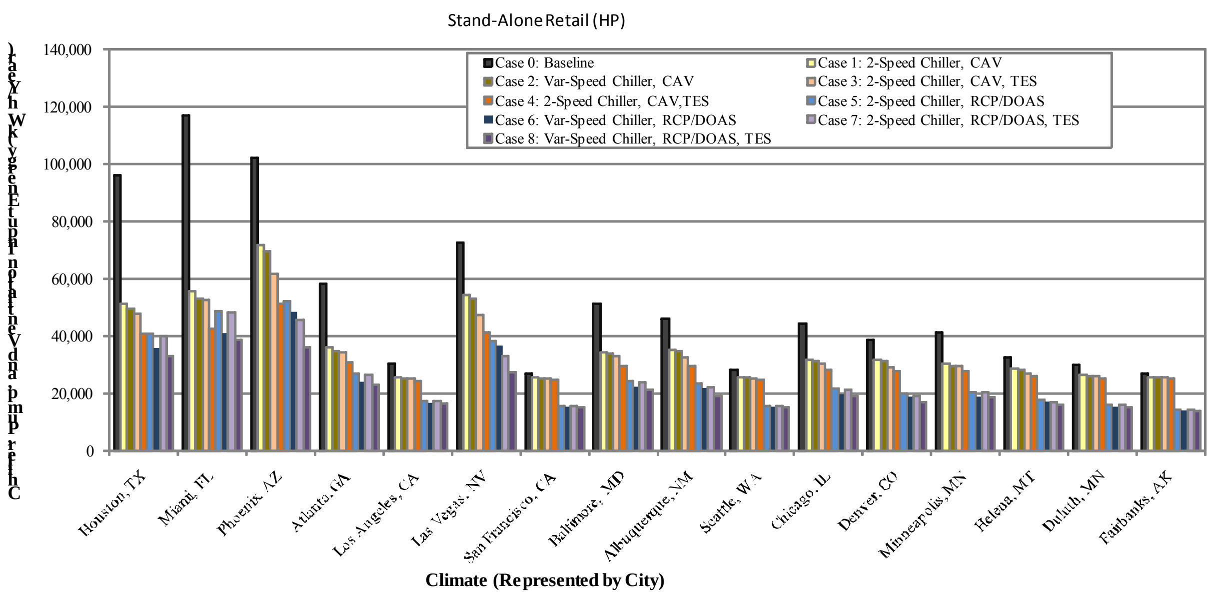


Figure: D-4 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Stand Alone Retail Building for Various System Configurations in 16 Locations

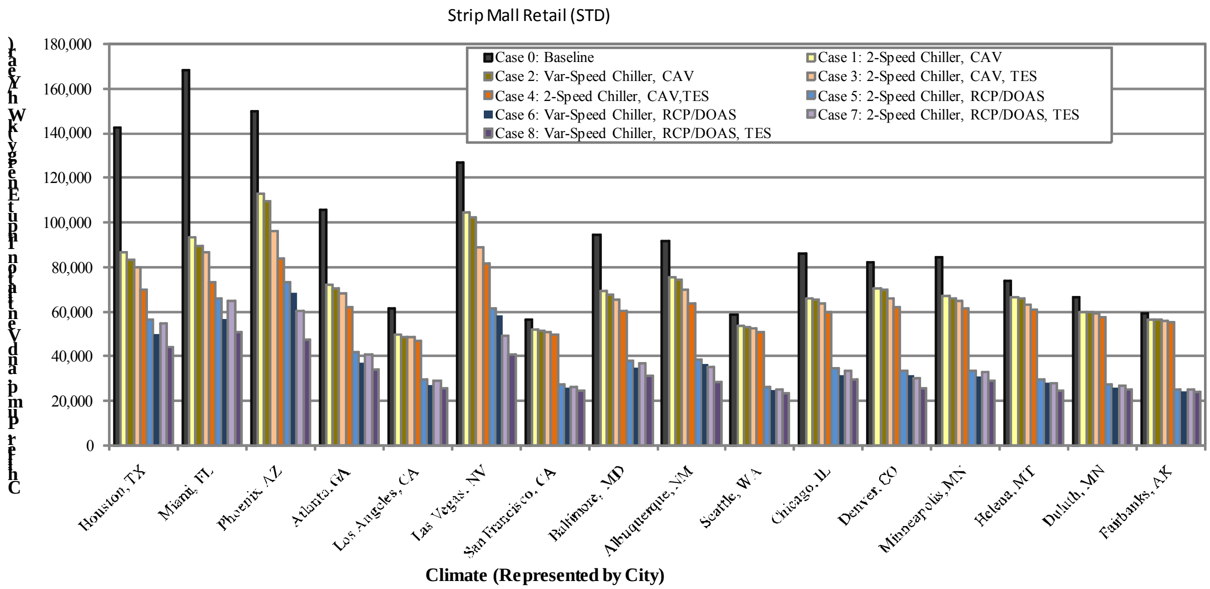


Figure: D-5 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Strip Mall Retail Building for Various System Configurations in 16 Locations

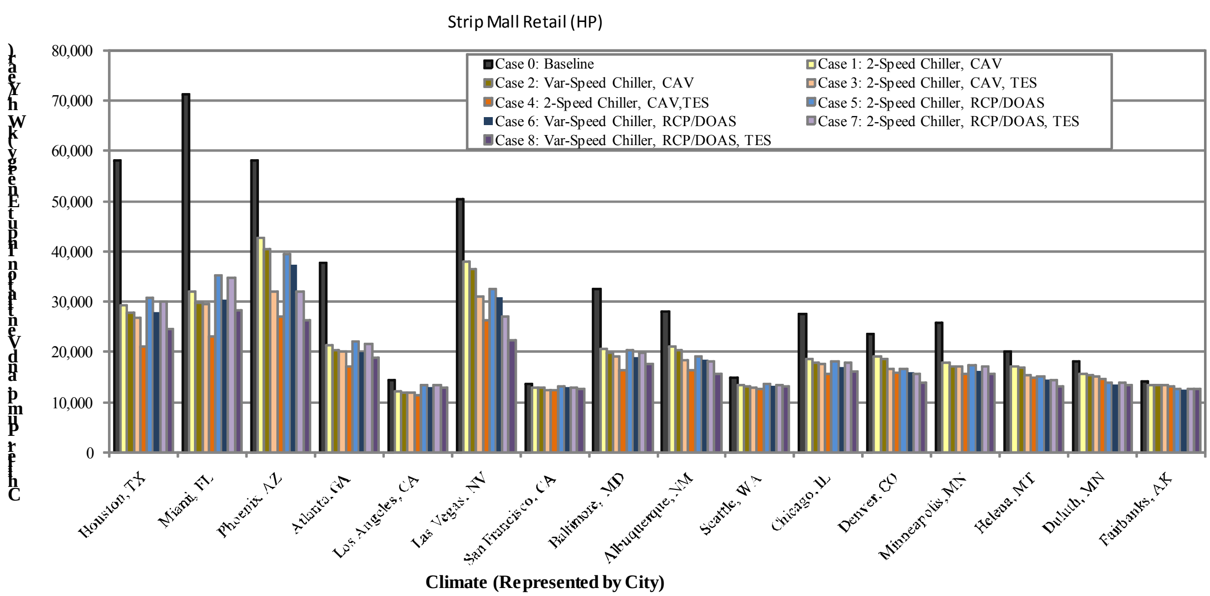


Figure: D-6 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Strip Mall Retail Building for Various System Configurations in 16 Locations

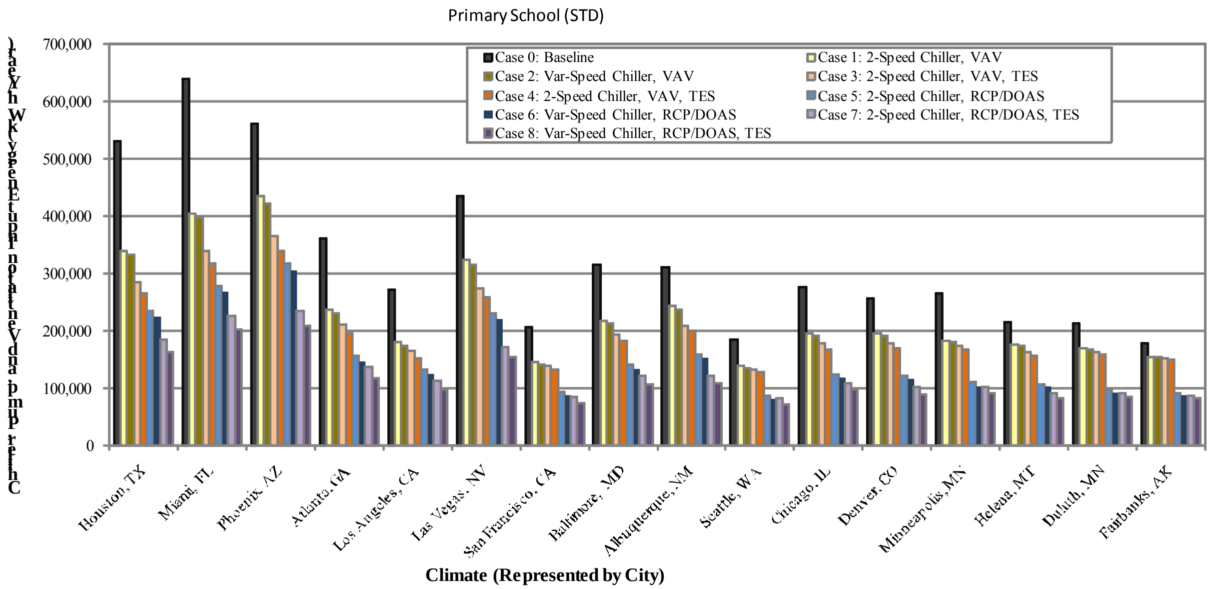


Figure: D-7 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Primary School Building for Various System Configurations in 16 Locations

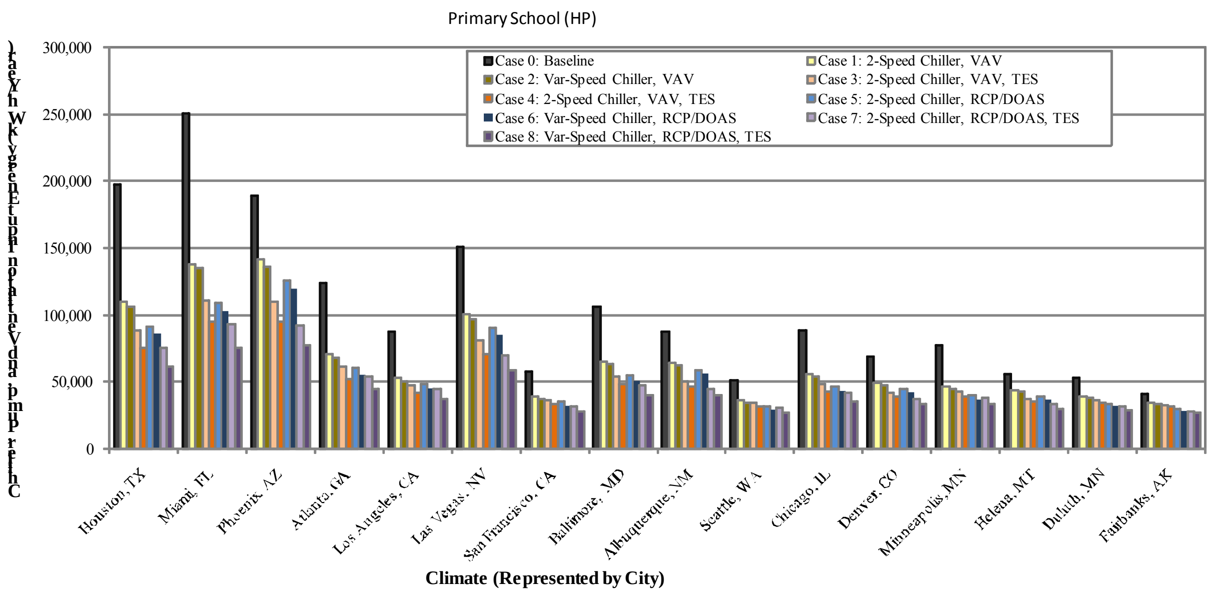


Figure: D-8 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Primary School Building for Various System Configurations in 16 Locations

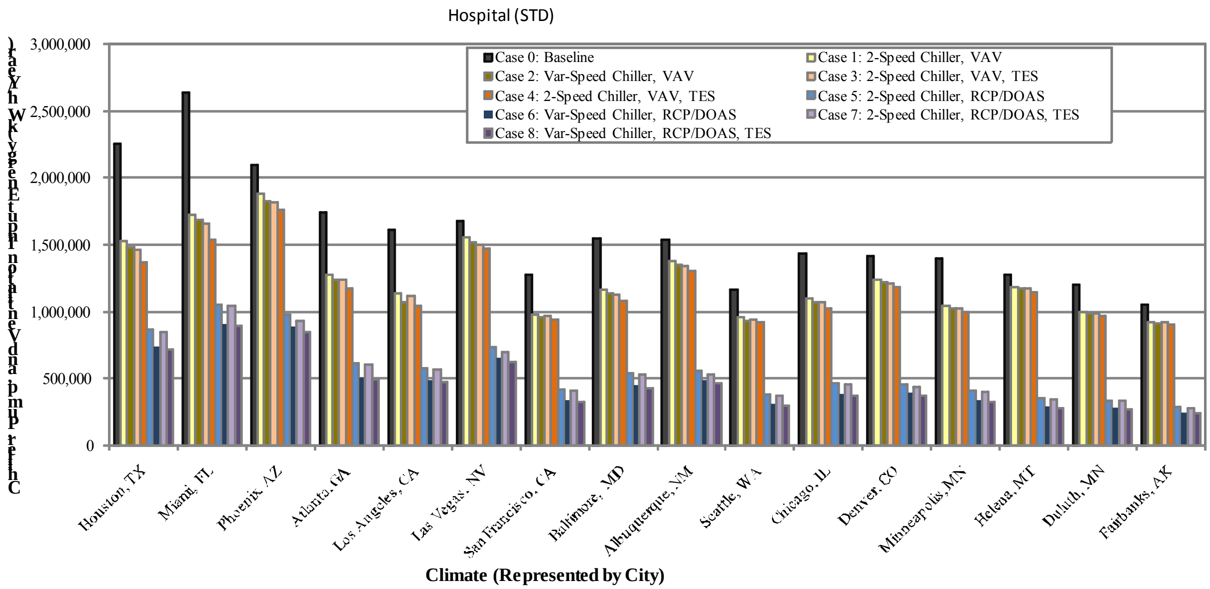


Figure: D-9 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Hospital Building for Various System Configurations in 16 Locations

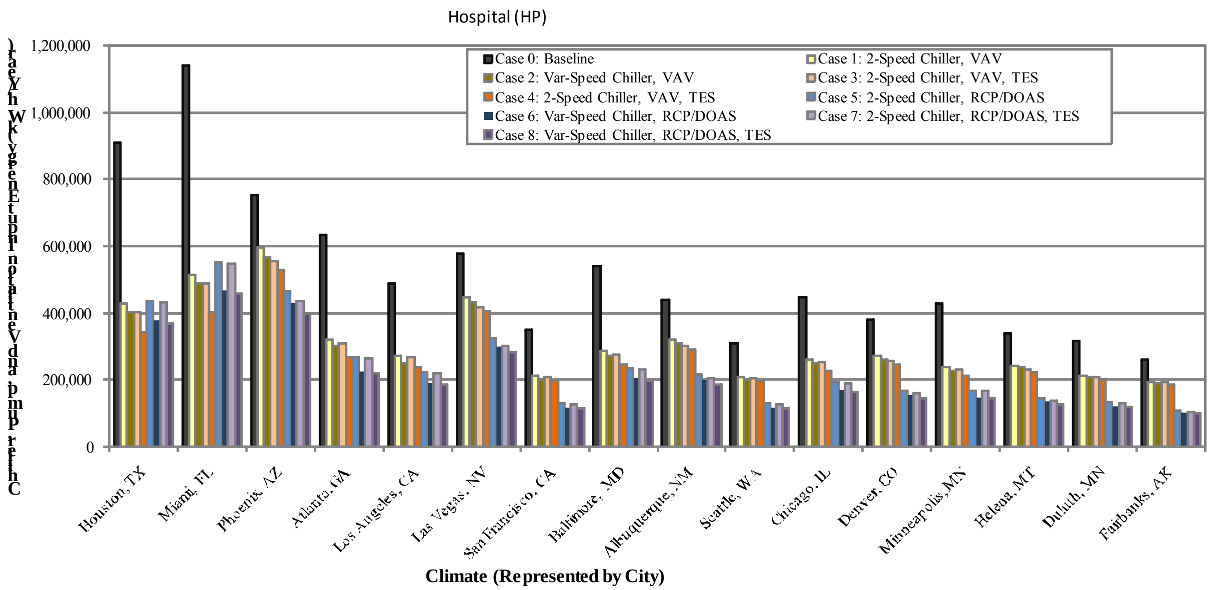


Figure: D-10 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Hospital Building for Various System Configurations in 16 Locations

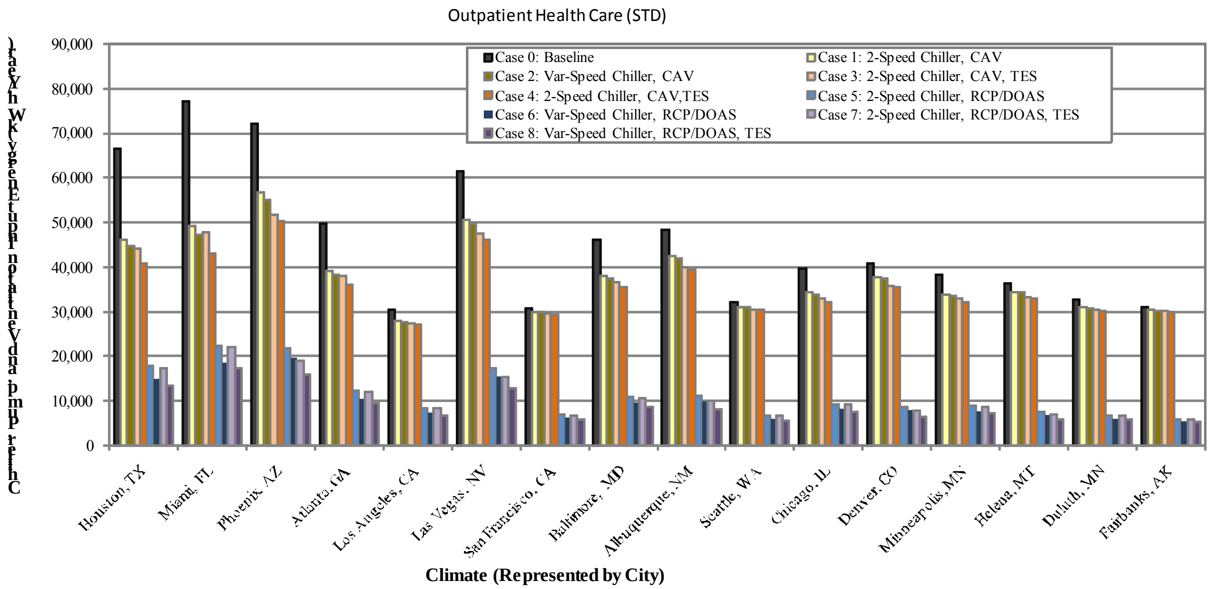


Figure: D-11 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Outpatient Health Care Building for Various System Configurations in 16 Locations

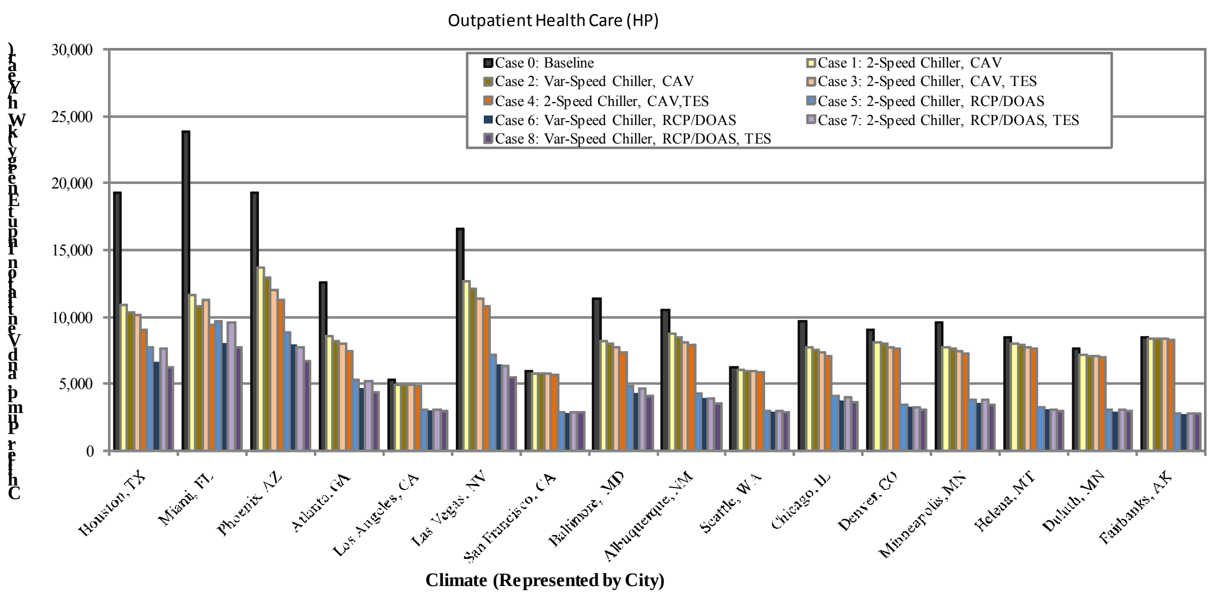


Figure: D-12 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Outpatient Health Care Building for Various System Configurations in 16 Locations

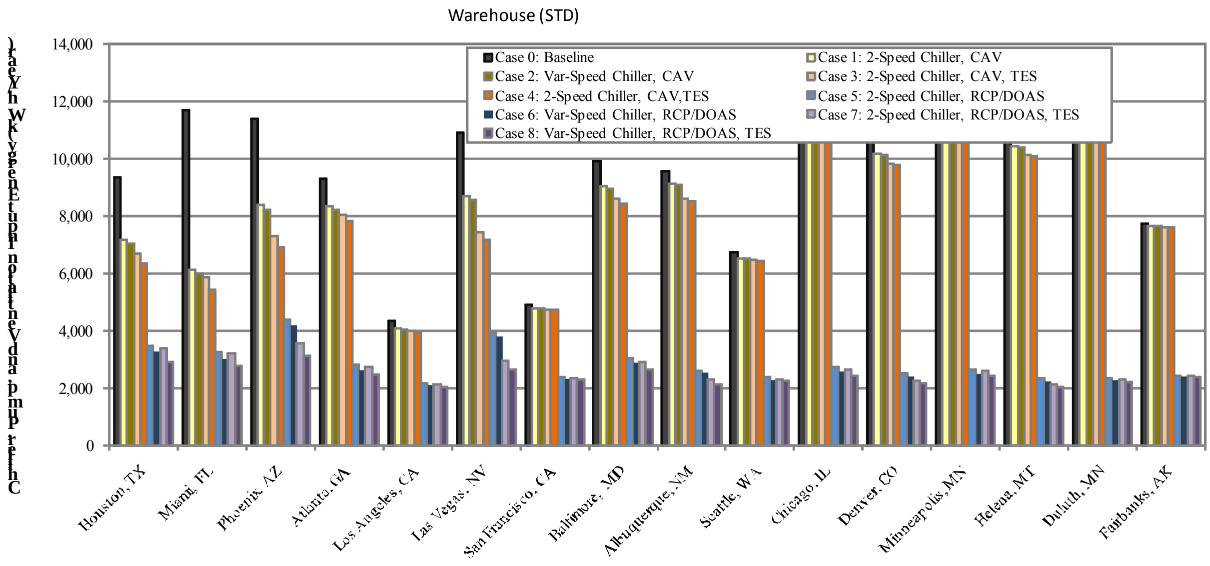


Figure: D-13 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Warehouse Building for Various System Configurations in 16 Locations

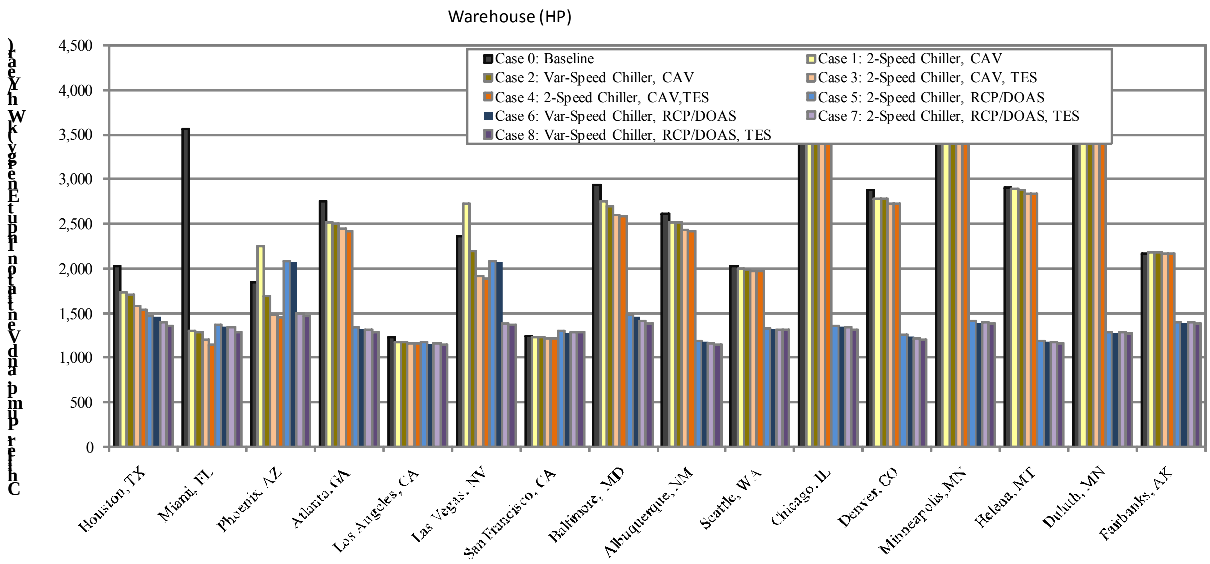


Figure: D-14 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Warehouse Building for Various System Configurations in 16 Locations

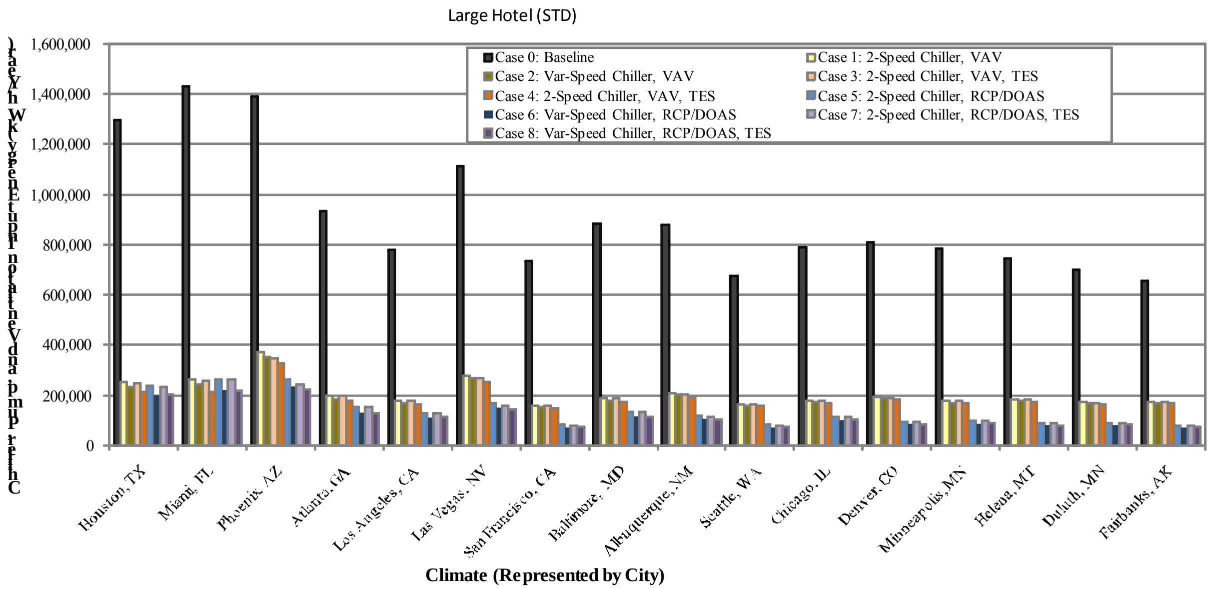


Figure: D-15 Comparison of Annual Chiller and Distribution Energy Consumption for Standard-Performance Large Hotel Building for Various System Configurations in 16 Locations

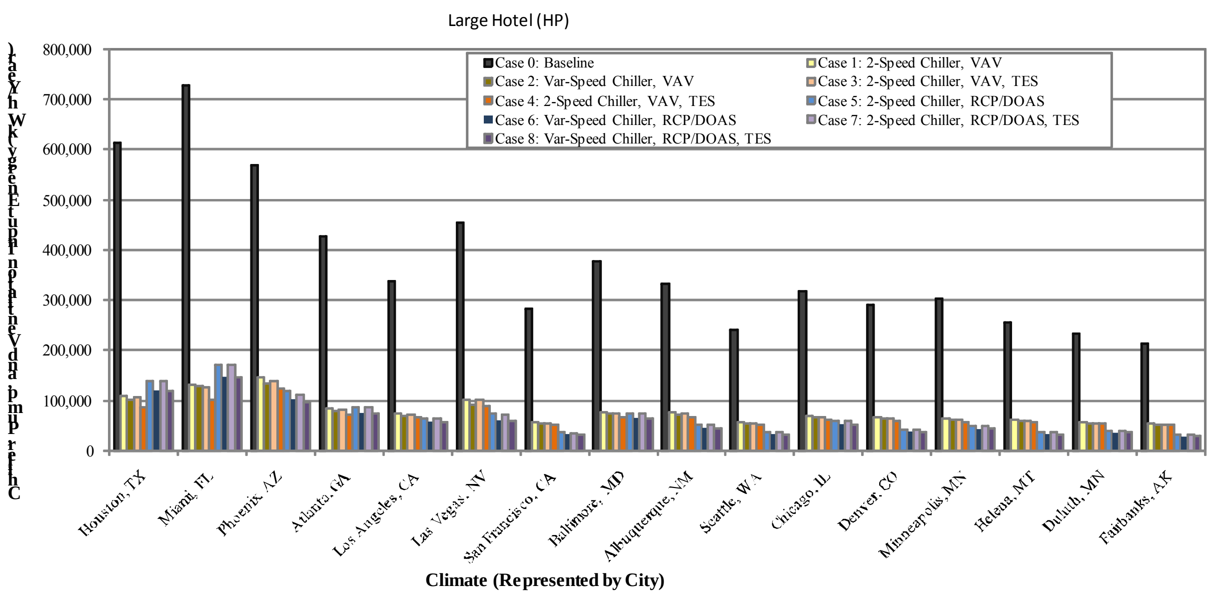


Figure: D-16 Comparison of Annual Chiller and Distribution Energy Consumption for High-Performance Large Hotel Building for Various System Configurations in 16 Locations

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by **Battelle** *Since 1965*

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)
www.pnl.gov

U.S. DEPARTMENT OF
ENERGY