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REPORT

Title: Capital Costs and Energy Savings Achieved by Energy Conservation Measures for Office Buildings in the Greater Philadelphia Region

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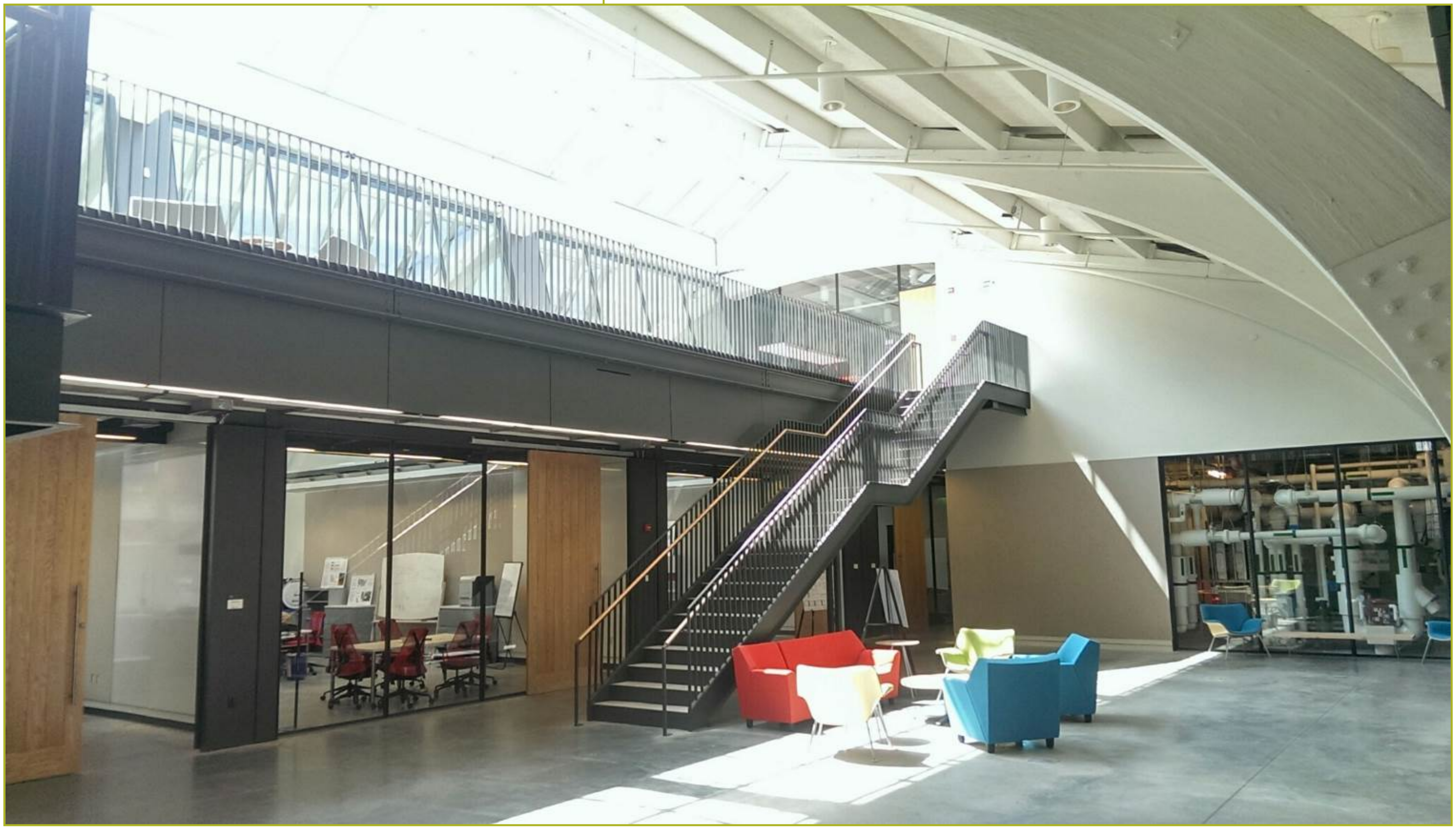
Report Author(s): Bill Sisson



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Report Abstract

Medium office buildings in the Greater Philadelphia offer high potential to reduce building energy consumption. This study assesses the impact of a wide set of ECMs in combinations as retrofit packages, and which combinations offer the most energy conservation for a given investment.

Contact Information for Lead Researcher

Name: Bill Sisson
Institution: United Technologies Research Center

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CAPITAL COSTS AND ENERGY SAVINGS ACHIEVED BY ENERGY CONSERVATION MEASURES FOR OFFICE BUILDINGS IN THE GREATER PHILADELHIA REGION

Liam Hendricken[1], Kevin Otto[2], Jin Wen[1], Patrick Gurian[1], William Sisson[3]
[1]Drexel University, Philadelphia, PA
[2]Robust Systems and Strategy, Taunton, MA
[3]United Technologies Research Centre, Hartford, CT

ABSTRACT

Building stakeholders often need to evaluate energy conservation measure (ECM) retrofit packages to reduce the cost of ownership and energy consumption. The considered alternatives are often ad-hoc and limited to familiar measures. To develop a more systematic evaluation of retrofit options, we study the impact of a wide set of ECMs in combinations as retrofit packages, and assess which combinations offer the most energy conservation for a given investment. We utilize EnergyPlus to evaluate the effectiveness of ECM packages in reducing energy use intensity, and use RSMeans to evaluate the costs of each package. We consider medium office buildings in the Greater Philadelphia region, because this sector offers high potential to reduce building energy consumption in the region. For any level of energy consumption reduction, we find there are several alternative packages of ECMs with varying costs. We identify the least cost alternatives for all levels of energy consumption reduction, and compare these against previous recommendations. This effort is part of an ongoing effort of the Greater Philadelphia Innovation Cluster (GPIC) HUB to create such analyses for common building types in the region.

INTRODUCTION

When opportunities for capital investment in buildings arise, stakeholders evaluate ways to maximize returns. Some investment options take the form of energy conservation measures (ECMs). The considered ECMs typically include those that the stakeholders are familiar with, either through exposure or experience, and are not typically exhaustive. Case studies (Martinez et al. 2005), journal papers (Commerford et al. 2008), and design guidelines typically serve as sources of reference for these types of decisions. However, many studies have shown the need to evaluate ECMs on a case-by-case basis (Chidiac 2011, Chidiac 2010, Liu et al. 2009), instead of taking these guideline recommendations and simply accepting them. In this paper, we conduct a systematic analysis whereby energy reduction guidelines for an entire sector can be developed, and further the sequence of cost effective alternatives as a function of increasing capital investment can also be identified. This allows prescriptive design guidelines to be defined for a climactic and end-use sector, along with best alternative packages near this prescriptive solution. We demonstrate this approach for the medium office sector in the Philadelphia Innovation Cluster (GPIC) HUB region, a ten-country area of southern Pennsylvania and adjacent portions of Delaware and New Jersey.

The approach presented here is in accordance with the results of a number of previous research efforts. A recent study by Chidiac et al. (2011) evaluated the effectiveness of both single and multiple ECMs in Canadian office buildings for three building types and a variety of vintages, using EnergyPlus to model ECM benefits. Three main conclusions were reached: (1) ECM benefits should not be assumed to be additive as the joint effect of combined ECMs is not as great as the sum of the impacts of the individual ECMs, (2) specific geography plays a large role in effectiveness of ECMs, and (3) as exhaustive a list of all combinations of ECMs as possible should be explored.

Others have done work comparing effectiveness of ECMs and their combinations. Ellis et al (2006) identified the Pareto optimal frontier of design alternatives for a particular building of study. We take a similar approach here, but for purposes of developing design guidelines for the entire mid-sized office building sector in the GPIC region. A study by Liu et al. (2009) provides a prescriptive path for reducing energy consumption in medium office buildings by 50% for all ASHRAE climates (including 4A, the climate GPIC is in). While providing a solution, they do not present alternatives and their trade-offs around this solution. Further, the study's medium office building is based on national characteristics which are not the same as those of office buildings in the GPIC region. An earlier study by Chidiac et al. (2010) evaluated single ECMs in terms of their benefits (again using EnergyPlus) and payback periods (based on first costs from RSMeans).

Within the GPIC region, medium-sized office buildings have a large potential to help GPIC meet its goal of reducing regional building energy consumption as much as 50% by the year 2050. In this region, not only does the building stock vary due to climate compared to the national average, but also the decision-making processes are highly variable from owner to owner as well, depending on factors such as the availability of capital and required payback period. Therefore, there is a need to evaluate a wide range of ECM retrofit packages on a regional scale, where the benefits are evaluated by energy simulation (in EnergyPlus) against expected first cost differences, and presented as differences from a nominal design guideline to show impact on energy benefits and first costs. Those differences can then be evaluated individually by different decision makers according to their own criteria (see Hamilton et al., 2012 for a discussion of regional decision processes).

METHODOLOGY

Based on characterization data gathered from the CoStar database (CoStar Realty, 2012), a typical medium-sized office building in the GPIC region is:

- Located in Philadelphia, PA
- 3 stories tall and 60,000 square feet (SF)
- Renovated or built in the last 20 years
- Has single pane windows with u-value of 1.0 Btu/hr-ft^2-°F and solar heat gain factor (SHGF) of 0.5 (Deru et al., 2011)
- EITHER: masonry construction with 20% glazing and roof-top, packaged air-conditioning (abbreviated MS)
- OR: steel construction with 60% glazing and packaged air-conditioning (abbreviated ST)

The basic methodology for defining the benefits of single and combined ECMs is to simulate particular retrofit packages of interest in EnergyPlus (to evaluate suspected synergies), compare the results from the simulation results with regional energy consumption data, and extrapolate those results over a broader set of ECM packages that could be estimated by incrementally changing the modeled ECMs.

EnergyPlus Modeling

Deru et al. (2011) have developed benchmark EnergyPlus models based on the 2003 Commercial Buildings Energy Consumption Survey (CBECS) (EIA, 2005). Among these benchmark models, the medium office model (referred to as the NREL model, and meeting ASHRAE 90.1-1989 code) that is in climate 4A and with post-1980 construction serves as a starting point for this study. The NREL model was modified to represent two baseline buildings for this study, having the characteristics previously described. Both buildings are modeled as having a deck roof with insulation entirely above the deck. The roof insulation has an R-value of 15. The roof is covered in an asphalt membrane, with a solar absorptance value of 0.9.The first baseline building, having masonry construction (referred to as MS) has the following exterior wall construction (from outside layer to inside layer):

- 1 inch of stucco
- 8 inch concrete masonry units
- R-6 continuous insulation
- ½ inch gypsum wallboard

The second baseline building, having steel construction (referred to as ST) has the following exterior wall construction (from outside layer to inside layer):

- 1 inch of stucco
- R-9.4 insulation between 24 in. o.c. steel studs
- ½ inch gypsum wallboard

Table 1. Baseline Internal and External Gains

VARIABLE	VALUE
Occupant Density	0.005 person/square foot
Ventilation Requirement	26.5 CFM/person
Lighting Power Density	1.5 watts/square foot
Interior Small Plug Loads	1.0 watts/square foot
Elevator Consumption	32,000 watts
Exterior Lighting	18,000 watts
Envelope Infiltration Rate	0.223 CFM/square foot

Important model inputs are summarized in Table 1and all of these assumptions come from Deru et al. (2011). These two baseline buildings are meant to represent less efficient medium office buildings in the GPIC region in terms of both envelope and equipment, but they are assumed to be commissioned, or running with good control algorithms and balanced systems.

Table 2. Baseline Mechanical Systems

	MS BASELINE	ST BASELINE
System	3 CAV, AHUs	3 CAV, RTUs
Main Cool Coil	DX, COP 3	DX, COP 3
Main Heat Coil	Hot water	NG furnace
Zone Reheat	Hot water	Electric
Heat Plant	Central Boiler	Packaged
Heat Efficiency	70% AFUE	70% AFUE

The baseline mechanical configurations are tabulated in Table 2. The baseline systems are either constant-air-volume (CAV) air-handling units (AHUs) or roof-top units (RTUs). Primary cooling is provided by electricity, achieved by a direct-expansion (DX) coil which is connected to a cooling source with a coefficient of performance (COP) of 3. Primary heating is provided by either a natural gas (NG) boiler with a hot water (HW) coil system, or a NG furnace, both of which have a 70% annual fuel efficiency utilization (AFUE). Zone reheat is provided by either HW from the central boiler, or electric resistance heating.

Table 3. ECM Abbreviations and Descriptions

	DESCRIPTION
MS/ST	Masonry/steel curtain baseline
L1	T-5 lighting upgrade
L2	LED light tube upgrade and exterior LED
K	High efficiency elevator upgrade
W	Double pane window upgrade
R	White roof upgrade
HE	High-efficiency plant upgrade
VAV	Variable-air-volume system upgrade
D	Dedicated outdoor-air system upgrade
CC	Central chiller plant upgrade
CB	Central boiler plant upgrade
TR	Temperature Reset Strategy

This study models a combination of ECMs in EnergyPlus, which are tabulated with their abbreviations and descriptions in Table 3. For lighting ECMs, this study assumes that the luminaire type is recessed, and only the lamps are changed. Baseline lighting assumes a distribution of 90% T-8 fluorescent and 10% incandescent lighting. The first lighting upgrade (L1) changes lighting to T-5 bulbs, reducing the lighting power density (LPD) from 1.5 to 1.0 watts per square foot. The second lighting upgrade (L2) replaces lamps with LED light tubes, altering LPD to 0.22 watts per square foot, which is not typically achieved by products currently available on the market, but is a projected future LPD that could be achieved by 2020 (Tsao, 2003). Additionally, it is assumed that for L2, exterior light bulbs are changed to LED bulbs as well. High efficiency elevators are modeled with an energy savings of 50% over the baseline (Kone Elevators, 2012). This ECM (K) reduces elevator consumption from 32 kW to 16 kW. The first envelope ECM modeled simulates updating from single to double pane windows (W), giving windows a u-value of 0.57 and an SHGF of 0.39 (ASHRAE, 2004). The second envelope ECM (R) simulates a white roof coating, which is modeled by changing the solar absorptance value of the membrane from 0.9 to 0.2 (Walton, 2012).Mechanical ECMs take one of three forms: an efficiency upgrade, a system upgrade, or a plant upgrade. Low efficiency cooling has a COP of 3, while high efficiency cooling has a COP of 5. Low efficiency heating has an AFUE of 70%, and high efficiency cooling has an efficiency of 95%. Low efficiencies are denoted by LE, and high efficiencies are denoted by HE. The first system upgrade replaces CAV components with variable-air-volume (VAV) components. The second system upgrade replaces VAV components with a hydronic, dedicated outdoor air system (D) with passive cooling supplied by a central chiller and heating supplied by a central boiler. The first plant upgrade replaces a DX system with a central chiller (CC). The second plant upgrade replaces NG furnaces and electric reheat coils with a central boiler and hydronic heating coils (CB). Only upgrades from the baseline models are abbreviated in the run descriptions in Table 3.Temperature reset (TR) is a supply air reset, but the specifics of modeling this in EnergyPlus were unknown at the time of developing the building stock. Therefore, TR was not modeled directly with EnergyPlus but as a post-process reduction in heating and cooling source energy. The previously summarized ECMs were simulated in isolation and combination as packages, which were applied as upgrades for each baseline model. For both baseline EnergyPlus models, there were 14 EnergyPlus models created, generating a total of 28 models. These models were created with the intention of isolating end-use consumption as well as power synergies and interactions. The combinations and their annual energy consumptions are outlined in Table 4 below.

Table 4.Annual Consumption (MWh/year) for 14 Models Simulated in EnergyPlus

	CONSUMPTION	
MODEL DESCRIPTION	**MS**	**ST**
MS or ST baseline model	1166	1249
+TR	1166	1249
+TR+L1	1007	1084
+TR+W	1125	1161
+TR+HE	1063	1154
+TR+K+L1+W	942	969
+TR+K+L2+W	815	835
+TR+L1+W+HE	865	886
+VAV+HE	986	1133
+VAV+K+L1+W	728	793
+CC+HE+VAV+K+L2+W	687	769
+TR+R	1162	1245
+R+CC+HE+VAV+K+L1+W	823	905
+D+R+CC+HE+K+L2+W	957	1079

Extension of Modeled Results to Other Alternatives

Synergies and end-use interactions of single and multiple ECM packages were explored using building simulation, which allows for joint impacts of multiple ECMs to be modeled based on physical principles. However, many ECMs are tedious to model in detail through building energy simulation.

Table 5. Scaling of Energy End-Use Based on EnergyPlus Modeling and Engineering Judgment

ECM	Interior Lighting	Exterior Lighting	Hot Water	Heating	Cooling	Pumps and Condensers	Fans	Elevators	Small Plug Loads
(U)	100%	100%	100%	120%	120%	120%	120%	100%	100%
L1	54%	100%	100%	141%	81%	100%	77%	100%	100%
L2	12%	15%	100%	145%	80%	100%	77%	100%	100%
K	100%	100%	100%	100%	100%	100%	100%	50%	100%
W	100%	100%	100%	75%	75%	100%	100%	100%	100%
TR	100%	100%	100%	89%	90%	100%	100%	100%	100%
CB	100%	100%	100%	70%	100%	100%	100%	100%	100%
CC	100%	100%	100%	100%	60%	100%	100%	100%	100%
VAV	100%	100%	100%	82%	42%	100%	65%	100%	100%
H	100%	100%	100%	33%	33%	100%	100%	100%	100%
G	100%	100%	100%	33%	23%	100%	100%	100%	100%
D	100%	100%	100%	88%	90%	100%	50%	100%	100%
R	100%	100%	100%	100%	98%	100%	99%	100%	100%
IW	100%	100%	100%	80%	80%	100%	100%	100%	100%
I	100%	100%	100%	10%	10%	100%	100%	100%	100%
S	100%	100%	100%	100%	100%	100%	100%	100%	100%
P	100%	100%	100%	100%	100%	100%	100%	100%	100%

Rather, field experience and engineering judgment can be more effective to estimate the impact on energy savings. For example, temperature reset strategies and control changes can be difficult to model but easy to estimate based on field experience. In such cases, the results of simulation conducted without the ECM can simply be scaled by the anticipated effect of the ECM on energy end-use. The calculated and presumed effect of ECMs on end-use energy for the medium offie building are captured in Table 5 above. Using these scaling factors, the number of ECM packages was expanded from 14 for each building (a total of 28) to 99 for each building (a total of 198 packages; ECMs of interest not shown in Table 3 are summarized in Table 7). Due to the list of measures being considered so exhaustive, only the most attractive configurations and technologies are discussed in this report. (The energy consumption data for the 198 models can be found in the corresponding Appendix uploaded with this document).

Comparison to Regional Building Energy Use Data

The results from the previous section on energy consumption of each alternative were compared to market energy consumption totals by adding up the existing stock of each alternative and comparing the result with known energy consumption totals. We find the estimated segment total to be off from the energy totals reported by CBECS by a 20% underestimation (EIA, 2005). This is not surprising given the typical state of repair, operation, and occupancy of existing buildings compared to our modeled results. To match the known segment energy consumption, we scaled the entire building stock (198 models) to match the observed segment consumption data.

Cost Modeling

The basic methodology for defining the benefits of ECM packages was to use RSMeans (Reeds Construction Data, 2011) to calculate the first cost of a retrofit. However, such cost models are known to be relatively correct but not necessarily precise on costs themselves. The costs estimated here using RSMeans under-reported the square foot first costs in the GPIC region by 23% for the office segment compared to recent data. Therefore, the computed cost estimates using RSMeans were scaled to match the reported value of construction for the segment, similar to the scaling of the energy simulation results. Data from a recent study (Hamilton et al., 2012) would suggest that GPIC-area decision-makers use many metrics for assessing attractiveness of options, but the limiting factor is first cost. Therefore, the most attractive options are those with the greatest benefit, and the lowest first cost.

RESULTS AND ANALYSIS

For each of the two baseline constructions, 99 models were evaluated on the basis of energy use intensity and first cost. These results are plotted in Figure 2 and Figure 3. Figure 2 plots all of the MS configurations and ECM packages, while Figure 3shows all of the ST configurations and ECM packages (represented by black, hollow circles). For each figure, the x-axis is first cost (in millions of dollars) and the y-axis is annual energy use intensity (EUI) (kWh/ft^2). On each figure, there are three important horizontal lines representing target EUIs. The first important EUI is 21 kWh/ft^2 and represents the current stock average, based on market segment data and population-weighted building data. The second line represents an EUI of 16 kWh/ft^2, which is the average between an MS and an ST configuration having VAV distribution (with mechanical components meeting ASHRAE 90.1-2004 minimum), and overall envelope thermal conductivities meeting ASHRAE 90.1-2004 minimum specifications (while keeping glazing areas at 20% and 60% respectively). The third line represents a 50% improvement over 90.1-2004, or an EUI of 8 kWh/ft^2.

EUI Reduction Potential by Building Configuration

Based on summary statistics, the MS retrofit packages have an average EUI of 16 kWh/ft^2 with a standard deviation of 5 kWh/ft^2. The ST retrofit packages have an average EUI of 15 kWh/ft^2 (lower than MS) but have a standard deviation of 6 kWh/ft^2. Therefore, an initial observation is that there is more potential for energy savings in ST configurations than in MS configurations. This idea is supported by reviewing the number of configurations which fall under the 50% savings lines. For instance, the MS population has only 1 configuration barely reaching the 50% reduction line. Alternatively, the ST population has 3 configurations falling under the 50% reduction line (these and other configuration statistics found in Table 6).

Table 6. Statistics by Building Configuration

	MS	**ST**
Mean EUI (kWh/ft^2)	16	15
Standard Deviation of EUI	5	6
# > Stock Average	10	12
Stock Ave ≥ # > 90.1-2004	25	20
90.1-2004≥ # > 50 % Over 90.1	63	62
# ≤ 50 % Over 90.1-2004	1	3

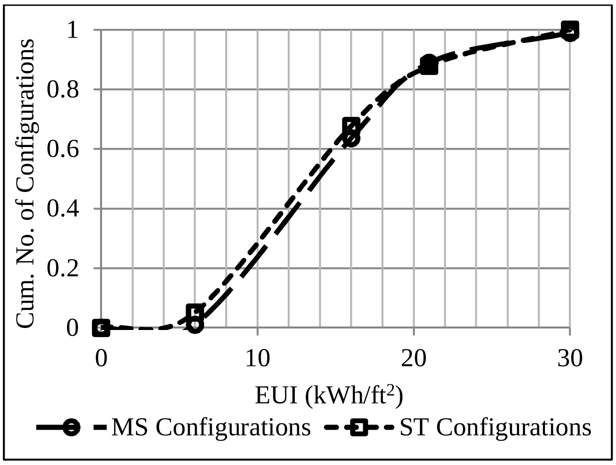

Figure 1. Cumulative Buildings Below Target EUIs

If all configurations are given equal weight, the cumulative number of configurations below target EUIs (Figure 1) supports the claim that ST configurations have greater potential of energy savings than MS configurations. If instead, each configuration (for both ST and MS buildings) represents a fraction of the building stock within the GPIC region, then the results would be weighted by that fraction. However, this analysis assumes equal weight for all configurations. Future work could apply the cost of the configuration in conjunction with its fraction of the population for a fuller understanding of regional potential in EUI.

Costs and Benefits of Retrofit Packages

Economic factors are included in these analyses using two methods (refer to Figure 2 and Figure 3). The first method identifies the least cost solutions for reducing EUI by at least 50% over the 90.1-2004 case (these configurations or ECM packages are highlighted as larger, red, circles). These configurations are tabulated in Table 8 (percentage reduction and cost in millions of dollars reported). These solutions fall close to the 50% savings line (given that energy models can have a 20% uncertainty in their estimates). The second method is a curve outlining configurations exhibiting the greatest EUI reduction for a given first cost investment (Curve points tabulated in Table 9 and Table 10, represented as black, filled circles, and show EUI in kWh/ft^2 relative to cost in millions of dollars). Configurations falling on this line exhibit the greatest return on investment, while configurations above this line represent less attractive investments on the basis of first cost and EUI reduction. The configurations at the head (left) of this curve represent configurations which have that greatest return on investment, while configurations towards the tail (right) of this curve offer diminishing returns on investment. This discussion addresses the least cost configurations used to develop this Pareto curve (for information on all configurations refer to Hamilton et al., 2012).

Insulated roof (I) represents an R30 insulated roof, and Insulated wall upgrade (IW) represents an R11 wall. Heat pump (H) mechanical represents a COP 4 in cooling air to air heat pump, while a ground-source heat pump (G) represents a COP 6 for the cooling system. A photovoltaic system (P) represents a system with 50% roof coverage. Smart grid refers to an operational scheme which reduces the peak consumption of end-use components effectively making them more efficient or shutting them off. This study assumes that smart grid controls save no energy per se, but reduce the building level demand energy by 15%.

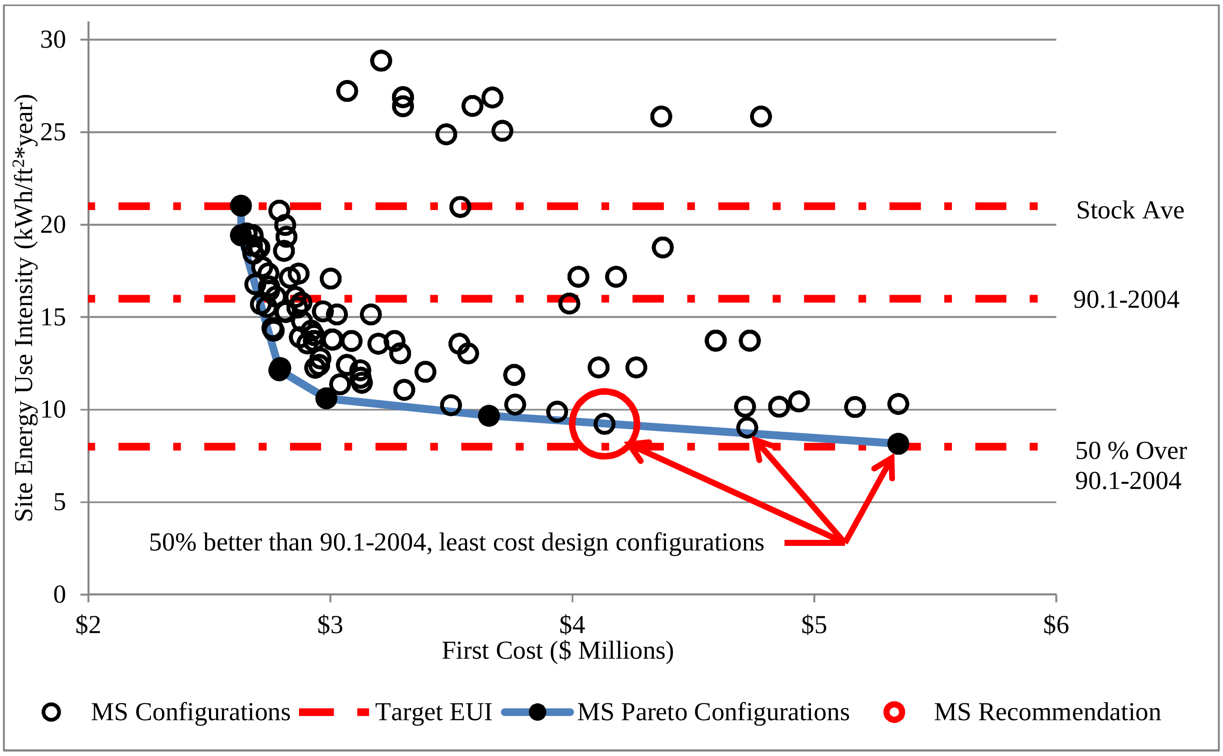

Figure 2. MS Retrofit Packages by EUI and Cost

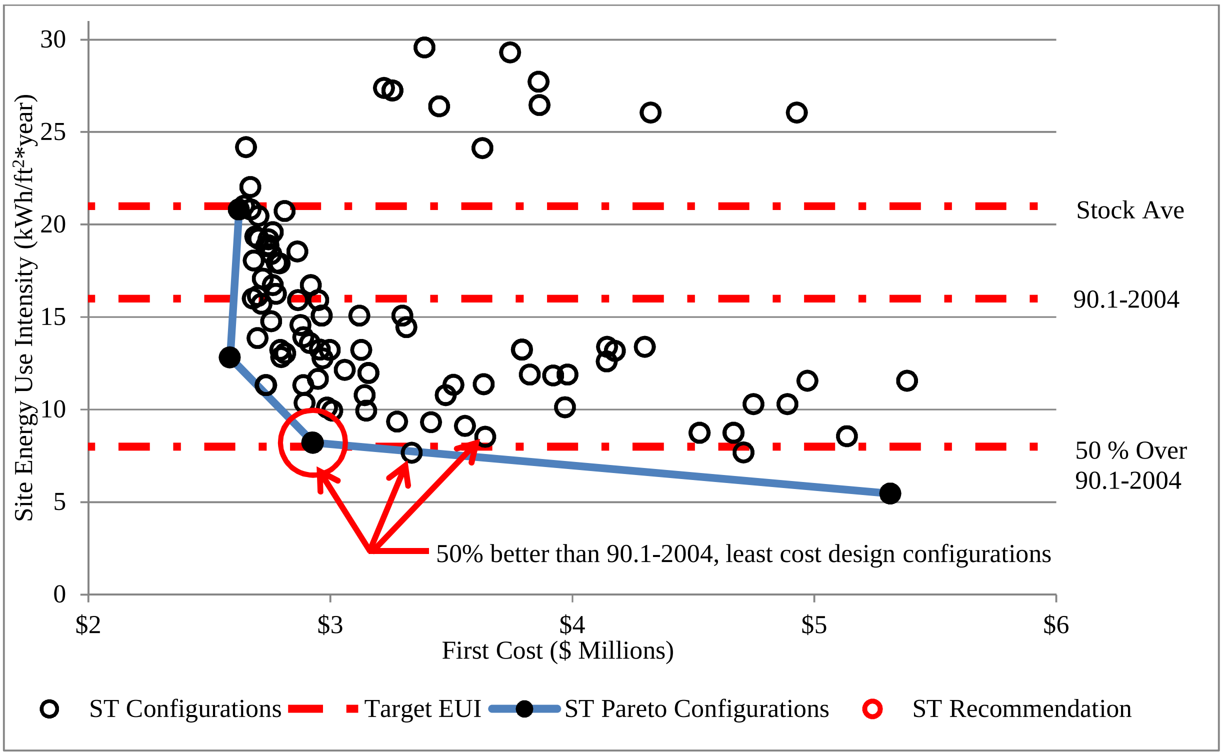

Figure 3. ST Retrofit Packages by EUI and Cost

Table 7. ECM Abbreviations and Descriptions

	DESCRIPTION
MS/ST	Masonry/steel curtain baseline
(U)	Uncommissioned configuration
L1	T-5 lighting upgrade
L2	LED light tube upgrade and exterior LED
K	High efficiency elevator upgrade
W	Double pane window upgrade
R	White roof upgrade
I	Insulated roof upgrade
IW	Insulated walls upgrade
HE	High-efficiency plant upgrade
VAV	Variable-air-volume system upgrade
D	Dedicated outdoor-air system upgrade
H	Heat pump
G	Ground-source heat pump
CB	Central boiler
P	Photovoltaics
S	Smart grid controls

Table 8. 50% Least Cost Solutions

MODEL DESCRIPTION	%	COST
MS+P+S+IW+I+CC+VAV+K+L1+W	50%	4.11
ST+H+VAV+K+L2+W	50%	2.93

Table 9. MS Optimal Returns on Investment

MODEL DESCRIPTION	EUI	COST
MS(U)	21	2.63
MS	19	2.63
MS+VAV+HE+CB+K+L1	12	2.79
MS+VAV+HE+K+L2+W	11	2.98
MS+P+S+R+G+VAV+K+L1+W	10	3.66
MS+P+S+D+IW+I+G+K+L2+W	8	5.35

Table 10.ST Optimal Returns on Investment

MODEL DESCRIPTION	EUI	COST
ST	21	2.62
ST+R+TR	13	2.59
ST+H+VAV+K+L2+W	8	2.93
ST+P+S+D+IW+I+G+K+L2+W	5	5.31

There are some interesting findings from these results. Firstly, there are a number of configurations that are above the stock average (again, 21 kWh/ft^2) and fairly costly. These configurations all made use of combined heating and power (CHP) or combined cooling, heating, and power (CCHP) systems, which for this building type in this climate were not effective. Secondly, the ST buildings relative to the MS buildings provided interesting findings. This is primarily due to it being cheaper to upgrade the envelope u-value for ST configurations, which have a 60% glazing area compared, to the 20% glazing area on the MS configurations, given that wall insulation upgrades cost more than window upgrades.

Recommended Retrofit Packages

To achieve a 50% reduction in energy use over the 90.1-2004 configuration in the GPIC region at minimum first cost, one can examine Figures 2 and 3 for configurations that meet the 50% solution line (within a 20% error bound). We recommend the configurations in Table 8. The lowest first cost MS building in the GPIC region should be retrofitted to include: photovoltaics, smart grid controls, VAV distribution, a central chiller, T-5 lighting, wall and roof insulation upgrades, high efficiency elevators, and double pane windows. An ST building in the GPIC region should be retrofitted to include VAV distribution, heat pumps, LED lighting, high efficiency elevators, and double pane windows. These configurations differ slightly from the recommendations by Liu et al. (2009). The 50% solution for the Liu et al. (2009) model included a DOAS system, envelope upgrades, a white roof, double pane windows, and lighting upgrades. It also included ECMs out of the scope of this project, such as permanent shading and daylight harvesting. When the Liu et al. package was applied to the MS and ST constructions (except for shading devices and daylight harvesting) for the GPIC region, it resulted in an EUI around 10 kWh/ft^2 (only a 37% reduction). The MS and ST retrofit packages did not include permanent shading devices and daylight harvesting, since these measures are not universally applicable, site dependent, and often extensive as retrofit applications. Furthermore, different ECMs such as photovoltaics and ground source heat pumps are alternative means to reach and exceed the 50% reduction goal. However, these ECMs are capital intensive technologies and so appear off the lowest cost boundary of Figures 2 and 3.

CONCLUSIONS

As supported by Chidiac et al. (2011), it is important to remember that the results of this study are specific to the geography and buildings within the GPIC region. The framework for this study can be replicated to develop an understanding of which ECM packages from an exhaustive list apply most to a specific building or building stock. Noting this, there are important conclusions for the GPIC region building stock:

- Retrofit packages along the Pareto curve are the designs to select given a specified first cost, as these packages represent optimal return on investment
- The least-cost 50% reduction in energy use designs are slightly different than the Liu et al. (2009) 50% solution for an ASHRAE 4A climate. While the results presented here are more specific to the GPIC region, Liu et al. considered daylighting and shading, which are potentially attractive options and warrant consideration in future research, although

they are not expected to be universally applicable, given site constraints.

Overall, we find this approach useful for establishing the most cost-effective solutions for typical masonry and steel buildings in the GPIC region. Not only does it provide the least-cost alternative, but it also indicates the tradeoffs between first cost and energy reduction visually on the Pareto curve and allows for decision makers to add or decrement from proposed solutions based on their specific decision making criteria and goals.

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DISCLAIMER

REFERENCES

ASHRAE. (1989). Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings. ANSI/ASHRAE/IESNA Standard 90.1-1989. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. (2004). Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings. ANSI/ASHRAE/IESNA Standard 90.1-2004. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Chidiac, S. E., E. J. Catania, E. Morofsky, and S. Foo. "A Screening Methodology for Implementing Cost Effective Energy Retrofit Measures in Canadian Office Buildings." *Energy and Buildings* 43.2-3 (2011): 614-20. Elsevier, 12 Nov. 2010. Web.

Chidiac, S. E., E. J. Catania, E. Morofsky, and S. Foo."Effectiveness of Single and Multiple Energy Retrofit Measures on the Energy Consumption of Office Buildings."*Energy* 36 (2011): 5037-052. Elsevier, 1 July 2011. Web.

Commerford, E., P.L. Gurian, and J. Wen, S.R. Cook. 2008. “Design of a Site-Built Integrated Collector Storage Solar Water Heater Under Uncertainty,” *The Open Renewable Energy Journal*, *1*:17-25.

CoStar Realty. "# 1 Commercial Real Estate Information Company."*CoStar*.Web. 24 Feb. 2012. <http://www.costar.com/>.

Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., et al. (2011).U.S. Department of Energy Commercial Reference Building Models of the National Building Stock.National Renewable Energy Laboratory.

EIA.(2005). *2003 Commercial Buildings Energy Consumption Survey*.Washington, DC: Energy Information Administration. Available at <http://www.eia.doe.gov>.

Ellis, P., Griffith, B., Long, N., Torcellini, P., and D. Crawley, “Automated Multivariate Optimization Tool for Energy Analysis,”*IBPSASimBuild 2006 Conference*, Cambridge, MA, 2006.

Hamilton, Michael, Liam Hendricken, Jared Langevin, Yizhe Wang, Patrick Gurian, and Jin Wen.*Drexel University Year 1: GPIC Policy, Markets, and Behavior Research*. Tech. Greater Philadelphia Innovation Cluster, 2012. Print.

Kone Elevators. "KONE Announces 50% Energy Reduction in Its Volume Elevators." *Kone*.Web.2012. http://www.kone.com.

Liu, B., W. Wang, M. D. Lane, M. I. Rosenberg, and B. A. Thornton. "Technical Support Document: 50% Energy Savings Design Technology for Medium Office Buildings." (2009). *Pacific Northwest National Laboratory*.Web.

Martinez, V.H., P.L. Gurian, and S.R. Cook, “Improving Energy Efficiency and Temperature Control in a Passive-solar Housing Development,” Proceedings of the 2005 World Solar Congress, Orlando, FL (2005).

Reeds Construction Data, *RSMeans Square Foot Costs*, 32nd Edition, 2011.

Tsao, Jeffrey. "Roadmap Projects Significant LED Penetration of Lighting Market by 2010." *Laser Focus World* (2003).

Walton, Terry E. "Top Level Decisions to Help Cool Coatings Work: Flat Roof Replacement: Reflective Roof Coating." Web. 16 Jan. 2012. <http://www.americanweatherstar.com /pages/estar/cool.html>.