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Modeled Retrofit Package Performance for Schools

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Modeled Retrofit Package Performance for Schools

Prepared by Lawrence Berkeley National Laboratory (LBNL)

This report details modeled energy performance and savings from retrofit packages in prototypical school buildings in climate zones throughout the U.S. The information herein serves as a reference for elementary and secondary schools interested in implementing retrofit packages in their facilities for energy savings as well as health and safety benefits. School models developed for simulating package performance differentiated between rural and urban environments. Simulations were run for 10 distinct climate zones covering a range of climate conditions throughout the U.S. Results include savings estimates for electricity, natural gas, CO_2 emissions, and annual utility costs for nine different retrofit packages that combine energy conservation measures, including HVAC controls and equipment upgrades, lighting efficiency upgrades, and electrification technologies such as heat pumps for space conditioning and domestic hot water. Nine additional retrofit packages were also developed for elementary schools and modeled in two climate zones. Appendix B describes the additional retrofit packages and presents savings estimates.

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School Model Performance Characteristics

Whole building energy models were developed for elementary and secondary schools based on the U.S. Department of Energy (DOE) commercial reference building models.[1] These models are used to simulate energy savings associated with changes in energy codes and standards, and also from energy efficiency retrofits. The school models have building features representative of existing structures constructed in or after 1980 (unless otherwise noted) and where operations generally conform to ASHRAE Standard 90.1 (1989) performance levels. The buildings, as modeled, have features that vary according to climate zones, such as different equipment sizing for heating and cooling needs. The reference lighting system performance in the DOE models was modified to a baseline lighting power density more consistent with an existing T8 fluorescent system because the original reference model assumptions representative of T12 fluorescent bulbs and magnetic ballasts would have commonly been converted at some point to T8 systems with higher efficiency. Table 1 shows a selected list of key building features of the elementary and secondary school models.

The elementary school reference model heating, ventilation and air conditioning (HVAC) system uses packaged two-stage direct expansion (DX) rooftop units (RTUs) for air conditioning, with heating provided by a natural gas (hereafter gas) hot water boiler for primary heating and zone-level reheat coils. The system includes variable air volume (VAV) zones in most of the school but with a few small dedicated packaged units with gas heating and electric air conditioning for specific zones (cafeteria, gym, kitchen). The secondary school reference model HVAC system is also multi-zone VAV with reheat coils in most of the building, but with a central plant that includes an air-cooled chiller plus a gas boiler instead of packaged rooftop equipment. Similar to the elementary school model, the system also includes some single zone packaged equipment for several zones (gymnasium, auditorium, kitchen, cafeteria).

Table 1. Energy Model Characteristics for Prototype Schools

Characteristic	Elementary School	Secondary School
Floor area	73,959 ft^2	210,810 ft^2
Number of floors	1	2
Window to wall ratio	0.35	0.33
Floor-to-ceiling height	13.1 ft	
Roof type	Built-up flat roof, insulation entirely above deck. Insulation varies by location	
Wall type	Steel frame with batt insulation (performance varies by location)	

[1] https://www.energy.gov/eere/buildings/commercial-reference-buildings

Characteristic	Elementary School	Secondary School
HVAC system type	RTU multi-zone VAV with hot water reheat, + packaged single zone AC for gym, kitchen, cafeteria zones	Central plant multi-zone VAV with hot water reheat, + packaged single zone AC for gym, aux gym, auditorium, kitchen, & cafeteria zones
Heating type	Central gas boiler, except gas furnace for gym, kitchen, & cafeteria zones	Central gas boiler, except gas furnace for gym, aux gym, auditorium, kitchen, & cafeteria zones
Cooling type	Two speed direct expansion RTUs + packaged single zone AC for gym, kitchen, & cafeteria)	Air cooled chiller + packaged single zone AC for gym, aux gym, auditorium, kitchen, & cafeteria)
Fan control	Variable flow, except for packaged single-zone units	
Service water type	Gas heated, with storage tank	
Lighting system	Lighting power density assumptions for reference models modified to ASHRAE 90.1-2004 model levels, reflecting a T-8 fluorescent lighting system baseline typical in schools and averaging an installed lighting power density of 1.2W/ft^2	

Calculation of Fuel Costs

Electricity and gas cost calculations for the package performance analysis are based on local energy tariffs that were applied to the energy results from the building simulations. These tariffs were developed from commercial tariffs and rates available in each reference building location based on 2004 pricing. These electricity tariffs were then adjusted to correct for energy price inflation on a state-by-state basis from 2004-2022, using Energy Information Administration (EIA) commercial building average retail prices.[2] Gas prices were similarly adjusted to correct for inflation, also using state-by-state EIA gas price data.[3] Pricing for propane gas deliveries for CZ8 Alaska were also based on EIA data from analysis conducted by the National Council on Energy.[4] A propane cost of $0.097/kWh was used in our calculations, assuming 28 kWh/gallon of propane, and a price of $2.70/gallon.

Rural School Building Model Development

The DOE reference models are generally representative of schools in urban environments. The Lawrence Berkeley National Laboratory (LBNL) team also developed a set of equivalent school building models intended to better reflect distinctive aspects of rural schools based on a

[2] EIA https://www.eia.gov/electricity/data/browser/
[3] EIA https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PCS_DMcf_m.htm
[4] NCE https://www.consultenergy.org/propane/ak/

combination of literature review, data analysis, and expert interviews. Below is a summary of modifications made to the DOE reference models.

- A reduction in classroom occupancy of 20%, reflective of lower building utilization and occupant density.
- Changes to some HVAC equipment specifications, including from VAV systems to constant air volume (CAV) systems to reflect feedback from expert interviews.
- Changes to the building envelope, including wall, roof, and window performance specifications, to reflect the older building stock generally found in rural locations (see Appendix E).

For climate zone 8, Alaska, feedback from interviews confirmed that in the majority of rural areas, natural gas infrastructure is not common. Implementing fuel oil as a heating fuel, a more common option, was not feasible in the energy models however. Models for Alaska developed here therefore assume the use of propane gas, also common in rural areas.

Summary of Retrofit Packages

Retrofit packages were developed that involve multiple efficiency measures that can be implemented in schools to achieve deeper energy savings and help make schools safer, healthier, and more comfortable with lower energy costs, including packages focused on electrification and decarbonization. Table 2 briefly summarizes the energy efficiency measures included in each retrofit package, which are further described in Appendix F.

Table 2. Description of Measures per Package in Each Retrofit Package

Package	Description
1. Building Management System (BMS) Upgrade	BMS replacement, supply air temperature resets, variable frequency drives (VFD), optimum start programming, retro-commissioning of existing controls sequences.
2. Boiler Replacement + Controls	High efficiency condensing boiler, supply water temperature reset, lock-outs, networked thermostats, and super premium efficiency motors.
3. Rooftop Unit (RTU) Replacement + Controls (Elementary School Only)	Efficient RTU, CO_2 sensors for demand-controlled ventilation (DCV), outside air economizer controls, upgraded filters, VFDs, supply air temperature resets.

Package	Description
4. Chiller Replacement + Controls (Secondary School Only)	Efficient chiller, supply water temperature resets, efficient motors, BMS/controls upgrades.
5. HVAC Controls + Lighting + IEQ	Improved HVAC controls, outside air economizer repairs, supply air temperature resets and VFDs, efficient filters, CO_2 sensors and DCV, LED retrofit with occupancy sensing, daylight controls.
6. HVAC + Envelope +IEQ	The HVAC and filter improvements from Package 5 HVAC as well as equipment upgrades to higher efficiency RTUs (Elementary School) or chiller and boiler (Secondary School). Also envelope upgrades: window films, cool roof.
7. HVAC + Lighting + IEQ	The HVAC, filter, and lighting efficiency improvements from Package 5, as well as Package 6 HVAC equipment upgrades.
8. Partial Electrification + EE + IEQ	The HVAC, filter, and lighting efficiency improvements from Package 5, HVAC equipment upgrades from Package 6, and upgrading boiler for domestic water heating to heat pump water heater. In climate zones 7 and 8 cold climate-specific heat pump water heaters were modeled.
9. Full Electrification + EE + IEQ	All measures from Package 8, and replacing boiler for space heating with heat pump for an all-electric heating and cooling system. Also includes an energy recovery ventilator. In climate zones 7 and 8 cold climate-specific heat pumps for water heating and zone heating were modeled.

Cold Climate - Specific Measures

Initial analysis here found that in the coldest climate zones (7 and 8), Package 9, which includes full electrification of all heating, needed further development to ensure the comfort requirements of the space were being met. In these climates, cold climate-specific heat pumps for water and space heating were implemented.

Envelope Retrofit Measures

Improvements to the envelope in Package 6 were based on recommendations leveraging ASHRAE's Advanced Energy Design Guide (AEDG) for K-12 Schools - 50% Energy Savings. The supporting documentation developed by the National Renewable

Energy Laboratory (NREL)[5] for the AEDG contains recommended wall, roof, and window performance specifications. Appendix E lists baseline envelope performance for the rural and urban school models for each climate zone as well as retrofit measure envelope performance specifications.

Health and Safety Benefits of Retrofit Packages

Improving indoor environmental quality (IEQ) through energy efficiency retrofits can result in benefits to teacher and student health and comfort and support the learning environment. Benefits may include improvements to indoor air quality (IAQ), interior lighting quality, thermal comfort, and acoustics. IAQ improvements are prioritized for inclusion in the packages because they are among the recommended strategies to mitigate risks from airborne viruses[6], and studies have also demonstrated strong associations with improved IAQ and benefits to student performance and reduced absenteeism[7]. Appendix G provides examples of potential IEQ improvements from the retrofit package efficiency measures and the associated benefits. A school or district can reference this list to help provide a description of IEQ improvements and associated benefits that can be expected for proposed energy improvements. School safety improvements from the efficiency retrofits can include improving the resiliency of the facility to withstand extreme weather conditions, natural disasters, or other emergencies or improving site security, such as through effective outdoor lighting systems. A school or district should consider how any planned retrofit activities can be expected to better prepare the school for extreme events and other hazards.

Results

To calculate energy savings from retrofit packages, LBNL performed building energy simulations for packages of efficiency measures using the DOE's EnergyPlus software, modeling a range of different DOE climate zones for both elementary and secondary school buildings, leveraging DOE's reference building models. The simulation work characterizes retrofit package performance in terms of annual energy usage, carbon emissions, and energy cost. The simulation results are compared to baseline performance for savings estimates. Package implementation costs were estimated to calculate simple paybacks (in years) of the retrofit investments – payback results are provided in Appendix J. Simulations were performed for schools in ten locations representing distinct climate zones throughout the U.S., including

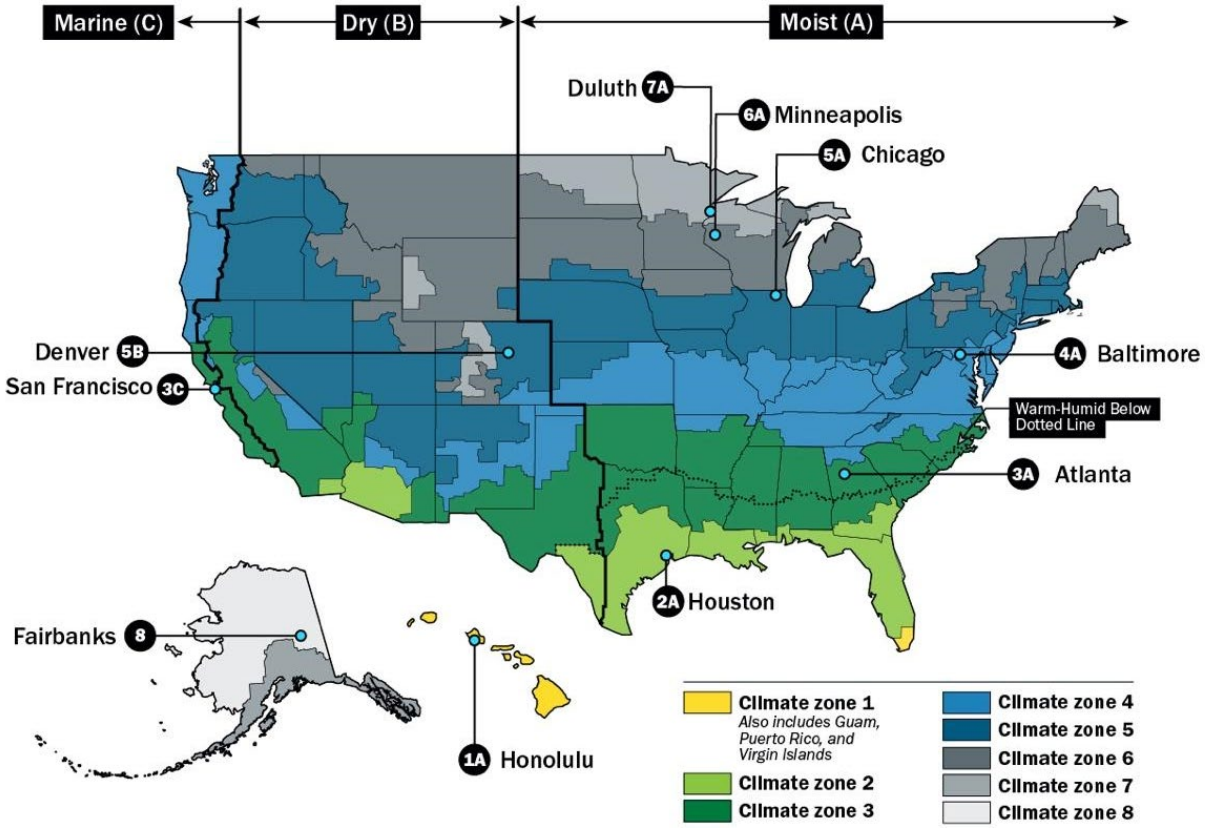
[5] Bonnema, Eric, Matthew Leach, Shanti Pless, and Paul Torcellini. *Development of the Advanced Energy Design Guide for K-12 Schools--50% Energy Savings*. No. NREL/TP-5500-51437. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2013. https://www.nrel.gov/docs/fy13osti/51437.pdf

[6] https://www.epa.gov/indoor-air-quality-iaq/clean-air-buildings-challenge

[7] D. Vakalis, C. Lepine, H. L. MacLean & J. A. Siegel (2020): Can green schools influence academic performance?, Critical Reviews in Environmental Science and Technology, DOI: 10.1080/10643389.2020.1753631

Alaska and Hawaii. Representative cities and climate zones in the retrofit package modeling are illustrated in the following map.

Modeled Climate Zones and Cities



Energy savings for the packages vary depending on location and climate, building type (elementary vs. secondary) and prevailing HVAC systems, construction type, and operating characteristics. To compare performance of all of the retrofit packages at a glance for a given climate zone and school type, charts are included below that plot annual savings percentages for electricity, gas, and utility costs. Packages are included on the x-axes in numeric order, with bins for each climate zone. Note that the elementary school plots include Package 3 (RTU replacement + controls), while the secondary school plots include Package 4 (chiller replacement + controls) – reflective of the building HVAC system types.

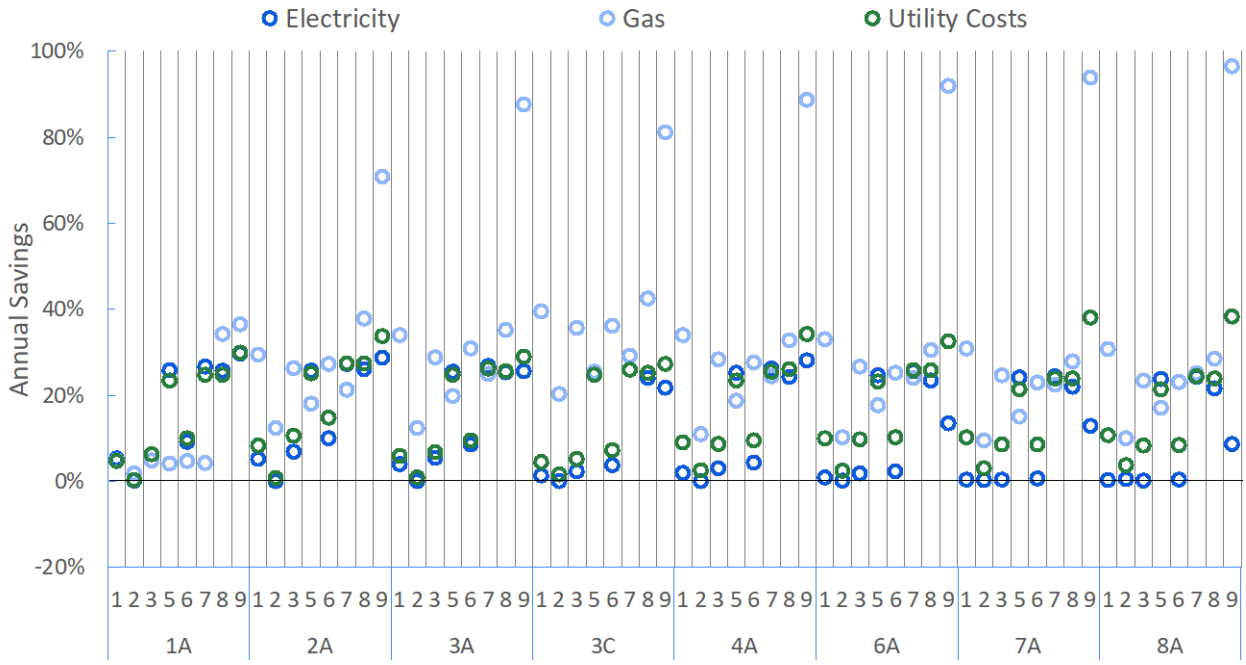
While the plots give some visual indication of relative performance of package options, a more thorough comparison of the benefits per climate zone for each school type can be constructed by looking at the savings tables for the climate zones, which also include annual CO_2 savings estimates. To complete the comparative analysis, Appendix J tables provide estimates of retrofit package implementation costs (including the full costs of labor and equipment), as well as simple paybacks results (years) based on annual utility cost savings. Implementation costs

and resulting project paybacks are subject to many site-specific variables so the appendix cost and payback figures should be taken only as very general guidance. Specific savings results for each package should be reviewed to draw more definitive conclusions, but some patterns are evident in the simulation results though these do not hold for all cases:

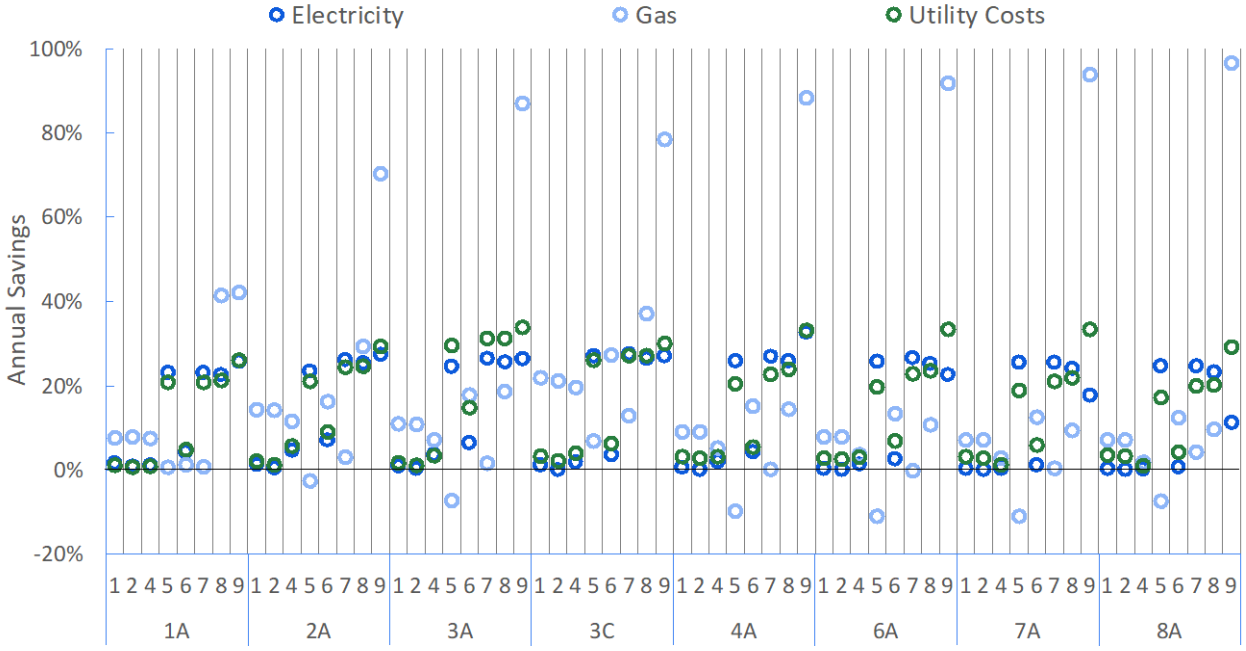
- Package numbering order (low to high) generally corresponds to level of retrofit intervention (e.g. more measures per package, more complexity in implementation), and the more involved packages tend to save more energy.
- In cooler climate zones with higher heating demands, the packages targeting heating equipment save more energy than the same packages in warmer climates.
- Particularly for warmer climate zones, with a higher proportion of electric energy usage relative to gas, utility cost savings tend to track closely with package electricity savings.
- Package 5 (HVAC controls, LEDs, IEQ) may hit a "sweet spot" in terms of savings relative to cost for many locations, evidenced by higher savings and better paybacks (see below) than similar package numbers, including high electricity savings in secondary schools, and in heating climates high gas savings in elementary schools. Package 5 does incur a gas penalty (increased usage) in secondary schools in most climate zones. This results from the LED retrofit that reduces internal heat gains. Packages 7, 8, and 9 also include LEDs but have net gas savings due to other gas-saving measures.
- Packages 8 and 9, which focus on electrifying energy end-uses, have the largest gas-savings impacts, from 20 - 30% gas savings in low-heating climate zones to up to 80 - 90% for climate zones that are heating dominant with significant gas usage. Electrification packages involve fuel-switching -- heating loads formerly met by gas are met by electricity – but there are still some electricity savings relative to baseline due to efficiency improvements in equipment and operation.
    - "Full electrification" Package 9 (all-electric space conditioning and water heating) has very large relative gas savings; in circumstances where that is a key decision driver, this package should be considered, though as the highest-intervention package it is also typically the costliest to implement.
    - For "partial electrification" Package 8, gas savings are dependent on HVAC equipment type and are lower in secondary schools (with boilers) and higher in elementary schools (with gas-fired RTUs).
- Packages 1 (BMS upgrade) and 3 (RTU) in elementary schools have higher electricity savings in warmer climates, and very little in cooler climates, and highest gas savings in medium-latitude climates, less savings in cool climates, and little in warm climates.
- The higher carbon intensity of source electric energy is reflected in CO_2 savings correlating with electricity savings, particularly for climate zones with less heating load. Utility cost savings also track quite closely to CO_2 savings for almost all packages.

- Package costs and paybacks:
    - Implementation costs for Packages 1 and 2 are the lowest, generally in the $100K range. Costs for Packages 3 and 4 are in the middle, generally $300K - $600K. Packages 5 - 9 implementation costs generally scale with package numbering, corresponding to more measures per package, from $300k - $2M in elementary schools to $600K - $3M or more in secondary schools.
    - Generally, paybacks are better in the secondary schools than in elementary schools due to higher baseline energy use and higher retrofit energy savings.
    - The higher-numbered, higher-cost packages still achieve paybacks under 10 years in many cases, particularly in mid-latitude climates with heating and cooling energy savings.
    - Package 5 consistently exhibits the best paybacks overall, with relatively lower implementation costs for the number of measures included (package does not include large equipment retrofits, other than the lighting replacement) and good energy savings. Package 1 is a lower-cost package with energy savings resulting in lower paybacks (under 10 years) in many locations, particularly in elementary schools. Package 7 (HVAC + Lighting + IEQ) paybacks are also under 10 years for many locations in secondary schools.
    - For some of the more complex packages (5, 7 - 9), package paybacks are relatively good in rural schools in the colder climate zones where heating fuel is generally more expensive relative to urban schools.
    - Package 6 includes envelope retrofits that are costly and does not include an LED retrofit (a high-savings measure), often leading to higher paybacks.

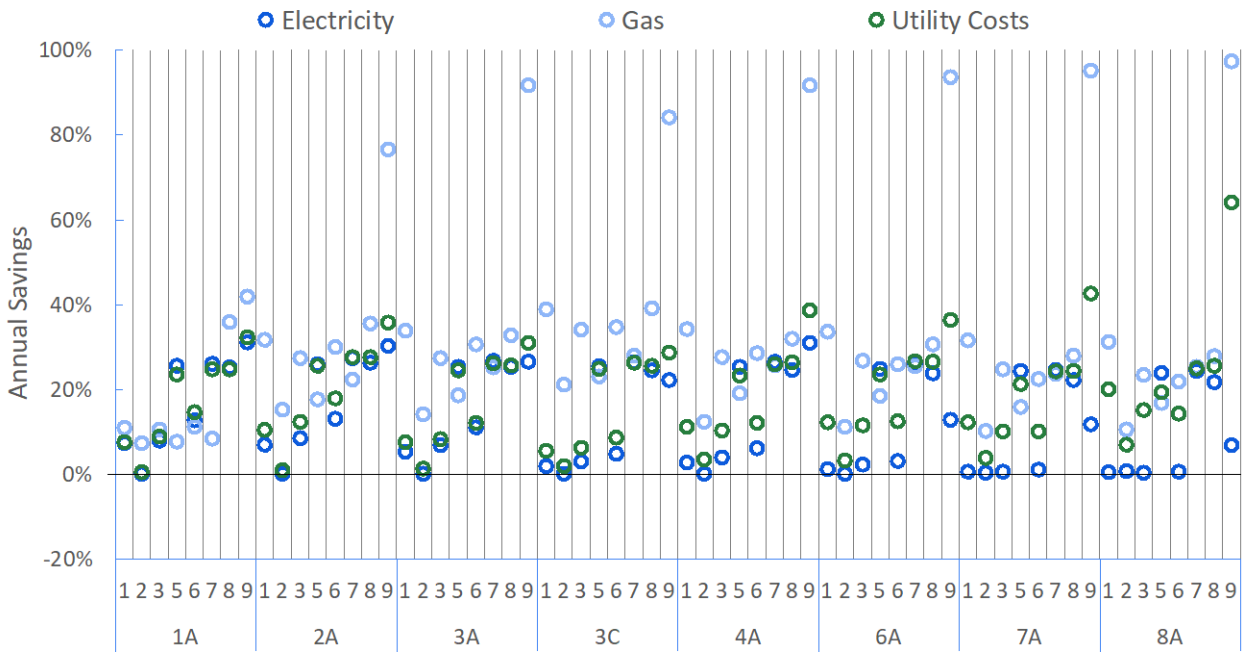
Summary Annual Electricity, Gas, and Cost Savings (%), Urban Elementary Schools



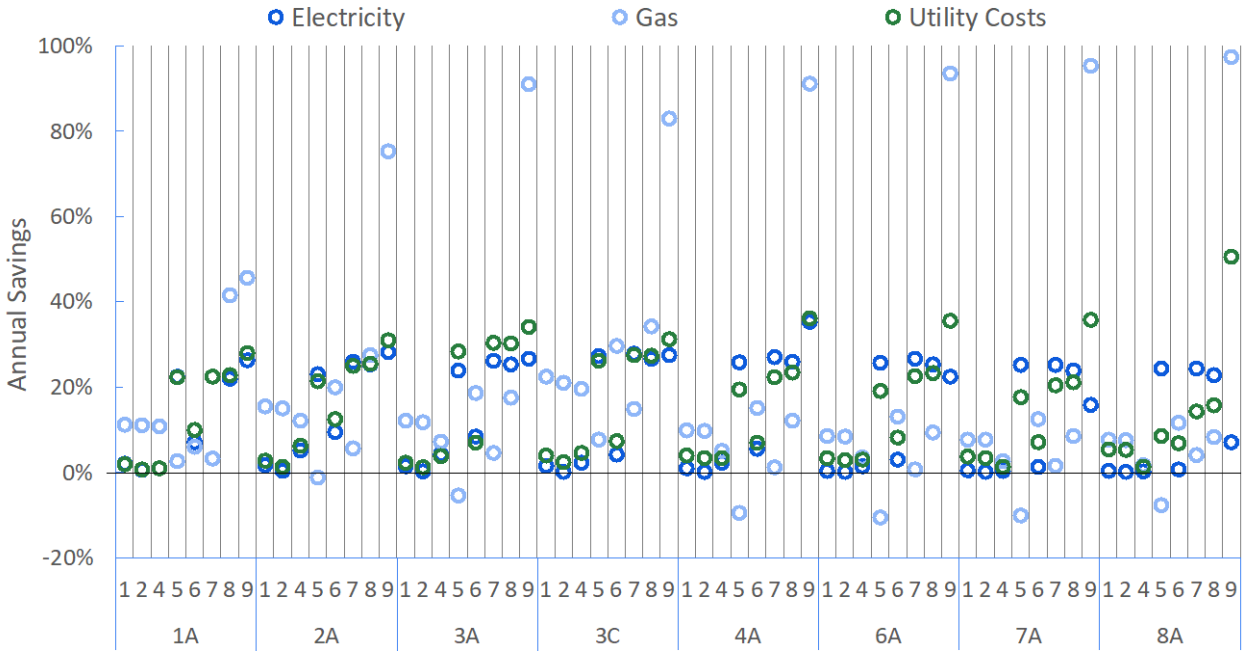
Summary Annual Electricity, Gas, and Cost Savings (%), Urban Secondary Schools



Summary Annual Electricity, Gas, and Cost Savings (%), Rural Elementary Schools

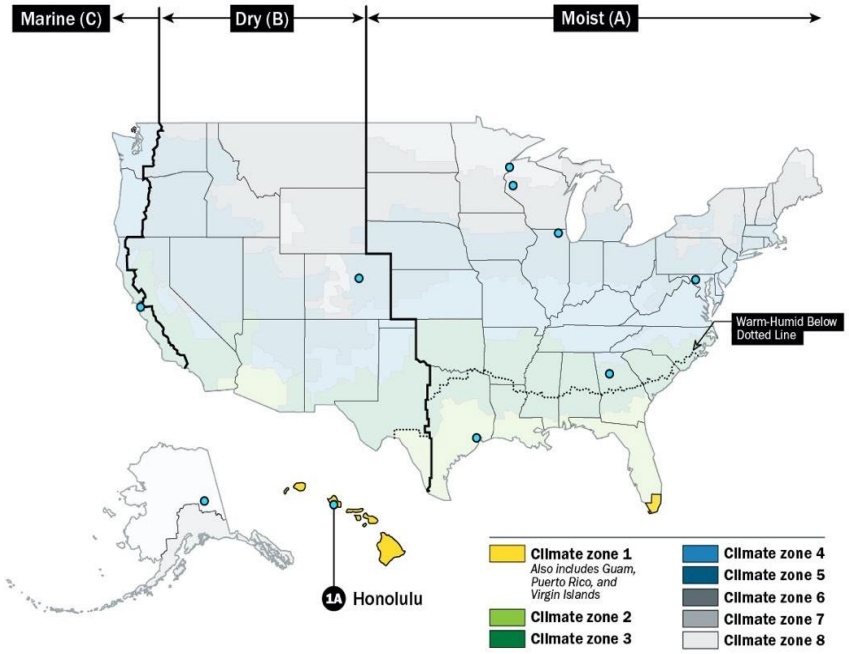


Summary Annual Electricity, Gas, and Cost Savings (%), Rural Secondary Schools



Savings Estimates per Climate Zone

Climate Zone 1A: Honolulu



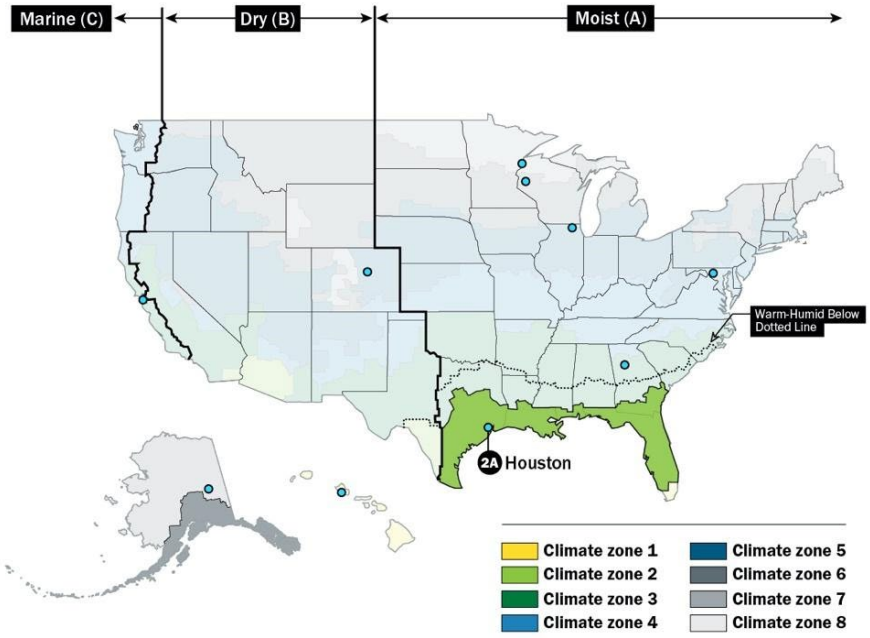
Annual Savings per Package for Urban Schools in Climate Zone 1A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	5.3%	4.9%	5.3%	4.8%	1.7%	7.7%	1.8%	1.1%
2. Boiler Replacement + Controls	0.2%	1.9%	0.2%	0.2%	0.9%	7.8%	1.0%	0.7%
3. RTU Replacement + Controls	6.2%	4.8%	6.2%	6.3%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				1.2%	7.5%	1.3%	0.9%
5. HVAC Controls + Lighting + IAQ	25.9%	4.1%	25.3%	23.5%	23.1%	0.7%	22.8%	20.8%
6. HVAC Equip + Controls, Envelope + IAQ	9.2%	4.8%	9.1%	10.0%	4.3%	1.2%	4.3%	4.8%
7. HVAC Equip + Controls, Lighting + IAQ	26.7%	4.2%	26.1%	24.8%	23.1%	0.8%	22.8%	20.8%
8. Partial Electrification + EE + IEQ	25.7%	34.3%	25.9%	24.8%	22.6%	41.5%	22.9%	21.2%
9. Full Electrification + EE + IEQ	29.6%	36.6%	29.8%	29.9%	25.8%	42.2%	26.1%	26.1%

Annual Savings per Package for Rural Schools in Climate Zone 1A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	7.3%	10.9%	7.4%	7.6%	2.1%	11.3%	2.3%	2.0%
2. Boiler Replacement + Controls	0.1%	7.3%	0.3%	0.4%	0.7%	11.1%	0.8%	0.8%
3. RTU Replacement + Controls	7.9%	10.6%	8.0%	8.8%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				1.1%	10.9%	1.2%	1.0%
5. HVAC Controls + Lighting + IAQ	25.5%	7.7%	25.1%	23.5%	22.5%	2.7%	22.2%	22.4%
6. HVAC Equip + Controls, Envelope + IAQ	12.8%	11.1%	12.7%	14.6%	7.1%	6.0%	7.1%	10.0%
7. HVAC Equip + Controls, Lighting + IAQ	26.0%	8.3%	25.6%	24.6%	22.5%	3.3%	22.2%	22.4%
8. Partial Electrification + EE + IEQ	25.2%	35.9%	25.4%	24.7%	22.1%	41.5%	22.4%	22.8%
9. Full Electrification + EE + IEQ	31.1%	41.9%	31.4%	32.3%	26.4%	45.7%	26.7%	28.0%

Climate Zone 2A: Houston



Annual Savings per Package for Urban Schools in Climate Zone 2A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	5.2%	29.4%	6.3%	8.4%	1.3%	14.3%	1.9%	2.1%
2. Boiler Replacement + Controls	0.1%	12.4%	0.7%	0.8%	0.5%	14.2%	1.1%	1.2%
3. RTU Replacement + Controls	6.9%	26.3%	7.8%	10.6%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				4.7%	11.6%	5.0%	5.7%
5. HVAC Controls + Lighting + IAQ	25.8%	18.1%	25.4%	25.2%	23.6%	-2.6%*	22.9%	21.0%
6. HVAC Equip + Controls, Envelope + IAQ	10.0%	27.3%	10.7%	14.7%	7.1%	16.3%	7.3%	9.0%
7. HVAC Equip + Controls, Lighting + IAQ	27.3%	21.3%	27.0%	27.4%	26.1%	3.1%	25.5%	24.4%
8. Partial Electrification + EE + IEQ	26.1%	37.9%	26.6%	27.4%	25.4%	29.4%	25.5%	24.7%
9. Full Electrification + EE + IEQ	28.7%	70.8%	30.6%	33.7%	27.4%	70.3%	28.5%	29.4%

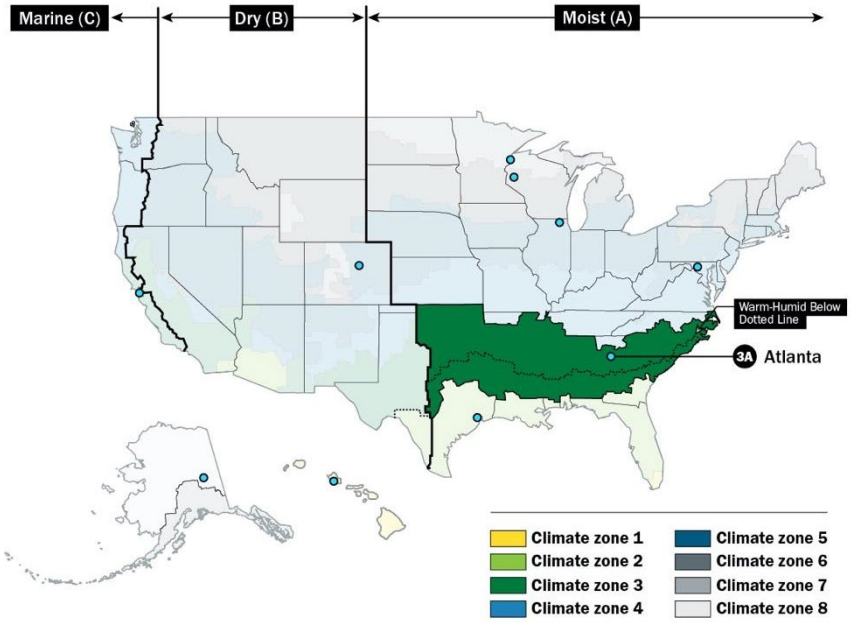
* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Annual Savings per Package for Rural Schools in Climate Zone 2A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	6.9%	31.6%	8.2%	10.5%	1.8%	15.6%	2.5%	2.8%
2. Boiler Replacement + Controls	0.1%	15.2%	0.9%	1.0%	0.4%	15.0%	1.2%	1.3%
3. RTU Replacement + Controls	8.6%	27.3%	9.5%	12.3%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				5.3%	12.1%	5.6%	6.3%
5. HVAC Controls + Lighting + IAQ	25.9%	17.6%	25.5%	25.5%	23.1%	-1.2%*	22.4%	21.4%
6. HVAC Equip + Controls, Envelope + IAQ	13.1%	30.0%	14.0%	17.8%	9.5%	20.0%	9.8%	12.6%
7. HVAC Equip + Controls, Lighting + IAQ	27.4%	22.3%	27.1%	27.6%	26.0%	5.7%	25.4%	25.0%
8. Partial Electrification + EE + IEQ	26.3%	35.5%	26.8%	27.6%	25.3%	27.6%	25.4%	25.4%
9. Full Electrification + EE + IEQ	30.2%	76.6%	32.6%	35.7%	28.2%	75.2%	29.6%	31.0%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Climate Zone 3A: Atlanta



Annual Savings per Package for Urban Schools in Climate Zone 3A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	4.0%	34.0%	7.1%	7.7%	1.0%	11.0%	2.2%	1.7%
2. Boiler Replacement + Controls	0.1%	12.4%	1.4%	0.9%	0.3%	10.9%	1.6%	1.2%
3. RTU Replacement + Controls	5.5%	28.8%	7.8%	6.8%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				3.7%	7.2%	4.1%	3.4%
5. HVAC Controls + Lighting + IAQ	25.5%	19.9%	24.9%	24.7%	24.5%	-7.3%*	22.7%	29.5%
6. HVAC Equip + Controls, Envelope + IAQ	8.5%	30.9%	10.8%	9.6%	6.5%	17.8%	7.1%	14.8%
7. HVAC Equip + Controls, Lighting + IAQ	26.8%	25.1%	26.6%	26.2%	26.5%	1.6%	25.0%	31.3%
8. Partial Electrification + EE + IEQ	25.3%	35.2%	26.3%	25.6%	25.6%	18.7%	25.2%	31.2%
9. Full Electrification + EE + IEQ	25.6%	87.6%	31.6%	28.9%	26.4%	87.0%	29.8%	33.9%

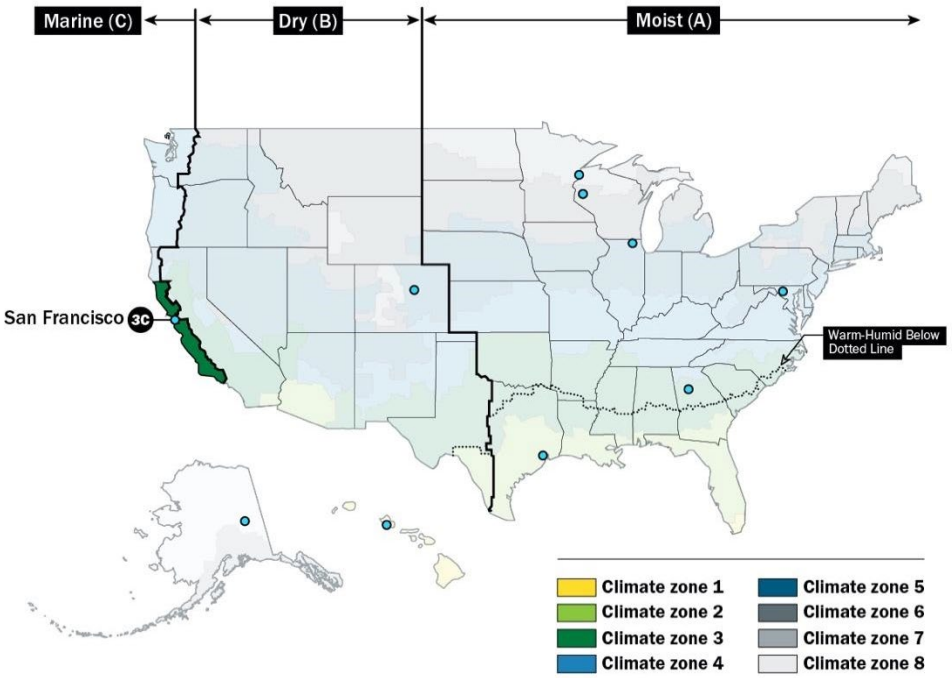
* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Annual Savings per Package for Rural Schools in Climate Zone 3A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	5.3%	33.8%	8.9%	7.5%	1.5%	12.2%	3.0%	2.3%
2. Boiler Replacement + Controls	0.1%	14.1%	1.9%	1.3%	0.3%	11.9%	1.9%	1.3%
3. RTU Replacement + Controls	6.8%	27.4%	9.4%	8.3%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				4.3%	7.3%	4.7%	3.9%
5. HVAC Controls + Lighting + IAQ	25.3%	18.6%	24.5%	24.4%	23.9%	-5.3%*	21.8%	28.3%
6. HVAC Equip + Controls, Envelope + IAQ	11.1%	30.6%	13.5%	12.2%	8.5%	18.7%	9.2%	7.1%
7. HVAC Equip + Controls, Lighting + IAQ	26.8%	25.2%	26.6%	26.2%	26.2%	4.6%	24.6%	30.4%
8. Partial Electrification + EE + IEQ	25.4%	32.7%	26.3%	25.7%	25.4%	17.5%	24.8%	30.3%
9. Full Electrification + EE + IEQ	26.5%	91.6%	34.3%	31.0%	26.6%	91.0%	31.0%	34.1%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Climate Zone 3C: San Francisco



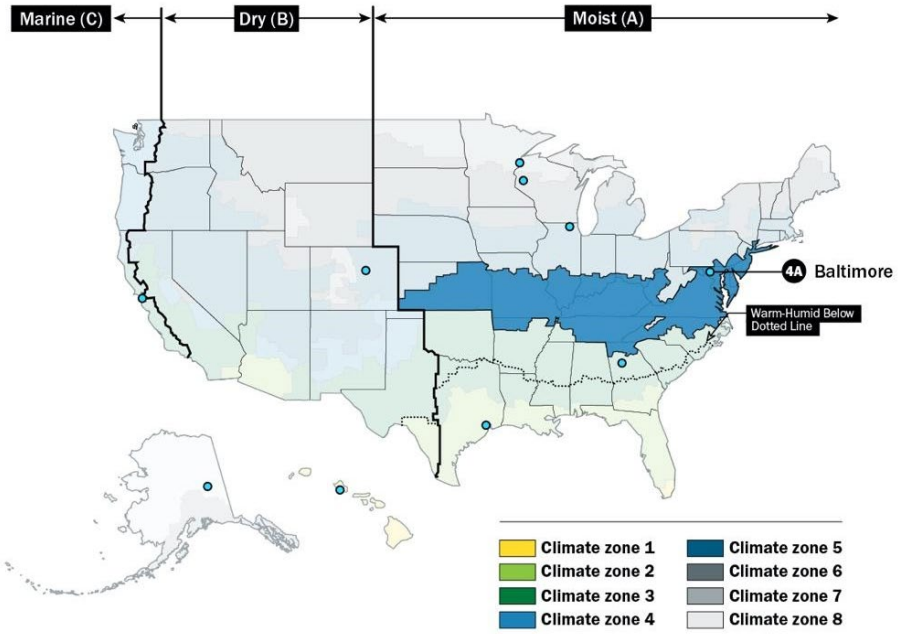
Annual Savings per Package for Urban Schools in Climate Zone 3C

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	1.4%	39.5%	9.0%	4.5%	1.2%	21.8%	6.1%	3.3%
2. Boiler Replacement + Controls	0.1%	20.3%	4.1%	1.6%	0.1%	21.2%	5.2%	2.2%
3. RTU Replacement + Controls	2.3%	35.7%	9.0%	5.2%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				2.0%	19.6%	6.2%	4.1%
5. HVAC Controls + Lighting + IAQ	25.1%	25.5%	25.2%	24.8%	27.1%	6.9%	24.8%	26.1%
6. HVAC Equip + Controls, Envelope + IAQ	3.8%	36.1%	10.3%	7.3%	3.6%	27.3%	6.4%	6.2%
7. HVAC Equip + Controls, Lighting + IAQ	26.0%	29.2%	26.6%	26.0%	27.6%	12.9%	25.9%	27.2%
8. Partial Electrification + EE + IEQ	24.1%	42.5%	27.7%	25.3%	26.5%	37.2%	27.7%	27.1%
9. Full Electrification + EE + IEQ	21.8%	81.2%	33.6%	27.3%	27.2%	78.5%	33.1%	30.0%

Annual Savings per Package for Rural Schools in Climate Zone 3C

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	1.9%	38.9%	10.2%	5.5%	1.6%	22.5%	4.1%	7.1%
2. Boiler Replacement + Controls	0.1%	21.1%	4.9%	2.0%	0.1%	21.1%	2.6%	5.7%
3. RTU Replacement + Controls	3.0%	34.1%	10.0%	6.2%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				2.3%	19.6%	6.9%	4.6%
5. HVAC Controls + Lighting + IAQ	25.4%	23.0%	24.8%	24.8%	27.2%	7.8%	24.5%	26.2%
6. HVAC Equip + Controls, Envelope + IAQ	4.8%	34.7%	11.6%	8.6%	4.2%	29.6%	7.8%	7.4%
7. HVAC Equip + Controls, Lighting + IAQ	26.4%	27.9%	26.7%	26.3%	27.9%	14.9%	26.1%	27.5%
8. Partial Electrification + EE + IEQ	24.5%	39.1%	27.8%	25.6%	26.7%	34.2%	27.8%	27.4%
9. Full Electrification + EE + IEQ	22.2%	84.1%	36.2%	28.7%	27.5%	82.9%	35.3%	31.2%

Climate Zone 4A: Baltimore



Annual Savings per Package for Urban Schools in Climate Zone 4A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	2.5%	34.8%	7.5%	10.4%	0.8%	9.3%	2.6%	3.0%
2. Boiler Replacement + Controls	0.1%	11.2%	1.8%	2.4%	0.2%	9.3%	2.0%	2.7%
3. RTU Replacement + Controls	3.7%	29.4%	7.6%	10.8%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				2.6%	5.5%	3.2%	4.3%
5. HVAC Controls + Lighting + IAQ	25.4%	20.6%	24.6%	24.2%	25.9%	-9.1%*	22.8%	20.5%
6. HVAC Equip + Controls, Envelope + IAQ	5.4%	29.8%	9.1%	12.8%	5.3%	15.9%	6.3%	8.9%
7. HVAC Equip + Controls, Lighting + IAQ	26.4%	25.9%	26.4%	26.6%	27.3%	0.6%	24.9%	23.7%
8. Partial Electrification + EE + IEQ	24.7%	34.8%	26.2%	27.2%	26.3%	15.7%	25.3%	24.8%
9. Full Electrification + EE + IEQ	28.3%	87.6%	31.8%	37.1%	30.8%	87.0%	31.1%	34.0%

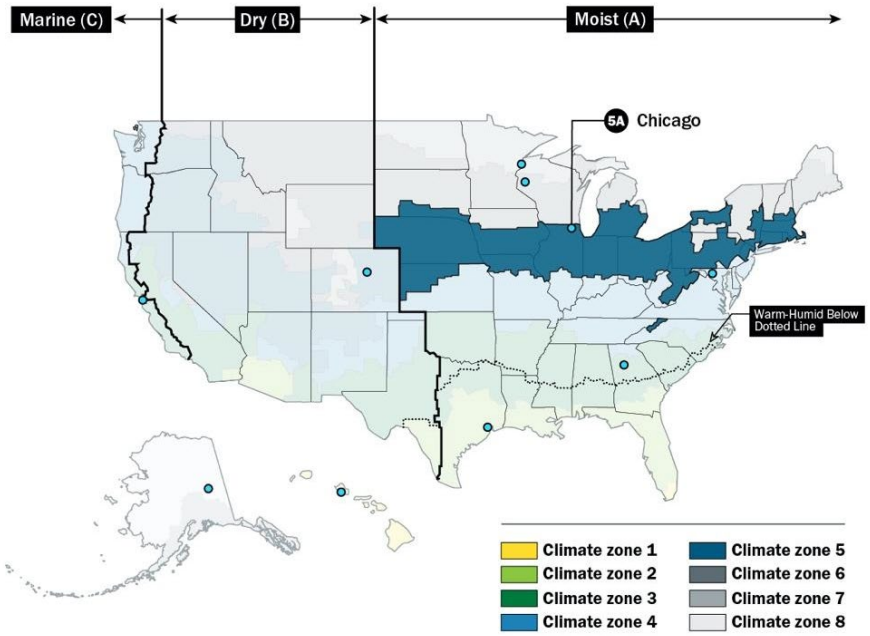
* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Annual Savings per Package for Rural Schools in Climate Zone 4A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	3.8%	34.4%	10.0%	13.2%	1.5%	10.7%	3.6%	4.2%
2. Boiler Replacement + Controls	0.1%	13.0%	2.8%	3.6%	0.2%	10.4%	2.6%	3.4%
3. RTU Replacement + Controls	5.1%	27.6%	9.7%	13.0%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				3.2%	5.4%	3.7%	4.9%
5. HVAC Controls + Lighting + IAQ	25.4%	19.7%	24.2%	23.6%	25.6%	-7.4%*	21.6%	20.6%
6. HVAC Equip + Controls, Envelope + IAQ	7.9%	30.2%	12.4%	16.3%	7.4%	16.5%	8.5%	12.7%
7. HVAC Equip + Controls, Lighting + IAQ	26.6%	26.6%	26.6%	26.8%	27.2%	3.3%	24.4%	24.5%
8. Partial Electrification + EE + IEQ	24.9%	32.6%	26.5%	27.3%	26.3%	13.7%	24.8%	25.5%
9. Full Electrification + EE + IEQ	30.0%	91.6%	36.4%	42.7%	31.8%	91.0%	33.6%	38.0%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Climate Zone 5A: Chicago



Annual Savings per Package for Urban Schools in Climate Zone 5A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	1.9%	33.1%	5.5%	6.8%	0.6%	8.4%	1.9%	2.8%
2. Boiler Replacement + Controls	0.1%	10.7%	1.3%	2.3%	0.1%	8.3%	1.4%	2.4%
3. RTU Replacement + Controls	3.0%	26.8%	5.8%	5.8%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				2.1%	3.9%	2.4%	1.9%
5. HVAC Controls + Lighting + IAQ	25.1%	18.4%	24.3%	23.2%	25.8%	-9.6%*	23.3%	20.6%
6. HVAC Equip + Controls, Envelope + IAQ	4.0%	26.5%	6.6%	6.2%	4.2%	14.6%	4.9%	2.1%
7. HVAC Equip + Controls, Lighting + IAQ	26.2%	24.6%	26.0%	24.9%	27.0%	1.0%	25.1%	22.4%
8. Partial Electrification + EE + IEQ	24.2%	31.3%	25.0%	24.7%	25.9%	12.0%	24.9%	22.9%
9. Full Electrification + EE + IEQ	26.2%	91.3%	25.2%	30.1%	32.2%	91.2%	28.8%	31.7%

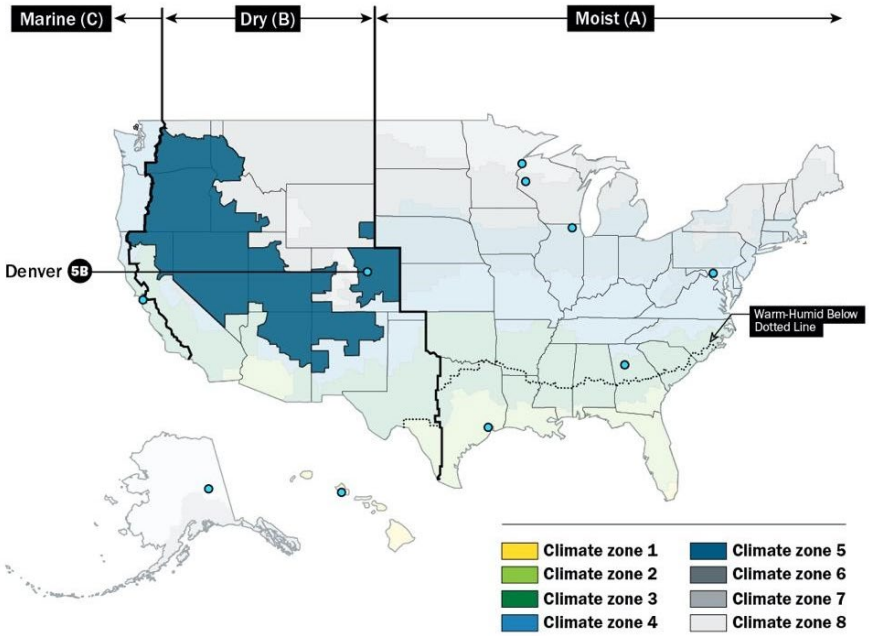
* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Annual Savings per Package for Rural Schools in Climate Zone 5A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	2.5%	33.8%	6.8%	8.4%	0.8%	8.9%	2.2%	3.3%
2. Boiler Replacement + Controls	0.1%	11.5%	1.7%	2.9%	0.2%	8.8%	1.7%	2.9%
3. RTU Replacement + Controls	3.6%	26.8%	6.8%	7.0%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				2.3%	3.8%	2.6%	2.0%
5. HVAC Controls + Lighting + IAQ	25.3%	19.4%	24.5%	23.2%	25.8%	-9.8%*	22.9%	19.2%
6. HVAC Equip + Controls, Envelope + IAQ	5.4%	28.0%	8.5%	8.0%	5.1%	13.8%	5.8%	2.0%
7. HVAC Equip + Controls, Lighting + IAQ	26.5%	26.2%	26.4%	25.3%	27.0%	1.3%	24.9%	21.3%
8. Partial Electrification + EE + IEQ	24.5%	31.5%	25.5%	25.2%	26.0%	10.3%	24.7%	21.6%
9. Full Electrification + EE + IEQ	30.0%	93.0%	27.1%	33.1%	35.7%	92.8%	30.0%	33.6%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Climate Zone 5B: Denver



Annual Savings per Package for Urban Schools in Climate Zone 5B

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	1.5%	34.1%	4.9%	9.8%	0.4%	9.6%	1.9%	3.7%
2. Boiler Replacement + Controls	0.1%	11.2%	1.3%	2.9%	0.1%	9.6%	1.6%	3.6%
3. RTU Replacement + Controls	2.6%	29.0%	5.4%	9.3%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				1.4%	6.3%	2.2%	3.2%
5. HVAC Controls + Lighting + IAQ	25.2%	17.4%	24.4%	23.1%	26.1%	-10.5%*	23.8%	20.1%
6. HVAC Equip + Controls, Envelope + IAQ	3.6%	26.7%	6.0%	9.5%	3.3%	15.0%	4.0%	5.2%
7. HVAC Equip + Controls, Lighting + IAQ	26.2%	22.7%	25.8%	25.1%	26.8%	-1.0%*	25.1%	22.2%
8. Partial Electrification + EE + IEQ	24.1%	32.5%	25.0%	26.2%	25.7%	15.7%	25.0%	24.1%
9. Full Electrification + EE + IEQ	29.7%	87.2%	25.5%	35.7%	35.1%	86.7%	27.7%	34.0%

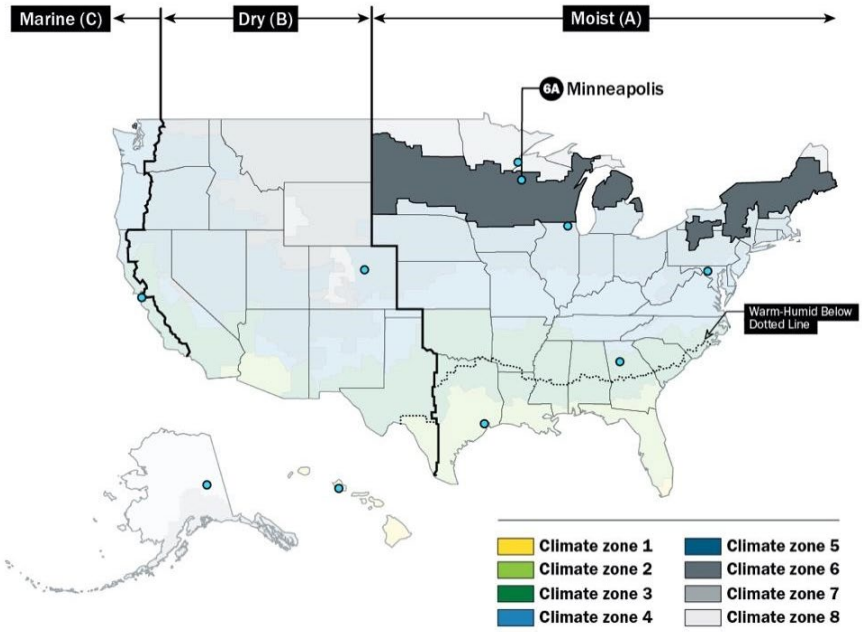
* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Annual Savings per Package for Rural Schools in Climate Zone 5B

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	1.9%	34.4%	6.2%	11.9%	0.6%	10.2%	2.3%	4.4%
2. Boiler Replacement + Controls	0.1%	12.4%	1.8%	3.9%	0.2%	10.1%	1.9%	4.1%
3. RTU Replacement + Controls	3.1%	28.3%	6.5%	10.9%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				1.7%	6.0%	2.4%	3.4%
5. HVAC Controls + Lighting + IAQ	25.3%	18.0%	24.3%	23.0%	26.1%	-11.2%*	23.2%	18.7%
6. HVAC Equip + Controls, Envelope + IAQ	5.2%	27.5%	8.1%	12.0%	4.4%	15.2%	5.3%	6.5%
7. HVAC Equip + Controls, Lighting + IAQ	26.4%	24.2%	26.1%	25.6%	26.9%	-0.7%*	24.8%	21.4%
8. Partial Electrification + EE + IEQ	24.4%	31.7%	25.4%	26.6%	25.8%	12.4%	24.7%	23.2%
9. Full Electrification + EE + IEQ	33.0%	90.2%	27.7%	40.1%	38.4%	89.5%	29.2%	36.9%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Climate Zone 6A: Minneapolis



Annual Savings per Package for Urban Schools in Climate Zone 6A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	1.0%	33.0%	7.0%	10.1%	0.3%	7.9%	2.3%	2.9%
2. Boiler Replacement + Controls	0.1%	10.2%	2.0%	2.5%	0.1%	7.8%	2.2%	2.5%
3. RTU Replacement + Controls	1.9%	26.7%	6.5%	9.8%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				1.4%	3.7%	2.0%	3.0%
5. HVAC Controls + Lighting + IAQ	24.7%	17.6%	23.4%	23.2%	25.8%	-11.0%*	21.4%	19.7%
6. HVAC Equip + Controls, Envelope + IAQ	2.3%	25.3%	6.7%	10.2%	2.6%	13.4%	3.9%	7.0%
7. HVAC Equip + Controls, Lighting + IAQ	25.6%	24.0%	25.3%	25.9%	26.6%	-0.2%*	23.4%	22.8%
8. Partial Electrification + EE + IEQ	23.4%	30.5%	24.8%	25.9%	25.4%	10.7%	23.6%	23.6%
9. Full Electrification + EE + IEQ	13.5%	92.0%	28.3%	32.6%	22.7%	91.9%	30.9%	33.4%

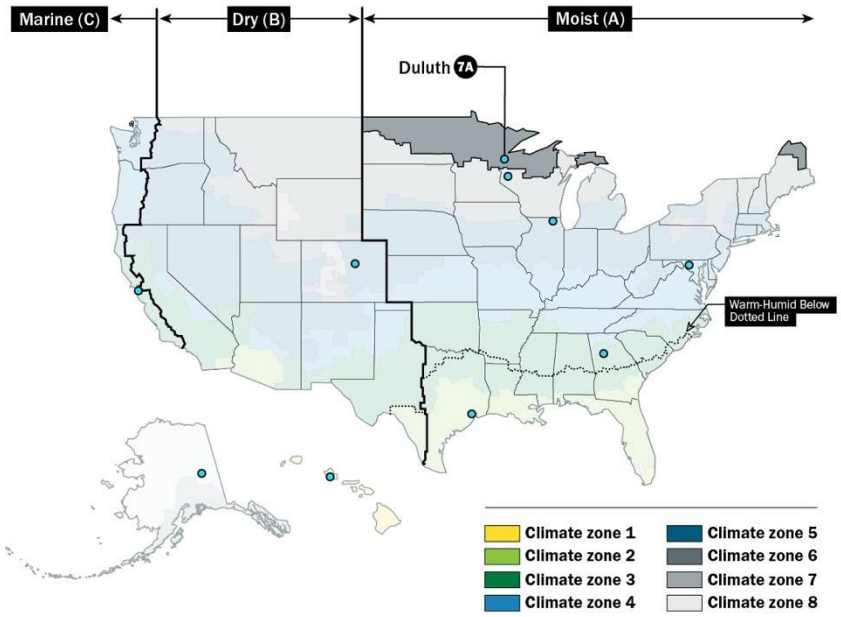
* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Annual Savings per Package for Rural Schools in Climate Zone 6A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	1.2%	33.6%	8.6%	12.2%	0.4%	8.5%	2.8%	3.4%
2. Boiler Replacement + Controls	0.2%	11.1%	2.6%	3.2%	0.1%	8.4%	2.6%	3.0%
3. RTU Replacement + Controls	2.2%	26.7%	7.8%	11.5%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				1.6%	3.5%	2.1%	3.1%
5. HVAC Controls + Lighting + IAQ	24.8%	18.5%	23.4%	23.5%	25.8%	-10.5%*	20.5%	19.2%
6. HVAC Equip + Controls, Envelope + IAQ	3.1%	25.9%	8.2%	12.4%	3.1%	13.2%	4.5%	8.2%
7. HVAC Equip + Controls, Lighting + IAQ	25.9%	25.4%	25.8%	26.6%	26.6%	0.8%	22.9%	22.7%
8. Partial Electrification + EE + IEQ	23.7%	30.6%	25.2%	26.5%	25.4%	9.4%	23.1%	23.3%
9. Full Electrification + EE + IEQ	12.8%	93.6%	31.0%	36.3%	22.5%	93.6%	32.8%	35.6%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Climate Zone 7A: Duluth



Annual Savings per Package for Urban Schools in Climate Zone 7A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	0.4%	30.9%	7.6%	10.3%	0.4%	7.1%	2.6%	3.1%
2. Boiler Replacement + Controls	0.3%	9.5%	2.4%	3.1%	0.1%	7.1%	2.4%	2.8%
3. RTU Replacement + Controls	0.4%	24.6%	6.1%	8.6%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				0.3%	2.8%	1.1%	1.3%
5. HVAC Controls + Lighting + IAQ	24.2%	15.1%	22.0%	21.4%	25.5%	-11.0%*	19.8%	18.8%
6. HVAC Equip + Controls, Envelope + IAQ	0.7%	23.0%	6.0%	8.5%	1.2%	12.5%	3.0%	6.0%
7. HVAC Equip + Controls, Lighting + IAQ	24.5%	22.5%	24.0%	23.9%	25.5%	0.4%	21.6%	21.0%
8. Partial Electrification + EE + IEQ	22.0%	27.9%	23.4%	24.0%	24.2%	9.4%	21.9%	21.9%
9. Full Electrification + EE + IEQ	12.9%	93.8%	32.0%	38.1%	17.8%	93.9%	29.6%	33.4%

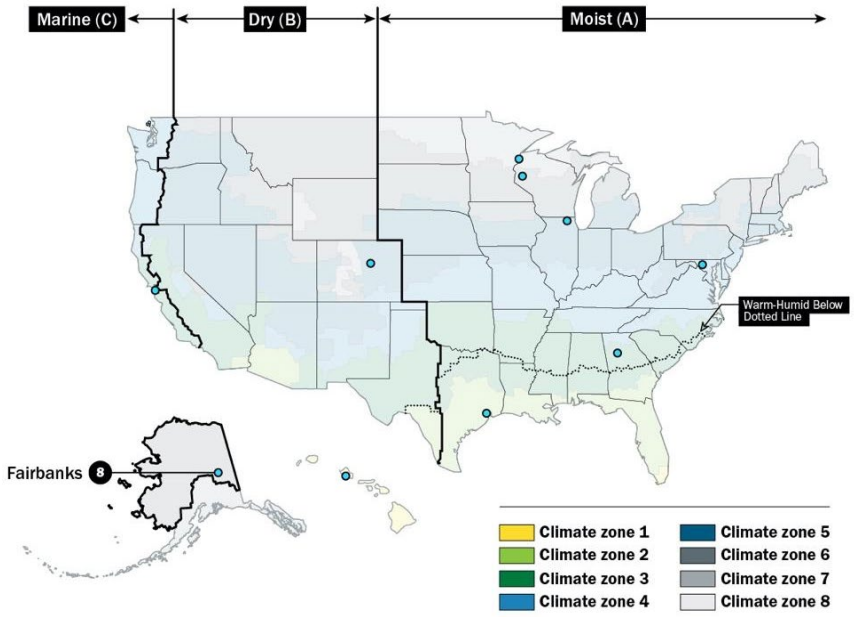
* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Annual Savings per Package for Rural Schools in Climate Zone 7A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	0.6%	31.5%	9.4%	12.3%	0.5%	7.7%	3.1%	3.8%
2. Boiler Replacement + Controls	0.4%	10.2%	3.2%	3.8%	0.1%	7.7%	2.8%	3.4%
3. RTU Replacement + Controls	0.5%	24.7%	7.4%	10.0%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				0.4%	2.7%	1.2%	1.4%
5. HVAC Controls + Lighting + IAQ	24.3%	15.8%	21.9%	21.2%	25.3%	-10.0%*	18.5%	17.7%
6. HVAC Equip + Controls, Envelope + IAQ	1.0%	22.5%	7.1%	10.1%	1.4%	12.6%	3.6%	7.1%
7. HVAC Equip + Controls, Lighting + IAQ	24.6%	23.7%	24.4%	24.3%	25.3%	1.7%	20.7%	20.5%
8. Partial Electrification + EE + IEQ	22.2%	27.9%	23.8%	24.4%	23.9%	8.5%	20.9%	21.2%
9. Full Electrification + EE + IEQ	11.7%	95.2%	35.4%	42.6%	15.9%	95.3%	31.2%	35.8%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Climate Zone 8A: Fairbanks



Annual Savings per Package for Urban Schools in Climate Zone 8A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	0.2%	30.8%	12.0%	10.7%	0.4%	7.2%	3.6%	3.5%
2. Boiler Replacement + Controls	0.5%	10.0%	4.2%	3.8%	0.1%	7.2%	3.5%	3.3%
3. RTU Replacement + Controls	0.2%	23.4%	9.1%	8.3%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				0.2%	1.8%	1.0%	1.0%
5. HVAC Controls + Lighting + IAQ	23.8%	17.1%	21.3%	21.4%	24.7%	-7.4%*	15.8%	17.2%
6. HVAC Equip + Controls, Envelope + IAQ	0.4%	23.1%	9.1%	8.4%	0.7%	12.4%	3.9%	4.2%
7. HVAC Equip + Controls, Lighting + IAQ	24.3%	25.2%	24.6%	24.5%	24.7%	4.3%	19.1%	19.9%
8. Partial Electrification + EE + IEQ	21.6%	28.4%	24.2%	23.9%	23.3%	9.6%	19.5%	20.2%
9. Full Electrification + EE + IEQ	8.7%	96.6%	42.5%	38.3%	11.2%	96.7%	34.9%	29.3%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Annual Savings per Package for Rural Schools in Climate Zone 8A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO_2	Cost	Elec	Gas	CO_2	Cost
1. BMS Replacement	0.4%	31.2%	14.1%	20.0%	0.4%	7.7%	4.1%	5.5%
2. Boiler Replacement + Controls	0.7%	10.6%	5.1%	7.0%	0.2%	7.6%	4.0%	5.4%
3. RTU Replacement + Controls	0.4%	23.4%	10.6%	15.1%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement + Controls	n/a (no chiller in elementary school model)				0.3%	1.8%	1.0%	1.3%
5. HVAC Controls + Lighting + IAQ	23.8%	16.8%	20.7%	19.4%	24.4%	-7.7%*	14.1%	8.5%
6. HVAC Equip + Controls, Envelope + IAQ	0.6%	21.8%	24.8%	14.3%	0.8%	11.7%	4.3%	6.9%
7. HVAC Equip + Controls, Lighting + IAQ	24.3%	25.3%	24.8%	25.0%	24.4%	4.1%	17.9%	14.4%
8. Partial Electrification + EE + IEQ	21.7%	27.9%	24.4%	25.6%	22.9%	8.3%	18.2%	15.8%
9. Full Electrification + EE + IEQ	6.8%	97.3%	47.1%	64.0%	7.1%	97.3%	36.1%	50.6%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Appendix A: References and Resources

(includes works referenced in Appendices)

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Appendix B: Additional Elementary School Packages with IAQ Benefits

Through the DOE-sponsored Beyond Widgets program, and working with utility partners in two regions of the U.S., LBNL developed additional retrofit packages for elementary schools, combining efficiency measures capable of delivering energy savings and improving IAQ, with the aim of improving cost-effectiveness and energy impact relative to performance of individual retrofit measures. These additional integrated system packages were modeled for elementary schools in two locations – San Jose, California and Charlotte, North Carolina. Energy savings were calculated from whole building annual energy simulations as done for Packages 1 – 9 and described in Section 1.

The additional IAQ retrofit packages, Packages 10 – 18, are summarized in Table A1 below. The retrofit measures included in these packages are described in more detail in Appendix F. Efficiency measures include LED lighting, HVAC equipment upgrades like replacing RTUs with air source heat pumps (ASHPs), adding energy recovery ventilators (ERVs) to air handlers, and replacing fan motors with premium efficiency motors. Along with IAQ measures similar to those in the prior packages, like outside air filter upgrades and CO_2 based demand control ventilation, EE measures with IAQ and/or comfort impacts include:

- Economizer retuning to fix faulty operation and adjust outside air temperature cut-off setpoint to bring in more ventilation air when effective for providing space cooling
- Select ASHRAE Guideline 36 measures to ventilate well while avoiding overcooling:
    - VAV terminal unit minimum flow retuning
    - Economizer control based on differential dry bulb temperature
    - Supply air temperature trim and respond
    - Standby heating and cooling setpoint setbacks based on occupant sensors
- Relief damper control to maintain neutral to positive building pressure, reducing infiltration, outdoor pollutants (energy impact not modeled due to software limitations)

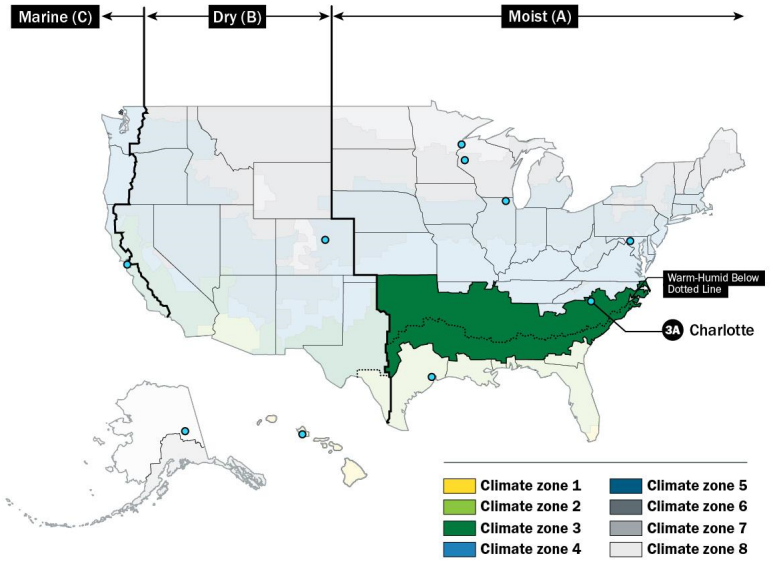
A few important distinctions between these additional packages and the original set are that these were only developed and modeled for elementary schools (package measures are applicable to the elementary school model's HVAC systems and building configuration), and were only modeled for two climate zones representative of utility partner service territories (3A and 3C). Finally, the reference model building condition for the original package simulations was post-1980 existing building, as described previously, while the additional packages discussed here were simulated in the pre-1980 reference elementary school model, per direction from partners that this vintage was most representative of existing building conditions in their territories. The building geometry is identical to the post-1980 existing building model as are mechanical equipment types, but system efficiencies as well as envelope performance differ slightly, reflecting the performance of an older existing building vintage. Similar to the

models for the original package simulations, baseline lighting system performance was set to the ASHRAE 90.1 2004 model performance levels, consistent with T-8 fluorescent technology.

Table A1. Description of Measures per Package in Additional IAQ Retrofit Packages

Package	Description
10. Efficient lighting (LEDs + Controls)	LED retrofit (50% reduction in lighting power density, or LPD) with occupancy sensing, daylight controls
11. LED upgrade (no controls changes) and ventilation	LED retrofit (without lighting controls changes), CO_2 sensors and DCV, outdoor air scheduling, MERV 14 filters
12. Efficient lighting and ventilation	LEDs with occ. sensing, daylight controls, CO_2 sensors and DCV, outside air scheduling, MERV 14 filters
13. Efficient lighting, ventilation, economizer	LEDs with occ. sensing, daylight controls, CO_2 sensors and DCV, retune economizer, outside air scheduling, MERV 14 filters
14. Efficient lighting, ventilation, Guideline 36, relief air damper	LEDs with occ. sensing, daylight controls, CO_2 sensors and DCV, G36 VAV min. retune, G36 economizer, outside air scheduling, MERV 14 filters, relief damper control
15. Efficient lighting, ventilation, Guideline 36, relief air damper and efficient fan motors	LEDs with occ. sensing, daylight controls, CO_2 sensors and DCV, G36 VAV min. retune, G36 economizer, outside air scheduling, MERV 14 filters, relief damper control, fan motor replacement (upgrade to premium efficiency)
16. Efficient lighting, ventilation, Guideline 36, relief air damper and ERV	LEDs with occ. sensing, daylight controls, CO_2 sensors and DCV, G36 VAV min. retune, G36 economizer, outside air scheduling, MERV 14 filters, relief damper control, ERV on air handlers
17. Efficient lighting, ventilation, Guideline 36+, relief air damper and AHSP	LEDs with occ. sensing, daylight controls, CO_2 sensors and DCV, G36 VAV min. retune, G36 economizer, G36 occ. standby, G36 supply air temperature (SAT) trim and respond, G36 optimal start, outside air scheduling, , MERV 14 filters, relief damper control, replace RTUs with ASHP
18. Efficient lighting, ventilation, Guideline 36+, relief air damper, ASHP and ERV	LEDs with occ. sensing, daylight controls, CO_2 sensors and DCV, G36 VAV min. retune, G36 economizer, G36 occ. standby, G36 SAT trim and respond, G36 optimal start, outside air scheduling, MERV 14 filters, relief damper control, ASHPs and ERVs

Climate Zone 3A: Charlotte

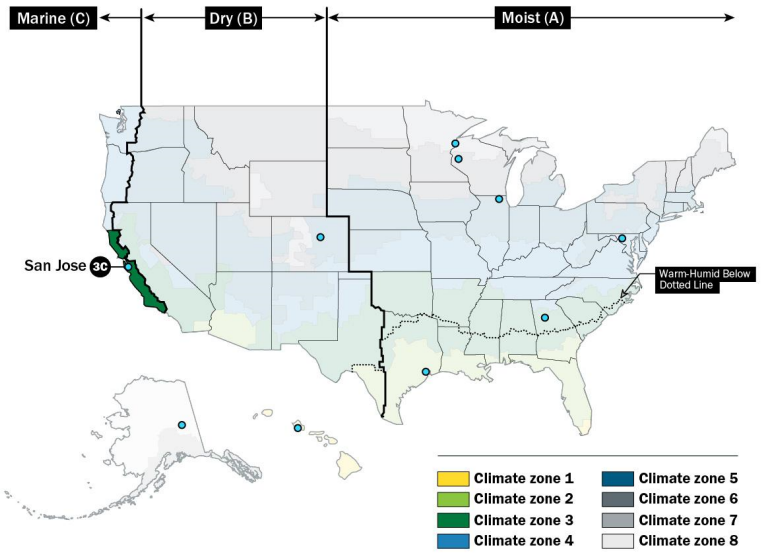


Electricity, Gas, and CO_2 Savings per Package for Climate Zone 3A in Urban Schools

Retrofit Package	Elementary School Annual Savings			
	Elec	Gas	CO2	Cost
10. Efficient lighting (LEDs + Controls)	23.0%	-7.1%*	19.5%	15.0%
11. LED upgrade (no controls) and ventilation	18.2%	10.4%	17.3%	15.5%
12. Efficient lighting and ventilation	24.3%	9.9%	22.6%	20.0%
13. Efficient lighting, ventilation, economizer	24.4%	9.9%	22.7%	20.1%
14. Efficient lighting, ventilation, Guideline 36, relief damper	27.7%	33.0%	28.3%	27.0%
15. Efficient lighting, ventilation, Guideline 36, relief damper, motors	27.7%	33.0%	28.4%	27.1%
16. Efficient lighting, ventilation, Guideline 36, relief damper, ERV	29.5%	36.9%	30.5%	30.1%
17. Efficient lighting, ventilation, Guideline 36+, relief damper, AHSP	27.3%	46.6%	29.7%	30.9%
18. Efficient lighting, ventilation, Guideline 36+, damper, ASHP, ERV	30.9%	46.6%	33.0%	34.3%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Climate Zone 3C: San Jose



Electricity, Gas, and CO_2 Savings per Package for Climate Zone 3C in Urban Schools

Retrofit Package	Elementary School Annual Savings			
	Elec	Gas	CO2	Cost
10. Efficient lighting (LEDs + Controls)	25.5%	-9.4%*	20.1%	22.5%
11. LED upgrade (no controls) and ventilation	18.4%	7.8%	16.8%	16.9%
12. Efficient lighting and ventilation	25.1%	6.4%	22.2%	23.2%
13. Efficient lighting, ventilation, economizer	25.7%	6.4%	22.8%	23.8%
14. Efficient lighting, ventilation, Guideline 36, relief damper	28.6%	33.2%	29.3%	27.5%
15. Efficient lighting, ventilation, Guideline 36, relief damper, motors	28.6%	33.2%	29.4%	27.5%
16. Efficient lighting, ventilation, Guideline 36, relief damper, ERV	28.9%	34.7%	29.8%	28.6%
17. Efficient lighting, ventilation, Guideline 36+, relief damper, AHSP	28.9%	48.1%	32.0%	30.0%
18. Efficient lighting, ventilation, Guideline 36+, damper, ASHP, ERV	30.2%	48.1%	33.1%	31.5%

* Slight heating penalty (i.e. increased heating energy) is associated with the lighting efficiency upgrade which results in reduced heat gains indoors.

Appendix C: Project Measurement and Verification for Energy and GHG Savings

The following sections outline methods, assumptions and analyses that can be used to measure and verify energy and emissions savings from the implementation of the retrofit packages.

Energy Reduction Measurement and Verification

To assess the overall energy efficiency benefits of the project, a school or district should assess energy impacts over a 12-month period, using pre-retrofit energy consumption data and comparing it to post-retrofit consumption. A school or district should collect at least one year of pre-retrofit utility bill data, including quantities of energy consumed and energy cost for the school. A school or district should use building level energy data where this is available, but should only campus level energy data exist, this will be accepted for measurement and verification purposes. A school or district may choose to further submeter their building, end use systems, or individual measures (e.g., photovoltaic system) to understand the energy performance of key systems or equipment.

Energy impacts should be measured and evaluated separately for each fuel source (e.g., electricity [kWh] and natural gas [therms]) where applicable. Absolute and relative energy impacts should be reported. Renewable generation is excluded from the energy efficiency metric calculation, as is electric vehicle charging. Energy impact should be reported for electricity (kWh), natural gas (therms), other fuels (kBTU), and a combined total (kBtu).

The building energy efficiency measurement & verification (M&V) approach should follow industry guidance such as International Performance Measurement and Verification Protocol (IPMVP) Option C[8] and ASHRAE Guideline 22. Baseline models should be created for a representative sample of buildings and meet industry best practice model fit guidelines[9] and independent variable coverage factor ranges defined in ASHRAE Guideline 22. Absolute change in energy use should be based on avoided energy consumption (Equation 1), annualized to a full year of post-implementation conditions. Relative change in annual energy use is calculated as shown in Equation 2, where the Reporting Period is the year following the implementation of energy efficiency measures, and Adjusted Baseline Period Energy is the sum total of predicted energy use through the reporting period (i.e., predicted by the baseline model when applied to the independent variables data throughout the reporting period).

Avoided Energy Consumption (kWh/therms/kBtu) = *Baseline Period Energy ± Routine Adjustments to Reporting Period Conditions*

[8] Efficiency Valuation Organization. "International Performance Measurement and Verification Protocol (IPMVP®) Core Concepts". Mar 2022

[9] Example best practice guidance: LBNL. 2020. *LBNL Guidance on Requirements for Meter-Based IPMVP Option C Savings Claims*. Lawrence Berkeley National Laboratory; and Caltrack (v2.0)

± Non-Routine Adjustments
- Reporting Period Energy
+ Displaced energy due to CHP use

Equation 1: Existing building absolute change in annual energy use (Avoided Energy Consumption, source: IPMVP Core Concepts 2016)

Relative change in energy use (%) = *Avoided Energy Consumption* / Adjusted Baseline Period Energy **100*

Equation 2: Existing building relative change in energy use (reported separately for electricity and natural gas, and for a combined total)

Greenhouse Gas Emission Reduction Calculations

Greenhouse gas (GHG) emission reduction may occur as the result of the decrease in energy use (e.g., electricity and natural gas), through the implementation of energy efficiency measures, or the removal of natural gas, propane, or fuel oil burning equipment and replacing it with electricity based equipment. GHG emission reduction can also occur through the removal of equipment containing refrigerants (e.g., air conditioning units, refrigerators, freezers, HVAC chillers).

Using the energy reduction estimates, carbon emission reduction may be estimated as follows. Total emissions reduction is the sum of emissions reduction stemming from reduced use of grid electricity, fuels burned on site, and district utilities:

$$C_{TOT} = SUM[E_i \ X \ Cf_i]$$

Where

E_i is the annual energy use reduction of each unit delivered energy i
Cf_i is the annual average emission factor for each unit delivered energy i

Annual average emission factors across the U.S. are provided in Appendix H for electricity use and Appendix I for other fuel types in Table A7.

Appendix D: Health and Safety Benefits Identification

The following sections outline methods, assumptions, and analyses that can be used to help identify potential health and safety benefits associated with various energy improvements. Other benefits may exist that are not listed below.

Health Improvements

A school or district should identify potential benefits to teacher and student health, comfort, and support of the learning environment through indoor environmental quality (IEQ) improvements. IEQ improvements may span indoor air quality (IAQ), interior lighting quality, thermal comfort, and acoustics. Improvements to IAQ should be prioritized for inclusion and description because it is among the recommended strategies to mitigate risks from airborne viruses[10], and studies have also demonstrated the strongest associations with benefits to student performance and absenteeism[11]. Appendix G provides examples of probable IEQ improvements and the associated benefits from the sample retrofit packages. A school or district should consider this list and provide a description of IEQ improvements and associated benefits that can be expected for their proposed energy improvements.

Health improvements may involve measurement and verification of the changes to Indoor environmental quality pre and post retrofits or by documenting that selected IEQ parameters met established guidelines or standards. A school or district may reference the measurement approaches from LEED[12], CHPS[13], and IPMVP (2001)[14] to define measurement and verification (M&V) goals and one or more IEQ parameters for assessment.

For example, IAQ improvements may be quantified by short-term monitoring of specified air pollutants of concern (e.g., particulate matter, ozone, formaldehyde) or long-term monitoring of carbon dioxide (CO_2) as an indicator of building ventilation. Outdoor air ventilation rate can be assessed as part of testing, adjusting, and balancing (TAB) verification. For thermal comfort, a school or district may measure parameters such as air temperature, relative humidity, and air velocity or conduct a survey to determine occupant satisfaction. For lighting improvements, a school or district may follow established protocols for making multi-parameter measurements or conduct an occupant survey to evaluate satisfaction.

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[10] https://www.epa.gov/indoor-air-quality-iaq/clean-air-buildings-challenge

[11] D. Vakalis, C. Lepine, H. L. MacLean & J. A. Siegel (2020): Can green schools influence academic performance?, Critical Reviews in Environmental Science and Technology, DOI: 10.1080/10643389.2020.1753631

[12] https://www.usgbc.org/resources/leed-v4-building-operations-and-maintenance-current-version

[13] https://chps.net/indoor-environmental-quality

[14] International Performance Measurement & Verification Protocol (2001). Concepts and Practices for Improved Indoor Environmental Quality Volume II.

Safety Improvements

School safety improvements can include improving the resiliency of the facility to withstand extreme weather conditions, natural disasters, or other emergencies or improving site security such as through effective outdoor lighting systems. A school or district should consider how the retrofits can be expected to better prepare the school for extreme events, such as heatwaves, high wind, winter storms, wildfires, power outages, floodings, or other hazards; for example, see Technical Resilience Navigator and National Risk Index as reference. A school or district is encouraged to consider the top hazards most relevant to their location and consider how the project can potentially minimize disruptions and impacts.

Resilience based safety improvements can be evaluated using the 'Hours of Safety' metric, which for cold events is the number of hours the building can provide thresholds of comfort and safety in the event of a power loss. This metric can be measured using a battery-operated temperature sensor (to log temperatures during power outage) and clock. The school should predetermine an appropriate temperature threshold for operations. The "Cold Stress Scale" sample thresholds below are based on a review of over a dozen data points from references from ASHRAE, the World Health Organization, the National Institutes of Health, and more[15].

Table A2. Cold Stress Scale

Minimum Safe Temperature for Vulnerable Populations	Minimum Safe Temperature for Healthy Populations	Mild Cold Stress for Healthy Populations	Moderate Cold Stress for Healthy Populations	Severe Cold Stress for Healthy Populations
>64F	60F	50-60F	50-40F	<40F

While a similar set of standards has not been developed for heat events under loss of power, a school or district may consider a similar measurement process with the comfort threshold of their choosing, appropriate for their local climate conditions, and using the measured heat index[16] for their location.

[15] Rocky Mountain Institute (RMI). "Hours of Safety in Cold Weather: A Framework for Considering Resilience in Building Envelope Design and Construction". Feb 2020.

[16] National Weather Service. https://www.weather.gov/ama/heatindex#:~:text=The%20heat%20index%2C%20also%20known,sweat%20to%20cool%20itself%20off.

Appendix E: Building Envelope Performance Characteristics

Table A3. Envelop Performance in Rural and Urban Models, for Elementary and Secondary Schools Respectively, including Measure Performance for Package 6 based on AEDG 50%

	Wall Insulation (RSI Value (W/m-K) / R-Value (ft2·°F·h/BTU))		Roof Insulation (RSI Value (W/m-K) / R-Value (ft2·°F·h/BTU))			Window U- Factor (W/m-k) / U-Value (BTU/ft2·°F·h)		Window Solar Heat Gain Coefficient		
Climate zone and nearest large city	Rural baseline	Urban baseline	Rural baseline	Urban baseline	Measure (Package 6)	Rural baseline	Urban baseline	Rural baseline	Urban baseline	Measure (Package 6)
1A_USA_FL_MIAMI	0.62 / 3.49	2.3 / 13.05	1.51 / 8.58	3.06 / 17.38	5.11 / 29	6.93 / 0.82	6.93 / 0.82	0.54	0.25	0.25
2A_USA_TX_HOUSTON	0.62 / 3.49	1.03 / 5.82	1.51 / 8.58	2.42 / 13.72	5.11 / 29	6.93 / 0.82	6.93 / 0.82	0.54	0.25	0.25
3A_USA_GA_ATLANTA	0.63 / 3.6	1.2 / 6.84	1.51 / 8.58	2.19 / 12.46	5.11 / 29	6.93 / 0.82	4.09 / 1.39	0.54	0.25	0.25
3C_USA_CA_SAN_FRANCISCO	0.64 / 3.61	1.2 / 6.84	1.51 / 8.58	1.75 / 9.93	5.11 / 29	6.93 / 0.82	4.09 / 1.39	0.54	0.39	0.25
4A_USA_MD_BALTIMORE	0.84 / 4.77	1.83 / 10.39	1.8 / 10.2	2.79 / 15.82	5.28 / 30	6.93 / 0.82	3.35 / 1.69	0.54	0.36	0.26
5A_USA_IL_CHICAGO-OHARE	0.98 / 5.56	2. / 11.35	2.25 / 12.77	3.13 / 17.75	6.34 / 36	3.52 / 1.61	3.35 / 1.69	0.41	0.39	0.26
5B_USA_CO_BOULDER	0.94 / 5.36	2. / 11.35	2.12 / 12.04	3.26 / 18.49	6.34 / 36	3.52 / 1.61	3.35 / 1.69	0.41	0.39	0.35
6A_USA_MN_MINNEAPOLIS	1.06 / 6.04	2.56 / 14.54	2.74 / 15.55	3.72 / 21.1	6.34 / 36	3.52 / 1.61	2.95 / 1.92	0.41	0.39	0.35
7A_USA_MN_DULUTH	1.15 / 6.51	2.89 / 16.39	2.68 / 15.24	4.15 / 23.57	6.34 / 36	3.52 / 1.61	2.95 / 1.92	0.41	0.49	0.4
8A_USA_AK_FAIRBANKS	1.26 / 7.15	3.76 / 21.37	2.74 / 15.55	5.48 / 31.14	9.16 / 52	3.52 / 1.61	2.95 / 1.92	0.41	0.62	0.4

Appendix F: Retrofit Package Details

Table A4. Details on Retrofit Measures per Package for Elementary and Secondary Schools

Package	Elementary School	Secondary School
1. BMS Upgrade	School districts often have to replace their Building Management System (BMS) due to obsolescence, frequent breakdowns, difficulty to maintain comfort, health and safety, etc. BMS replacements are a prime opportunity to implement energy efficiency measures related to controls. This package of complementary efficiency measures that can be combined with a BMS replacement includes supply air temperature reset, duct static pressure reset, supply fan variable flow, typically via variable frequency drives (VFD), chilled water pump VFD, chilled water temperature reset, heating hot water pump VFD, heating hot water temperature reset, optimum start programming, and comprehensive retro-commissioning of system.	
2. Boiler Replacement + Controls	This package of efficiency measures can be incorporated with a boiler replacement. In addition to a high efficiency condensing boiler, the package includes hot water supply temperature resets, variable flow hot water pump, boiler lock-outs, networked thermostats, and super premium efficiency motors. School districts with decarbonization goals should first consider replacing boilers with heat pumps or other approaches that do not require fossil fuels. This package does not serve that purpose and is only recommended as a "last resort" for school districts that are unable to electrify boilers via heat pump options.	
3. RTU Replacement + Controls	This package of efficiency measures can be incorporated with a rooftop unit (RTU) replacement. In addition to a high efficiency RTU, the package includes networked thermostats with CO_2 sensors and economizer controller, high capacity, low pressure drop filters, variable flow fans (typically using VFDs), economizer commissioning, and supply air temperature reset.	n/a (RTUs are not the primary air conditioning equipment in the reference Secondary School)

Package	Elementary School	Secondary School
4. Chiller Replacement + Controls	n/a (no chiller equipment in reference Elementary School)	This package of efficiency measures can be incorporated with a chiller replacement. In addition to a high efficiency chiller (air-cooled or water-cooled), the package includes several complementary measures that provide deeper savings and allied benefits, including chilled water supply temperature resets, variable flow chilled water pump, super premium efficiency motors, cooling tower replacement or upgrade, and BMS replacement or upgrade including controls upgrades to related HVAC systems.
5. HVAC Controls + Lighting + IEQ	This package includes improved HVAC controls, consistent with a BMS upgrade or significant tuning of existing BMS. The HVAC controls improvements include scheduling tune up, economizer repairs, supply air temperature reset, static pressure reset, and installation of supply fan VFD, heating hot water pump VFD and temperature reset. IEQ improvements include better air filtration, upgrading air filters from 2" MERV 8 filters to 4" MERV 13 (with a larger filter to avoid energy penalty due to pressure drop) and networked thermostats and CO_2 sensors for demand-controlled ventilation (DCV). The lighting measure includes lighting power density reduction	This package includes HVAC controls enhancements to improve AHU and central plant performance, consistent with a BMS upgrade or significant tuning of existing BMS. Improvements include scheduling tune up, economizer repairs, supply air temperature reset, static pressure reset, and installation of supply fan VFD, heating hot water pump VFD and temperature reset, chilled water pump VFD and temperature reset, condenser water pump VFD and temperature reset (if water cooled). IEQ improvements include better air filtration, upgrading air filters from 2" MERV 8 filters to 4" MERV 13 and networked thermostats and CO_2 sensors for demand-

Package	Elementary School	Secondary School
	consistent with an LED retrofit indoors and outdoors as well as occupancy sensor controls on indoor and outdoor lighting, and daylighting controls on indoor lighting.	controlled ventilation (DCV). The lighting measure includes lighting power density reduction consistent with an LED retrofit indoors and outdoors as well as occupancy sensor controls on indoor and outdoor lighting, and daylighting controls on indoor lighting.
6. HVAC Equipment and Controls + Envelope +IEQ	This package includes all of the HVAC and air filtration improvements in Package 5. This package also includes reduced solar heat gain through window coatings/films and the addition of a cool roof, as well as upgrading packaged HVAC equipment to more efficient RTUs for air conditioning.	This package includes all of the HVAC and air filtration improvements in Package 5. This package also includes reduced solar heat gain through window coatings/films and the addition of a cool roof, as well as upgrading HVAC plant equipment to a more efficient chiller, a high efficiency condensing boiler with improved hot water controls (timers and lockouts), and higher efficiency cooling towers with optimized staging (if water cooled), along with chilled water reset controls, premium efficiency motors and VFDs.
7. HVAC Equipment and Controls + Lighting + IEQ	This package includes all of the HVAC and air filtration improvements in Package 5 and the HVAC equipment upgrades of Package 6. This package adds the HVAC equipment measure of new, high efficiency condensing boilers for heating along with improved hot water controls (timers and lockouts), premium efficiency pump motors, and also includes all	This package includes all of the HVAC and air filtration improvements in Package 5 and the HVAC equipment upgrades of Package 6. This package also includes all of the lighting efficiency measures.

Package	Elementary School	Secondary School
	of the lighting efficiency measures.	
8. Partial Electrification + EE + IEQ	This package combines the HVAC equipment and controls improvements of previous packages and also adds a heat pump for domestic hot water. The package includes DCV and air filter upgrades, and all of the lighting efficiency measures.	This package combines the HVAC equipment and controls improvements of previous packages, and also adds a heat pump for domestic hot water. The package includes DCV and air filter upgrades, and all of the lighting efficiency measures.
9. Full Electrification + EE + IEQ	This package includes all-electric heating and cooling through high efficiency heat pump RTUs as well as a two-stage heat pump water heating system for zone reheat coils (eliminating gas boiler for reheat), along with all the improved HVAC controls measures. This package also includes heat pump domestic water, all lighting efficiency measures, and DCV and improved air filtration. This package also adds an energy recovery system for ventilation air.	This package includes all-electric heating and cooling through the addition of a two-stage heat pump water heating system for zone heating and reheat coils (eliminating gas boilers) as well as replacing single zone air conditioners with heat pump alternatives. This package also includes all of the improved HVAC equipment and controls measures and also includes heat pump domestic water, all lighting efficiency measures, DCV and improved air filtration. This package also adds an energy recovery system for ventilation air.
10. Lighting efficiency (LEDs + Controls)	Efficient LED fixtures (LPD reduction of 50%) with lighting controls upgrade (occupancy control and daylight dimming)	
11. LED upgrade (no controls changes) and	LED retrofit (LPD reduction of 50%), CO_2 based DCV control to maintain levels below 1,100 PPM (CO_2 sensors in each HVAC zone),	

Package	Elementary School	Secondary School
ventilation improvements	outdoor air scheduling change to reduce morning pre-conditioning by two hours, upgrading air filters from 2” MERV 8 filters to 4” MERV 14 (with a larger filter to avoid energy penalty due to pressure drop)	
12. Lighting efficiency and ventilation improvements	Efficient lighting (LEDs + controls), CO_2 based DCV, outdoor air scheduling change, MERV 14 filters	
13. Lighting efficiency, ventilation, economizer	Efficient lighting (LEDs + controls), CO_2 based DCV, outdoor air scheduling change, MERV 14 filters, retune economizer (it is common in existing buildings for the economizer, which provides “free cooling” when outside air conditions are appropriate, to be faulty, which was the baseline assumption; retuning the economizer restores normal operation and increases the high limit cutoff temperature for outside air to 75 deg F, from 65 deg F, to increase free cooling)	
14. Lighting efficiency, ventilation, Guideline 36, relief air damper	Efficient lighting (LEDs + controls), CO_2 based DCV, outdoor air scheduling change, MERV 14 filters, G. 36 VAV retuning measure (reset minimum damper position setting at VAV terminal unit from the factory setting assumed to be 30% to a lower minimum, of 15%), G. 36 economizer control measure (based on differential dry bulb	

Package	Elementary School	Secondary School
	temperature; when outdoor air temperature > return air temperature, economizer switches off), relief damper control (set damper to achieve neutral to minor positive building pressurization)	
15. Lighting efficiency, ventilation, Guideline 36, relief air damper and fan motor	Efficient lighting (LEDs + controls), CO_2 based DCV, outside air scheduling, MERV 14 filters, G. 36 VAV retuning, G. 36 economizer control, relief damper control, upgrade fan motor with base efficiency (85.5%) to premium efficiency motor (93%).	
16. Lighting efficiency, ventilation, Guideline 36, relief air damper and ERV	Efficient lighting (LEDs + controls), CO_2 based DCV, outside air scheduling, MERV 14 filters, G. 36 VAV retuning, G. 36 economizer control, relief damper control, energy recovery ventilator (ERV) installed in air handlers (rotary wheel-based heat exchanger that operates when heat recovery is available from exhaust air to precondition outdoor supply air).	
17. Lighting efficiency, ventilation, Guideline 36+ (additional Guideline 36 measures), relief air damper and AHSP	Efficient lighting (LEDs + controls), CO_2 based DCV, outside air scheduling, MERV 14 filters, G. 36 VAV retuning, G. 36 economizer control, G. 36 occupied standby mode (when zone is unoccupied during workday, setback heating 1 deg F and set up cooling 1 deg F, minimum ventilation air when unoccupied), G. 36 supply air temperature reset (when	

Package	Elementary School	Secondary School
	occupied and outside air is between 60 - 70 deg F, SAT resets proportionally within the range of 55 - 65 deg F.), G. 36 optimal start (pre-heating or cooling in advance of occupancy to achieve setpoint when first occupants arrive, start time / duration varies by outside air temperature), relief damper control, replace RTUs with Air Source Heat Pump (ASHP) with rated performance of 10.9 energy efficiency ratio (EER) for cooling mode and 3.3 Coefficient of Performance (COP) for heating mode.	
18. Lighting efficiency, ventilation, Guideline 36+, relief air damper, ASHP and ERV	Efficient lighting (LEDs + controls), CO_2 based DCV, outside air scheduling, MERV 14 filters, G. 36 VAV retuning, G. 36 economizer control, G. 36 occupied standby mode, G. 36 supply air temperature reset, G. 36 optimal start, relief damper control, replace RTUs with ASHPs, ERV on air handlers.	

Appendix G: IEQ Improvements and Associated Benefits from Retrofits

Table A5. Expected IEQ Improvements and Associated Benefits from each Retrofit Measure

Retrofit Type	Efficiency Measures and Impacts	Potential IEQ and Health Benefits
BMS Upgrade	Improve control of supply air temperature and airflow	Improve the likelihood of thermal comfort being maintained
	HVAC retro-commissioning help to ensure proper ventilation is provided during occupancy	Improve the likelihood of adequate outdoor air ventilation, thus improving IAQ
Boiler / Chiller Replacement	Networked thermostats to provide measurements of air temperature	Improve the likelihood of thermal comfort being maintained
RTU Replacement	Newer RTU specification including lower equipment noise	Lower background noise to support learning in classroom
	Networked thermostats with CO2 sensors for demand-controlled ventilation (DCV)	Improve the likelihood of adequate outdoor air ventilation, thus improving IAQ
	Air economizer commissioning to bring in large amount of outside air when conditions are met	Increase outdoor air ventilation and dilution of indoor emitted air pollutants, including respiratory aerosols for infection control
	High-capacity, low pressure drop air filters	Enhance removal of particulate matter (e.g., traffic emissions, wildfires) and respiratory aerosols for infection control
Lighting Retrofit	Indoor LED retrofits, including occupancy sensing and daylighting controls	Improve indoor lighting quality
	Outdoor LED retrofits, including occupancy sensing	Improve site security by improving outdoor light distribution
Envelope Improvement	Reduced solar heat gain through window coatings/films	Improve occupant thermal comfort
	Addition of cool roof	Improve the likelihood of thermal

Retrofit Type	Efficiency Measures and Impacts	Potential IEQ and Health Benefits
		comfort being maintained; can also reduce heat island effect in the vicinity

Appendix H: Emissions Rates from Electricity Generation, per State

Table A6. State Electricity Generation Output Emission Rates (from eGRID)[17]

State	Total electricity grid output emission rates (lb/MWh) CO_2e (carbon emissions)
AK	966.1
AL	721.1
AR	951.3
AZ	737.0
CA	453.1
CO	1,219.2
CT	529.8
DC	801.1
DE	755.0
FL	842.2
GA	723.5
HI	1,526.5
IA	615.2
ID	213.4
IL	556.4
IN	1,549.5
KS	804.2
KY	1,684.9
LA	761.7
MA	879.9
MD	645.3
ME	228.2
MI	938.0
MN	770.4
MO	1,618.4
MS	894.1
MT	912.6
NC	648.4
ND	1,388.1
NE	1,200.7
NH	247.9
NJ	492.3
NM	1,259.9
NV	716.6
NY	416.7
OH	1,253.3
OK	708.7
OR	341.6
PA	697.5
PR	1,608.5
RI	827.6
SC	513.9
SD	340.6
TN	571.4
TX	857.5
UT	1,565.8
VA	644.8
VT	30.3
WA	213.3
WI	1,192.0
WV	1,924.7
WY	1,990.1
U.S.	**822.6**

[17] EPA eGRID website. https://www.epa.gov/egrid/summary-data Accessed Sept 2022.

Appendix I: Fuel Emissions Factors

Table A7. CO_2e Emissions Factors for Fuels Burned on site[18]

Fuel Type	CO2e Emissions (kg/MBtu)
Natural Gas	53.11
Propane	64.25
Fuel Oil (No. 1)	73.50
Fuel Oil (No. 2)	74.21
Fuel Oil (No. 4)	75.29
Fuel Oil (No. 5,6)	75.35
Diesel Oil	74.21
Kerosene	77.69
Gasoline[19]	71.30
Coal (anthracite)	104.44
Coal (bituminous)	94.03
Coke	114.42
Wood	95.05

[18] ENERGY STAR technical reference. Greenhouse Gas Emissions (except where noted).

[19] From EIA Carbon Dioxide Emissions Coefficients by Fuel - https://www.eia.gov/environment/emissions/xls/co2_vol_mass.xls

Appendix J: Estimated Retrofit Package Costs, Energy Cost Savings and Paybacks

The following tables present estimated retrofit package project costs ($), annual cost savings based on energy savings converted to dollars given utility rates ($/year), and simple project payback estimates (in years). The packages as numbered in the following tables are described in full detail in the section summarizing the retrofit packages, as well as Table 2 and Appendix F. Briefly, the packages numbered 1 to 9 correspond to:

1. BMS Replacement
2. Boiler Replacement + Controls
3. RTU Replacement + Controls
4. Chiller Replacement + Controls
5. HVAC Controls + Lighting + IAQ
6. HVAC Equip + Controls, Envelope + IAQ
7. HVAC Equip + Controls, Lighting + IAQ
8. Partial Electrification + Efficiency measures + IEQ
9. Full Electrification + Efficiency measures + IEQ

Costs and savings estimates are rounded to 1,000s place. Payback result displayed may not match exactly payback calculated from rounded values. For some packages in some climate zones, the economic value in energy cost savings is not sufficient to achieve meaningful simple paybacks. For packages with long paybacks, drawing a line at greater than 40 years for the purposes of this report, the specific payback figure is not very useful. Accordingly, paybacks over 40 years are simply denoted as ">40" in the results tables below. In such cases, as well as in the cases of some retrofit packages with lower paybacks, the packages may present good value beyond just energy savings, for example when considering non-energy benefits such as health and safety improvements. Simple energy-based payback alone may not motivate the investment decision of the school or district in such cases.

Table A8. Urban Schools Retrofit Package Costs, Energy Cost Savings and Paybacks

Climate Zone	Retrofit Package	Elementary School			Secondary School		
		Project Cost	Annual Cost Savings	Payback (yrs)	Project Cost	Annual Cost Savings	Payback (yrs)
1A	1	$110,000	$11,000	9.9	$184,000	$8,000	22.5
	2	$99,000	$1,000	>40	$116,000	$5,000	24.6
	3	$628,000	$14,000	>40	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$422,000	$6,000	>40
	5	$373,000	$55,000	6.8	$732,000	$133,000	5.5
	6	$1,028,000	$23,000	>40	$1,135,000	$31,000	37.0
	7	$1,101,000	$58,000	19.0	$1,271,000	$133,000	9.6
	8	$1,140,000	$58,000	19.7	$1,369,000	$135,000	10.1
	9	$1,563,000	$70,000	22.4	$2,617,000	$166,000	15.7
2A	1	$93,000	$13,000	7.3	$154,000	$9,000	17.3
	2	$91,000	$1,000	>40	$110,000	$5,000	20.5
	3	$520,000	$16,000	32.3	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$333,000	$25,000	13.3
	5	$297,000	$38,000	7.8	$580,000	$79,000	7.4
	6	$822,000	$22,000	36.6	$865,000	$34,000	25.4
	7	$908,000	$41,000	21.9	$1,022,000	$92,000	11.2
	8	$940,000	$41,000	22.7	$1,116,000	$93,000	12.0
	9	$1,421,000	$51,000	27.8	$2,466,000	$110,000	22.3
3A	1	$96,000	$10,000	9.3	$160,000	$9,000	17.8
	2	$101,000	$2,000	>40	$64,000	$6,000	10.6
	3	$517,000	$12,000	>40	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$324,000	$18,000	18.1
	5	$308,000	$43,000	7.1	$582,000	$141,000	4.1
	6	$840,000	$17,000	>40	$894,000	$70,000	12.7
	7	$926,000	$46,000	20.3	$971,000	$149,000	6.5

Climate Zone	Retrofit Package	Elementary School			Secondary School		
		Project Cost	Annual Cost Savings	Payback (yrs)	Project Cost	Annual Cost Savings	Payback (yrs)
	8	$979,000	$45,000	21.9	$1,078,000	$149,000	7.3
	9	$1,470,000	$51,000	29.1	$2,658,000	$162,000	16.5
3C	1	$139,000	$10,000	13.3	$231,000	$20,000	11.5
	2	$125,000	$4,000	33.3	$156,000	$13,000	11.6
	3	$840,000	$12,000	>40	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$391,000	$25,000	15.9
	5	$468,000	$57,000	8.2	$887,000	$151,000	5.9
	6	$1,267,000	$17,000	>40	$1,151,000	$36,000	31.9
	7	$1,433,000	$60,000	23.9	$1,434,000	$157,000	9.1
	8	$1,493,000	$58,000	25.6	$1,600,000	$157,000	10.2
	9	$2,054,000	$63,000	32.6	$3,220,000	$174,000	18.5
4A	1	$101,000	$14,000	7.3	$169,000	$13,000	13.2
	2	$106,000	$3,000	32.8	$68,000	$11,000	6.0
	3	$548,000	$14,000	38.0	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$342,000	$18,000	18.9
	5	$325,000	$32,000	10.1	$613,000	$69,000	8.9
	6	$889,000	$17,000	>40	$943,000	$30,000	31.6
	7	$979,000	$36,000	27.6	$1,023,000	$80,000	12.8
	8	$1,025,000	$36,000	28.3	$1,160,000	$83,000	13.9
	9	$1,640,000	$49,000	33.2	$2,806,000	$114,000	24.6
5A	1	$121,000	$9,000	13.0	$201,000	$11,000	18.9
	2	$131,000	$3,000	>40	$254,000	$9,000	27.5
	3	$653,000	$8,000	>40	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$407,000	$7,000	>40
	5	$383,000	$32,000	12.1	$723,000	$66,000	11.0
	6	$1,048,000	$8,000	>40	$1,110,000	$7,000	>40

Climate Zone	Retrofit Package	Elementary School			Secondary School		
		Project Cost	Annual Cost Savings	Payback (yrs)	Project Cost	Annual Cost Savings	Payback (yrs)
	7	$1,167,000	$34,000	34.5	$1,384,000	$71,000	19.5
	8	$1,235,000	$34,000	36.7	$1,560,000	$73,000	21.5
	9	$2,008,000	$41,000	>40	$3,801,000	$101,000	37.7
5B	1	$97,000	$7,000	14.4	$161,000	$8,000	20.8
	2	$105,000	$2,000	>40	$216,000	$7,000	29.3
	3	$414,000	$6,000	>40	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$176,000	$7,000	26.3
	5	$315,000	$16,000	19.9	$595,000	$32,000	18.7
	6	$731,000	$6,000	>40	$736,000	$8,000	>40
	7	$834,000	$17,000	>40	$987,000	$35,000	28.0
	8	$888,000	$18,000	>40	$1,118,000	$38,000	29.3
	9	$1,489,000	$24,000	>40	$2,620,000	$54,000	>40
6A	1	$113,000	$12,000	9.1	$188,000	$11,000	16.5
	2	$127,000	$3,000	>40	$265,000	$10,000	26.5
	3	$561,000	$12,000	>40	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$361,000	$12,000	30.1
	5	$358,000	$29,000	12.5	$676,000	$60,000	11.2
	6	$915,000	$13,000	>40	$989,000	$21,000	>40
	7	$1,045,000	$32,000	32.8	$1,302,000	$70,000	18.6
	8	$1,109,000	$32,000	34.8	$1,475,000	$72,000	20.4
	9	$1,985,000	$40,000	>40	$3,737,000	$102,000	36.6
7A	1	$105,000	$13,000	8.1	$175,000	$13,000	13.8
	2	$114,000	$4,000	29.4	$222,000	$11,000	19.5
	3	$521,000	$11,000	>40	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$260,000	$5,000	>40
	5	$337,000	$27,000	12.5	$638,000	$58,000	11.0

Climate Zone	Retrofit Package	Elementary School			Secondary School		
		Project Cost	Annual Cost Savings	Payback (yrs)	Project Cost	Annual Cost Savings	Payback (yrs)
8A	6	$858,000	$11,000	>40	$855,000	$18,000	>40
	7	$973,000	$30,000	32.1	$1,120,000	$65,000	17.3
	8	$1,041,000	$30,000	34.3	$1,295,000	$67,000	19.2
	9	$1,670,000	$48,000	34.7	$2,764,000	$103,000	26.9
	1	$110,000	$14,000	8.1	$183,000	$22,000	8.3
	2	$130,000	$5,000	27.3	$266,000	$21,000	12.9
	3	$445,000	$17,000	26.7	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$200,000	$6,000	31.5
	5	$363,000	$44,000	8.2	$687,000	$35,000	35.6
	6	$855,000	$17,000	>40	$929,000	$9,000	>40
	7	$937,000	$51,000	18.5	$1,152,000	$40,000	28.6
	8	$1,008,000	$49,000	20.4	$1,335,000	$40,000	33.3
	9	$1,872,000	$79,000	23.6	$3,551,000	$140,000	25.4

Table A9. Rural Schools Retrofit Package Costs, Energy Cost Savings and Paybacks

Climate Zone	Retrofit Package	Elementary School			Secondary School		
		Project Cost	Annual Cost Savings	Payback (yrs)	Project Cost	Annual Cost Savings	Payback (yrs)
1A	1	$106,000	$20,000	5.3	$176,000	$16,000	11.2
	2	$93,000	$1,000	>40	$109,000	$6,000	18.1
	3	$532,000	$21,000	24.9	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$413,000	$8,000	51.5
	5	$357,000	$62,000	5.8	$697,000	$157,000	4.5
	6	$912,000	$30,000	30.9	$1,089,000	$70,000	15.6
	7	$983,000	$56,000	17.7	$1,219,000	$157,000	7.8
	8	$1,021,000	$49,000	20.7	$1,316,000	$159,000	8.3
	9	$1,430,000	$64,000	22.2	$2,519,000	$196,000	12.9
2A	1	$81,000	$17,000	4.7	$133,000	$13,000	10.1
	2	$74,000	$2,000	>40	$89,000	$6,000	14.2
	3	$414,000	$20,000	20.3	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$309,000	$29,000	10.5
	5	$258,000	$42,000	6.1	$495,000	$86,000	5.7
	6	$670,000	$29,000	22.8	$758,000	$51,000	15.0
	7	$746,000	$46,000	16.2	$893,000	$101,000	8.8
	8	$777,000	$46,000	17.0	$980,000	$103,000	9.6
	9	$1,198,000	$59,000	20.4	$2,169,000	$125,000	17.4
3A	1	$83,000	$14,000	5.8	$136,000	$13,000	10.5
	2	$81,000	$3,000	32.2	$54,000	$7,000	7.4
	3	$406,000	$16,000	26.1	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$298,000	$22,000	13.6
	5	$264,000	$45,000	5.9	$493,000	$142,000	3.5
	6	$673,000	$26,000	26.2	$768,000	$35,000	21.7
	7	$751,000	$49,000	15.3	$845,000	$153,000	5.5

Climate Zone	Retrofit Package	Elementary School			Secondary School		
		Project Cost	Annual Cost Savings	Payback (yrs)	Project Cost	Annual Cost Savings	Payback (yrs)
	8	$800,000	$49,000	16.2	$945,000	$152,000	6.2
	9	$1,224,000	$67,000	18.3	$2,303,000	$171,000	13.5
3C	1	$122,000	$13,000	9.3	$200,000	$25,000	8.0
	2	$102,000	$5,000	21.9	$128,000	$15,000	8.3
	3	$664,000	$15,000	>40	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$366,000	$29,000	12.8
	5	$409,000	$59,000	6.9	$767,000	$155,000	4.9
	6	$1,028,000	$21,000	>40	$1,011,000	$44,000	23.1
	7	$1,176,000	$63,000	18.8	$1,261,000	$163,000	7.7
	8	$1,232,000	$61,000	20.2	$1,418,000	$163,000	8.7
	9	$1,730,000	$69,000	25.0	$2,851,000	$185,000	15.4
4A	1	$92,000	$20,000	4.5	$152,000	$20,000	7.7
	2	$92,000	$6,000	16.7	$61,000	$16,000	3.8
	3	$449,000	$20,000	22.4	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$323,000	$23,000	14.2
	5	$294,000	$37,000	8.0	$550,000	$78,000	7.1
	6	$751,000	$25,000	29.8	$854,000	$48,000	17.9
	7	$835,000	$41,000	20.1	$934,000	$92,000	10.2
	8	$879,000	$42,000	20.8	$1,065,000	$96,000	11.1
	9	$1,435,000	$66,000	21.7	$2,555,000	$143,000	17.9
5A	1	$109,000	$12,000	9.2	$181,000	$13,000	13.5
	2	$113,000	$4,000	27.0	$229,000	$12,000	19.8
	3	$536,000	$10,000	>40	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$385,000	$8,000	>40
	5	$346,000	$33,000	10.5	$649,000	$63,000	10.4
	6	$886,000	$12,000	>40	$1,006,000	$6,000	>40

Climate Zone	Retrofit Package	Elementary School			Secondary School		
		Project Cost	Annual Cost Savings	Payback (yrs)	Project Cost	Annual Cost Savings	Payback (yrs)
	7	$996,000	$36,000	27.5	$1,263,000	$69,000	18.2
	8	$1,061,000	$36,000	29.3	$1,431,000	$70,000	20.3
	9	$1,760,000	$50,000	35.5	$3,453,000	$109,000	31.6
5B	1	$84,000	$9,000	9.5	$138,000	$10,000	14.4
	2	$85,000	$3,000	29.2	$188,000	$9,000	21.0
	3	$308,000	$8,000	38.2	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$162,000	$7,000	21.7
	5	$272,000	$17,000	16.1	$508,000	$31,000	16.3
	6	$574,000	$9,000	>40	$629,000	$11,000	>40
	7	$665,000	$19,000	35.0	$858,000	$36,000	24.0
	8	$716,000	$20,000	35.9	$980,000	$39,000	25.4
	9	$1,233,000	$32,000	39.0	$2,270,000	$62,000	36.9
6A	1	$100,000	$16,000	6.1	$164,000	$14,000	11.5
	2	$106,000	$4,000	24.9	$233,000	$12,000	18.7
	3	$453,000	$15,000	29.7	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$336,000	$13,000	26.0
	5	$316,000	$30,000	10.4	$590,000	$61,000	9.6
	6	$757,000	$19,000	>40	$874,000	$26,000	33.3
	7	$874,000	$35,000	24.9	$1,159,000	$72,000	16.0
	8	$934,000	$36,000	26.1	$1,323,000	$75,000	17.7
	9	$1,702,000	$57,000	29.9	$3,304,000	$114,000	29.0
7A	1	$95,000	$17,000	5.6	$156,000	$16,000	9.7
	2	$98,000	$5,000	18.6	$198,000	$15,000	13.5
	3	$429,000	$14,000	31.1	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$246,000	$6,000	>40
	5	$303,000	$28,000	10.8	$568,000	$58,000	9.9

Climate Zone	Retrofit Package	Elementary School			Secondary School		
		Project Cost	Annual Cost Savings	Payback (yrs)	Project Cost	Annual Cost Savings	Payback (yrs)
8A	6	$725,000	$16,000	>40	$768,000	$19,000	>40
	7	$831,000	$33,000	25.0	$1,013,000	$62,000	16.4
	8	$896,000	$34,000	26.2	$1,181,000	$55,000	21.6
	9	$1,458,000	$69,000	21.3	$2,489,000	$92,000	27.2
	1	$103,000	$27,000	3.7	$170,000	$64,000	2.7
	2	$118,000	$10,000	12.3	$242,000	$62,000	3.9
	3	$332,000	$42,000	7.9	n/a (no RTUs in secondary school model)		
	4	n/a (no chiller in elementary school model)			$192,000	$15,000	13.2
	5	$340,000	$80,000	4.3	$640,000	$62,000	10.3
	6	$711,000	$30,000	23.8	$865,000	$46,000	18.6
	7	$790,000	$91,000	8.6	$1,074,000	$98,000	11.0
	8	$859,000	$88,000	9.8	$1,252,000	$99,000	12.6
	9	$1,663,000	$134,000	12.5	$3,322,000	$312,000	10.7