Modeled Retrofit Package Performance for Prototype Schools

Prepared by Lawrence Berkeley National Laboratory (LBNL)

This report details modeled energy performance and savings from retrofit packages in prototype 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. Results include electric and gas savings from 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. CO_2 emissions reductions and annual energy cost savings are also estimated.

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1. School Prototype - Building Characteristics

The elementary and secondary school models were developed based on the U.S. Department of Energy prototype building models. 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 descriptive of existing structures constructed in or after 1980, and where operations are generally conforming to ASHRAE Standard 90.1 (1989) performance levels. The buildings as modeled have features that vary according to climate zones, such as equipment sizing for heating and cooling needs. Table A shows a selected list of key building features of the elementary and secondary schools.

The elementary school prototype model HVAC system uses packaged two-stage direct expansion (DX) roof top units (RTUs) for air conditioning, with heating provided by a 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 prototype 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 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 A. 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)	
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

Characteristic	Elementary School	Secondary School
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	Variable, except for packaged single-zone units
Service water type	Gas heated, with storage tank	

2. 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 B briefly summarizes the retrofit packages, which are further described in Appendix Table C.

Table B. Description of Measures in Each Retrofit Package

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

Package	Description
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.
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 energy recovery ventilator.

3. 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[1], and studies have also demonstrated strong associations with improved IAQ and benefits to student performance and reduced absenteeism[2]. Table D in the appendix 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.

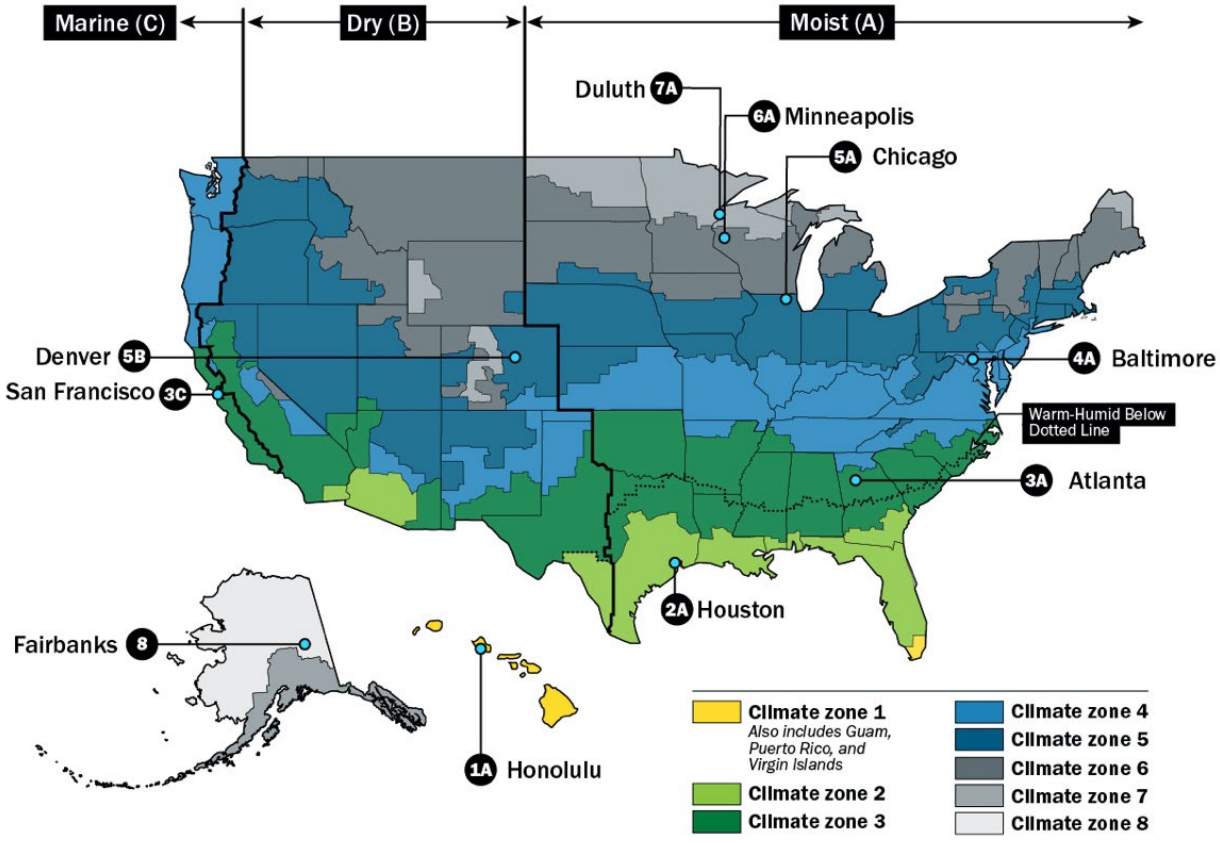
[1] https://www.epa.gov/indoor-air-quality-iaq/clean-air-buildings-challenge

[2] 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

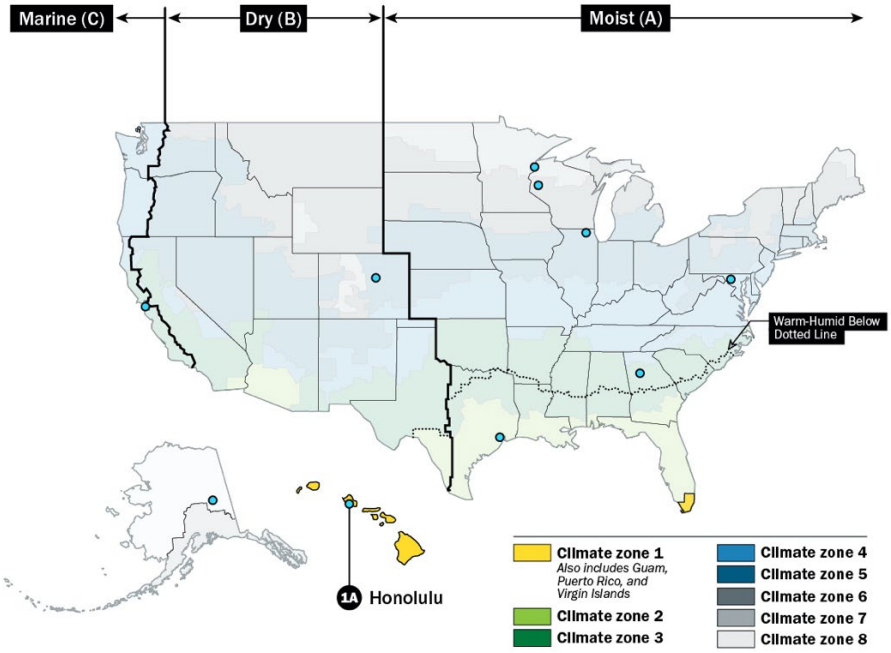
4. Retrofit Packages and Energy Savings Estimates based on Climate Zones

To calculate energy savings from retrofit packages, Lawrence Berkeley National Laboratory (LBNL) performed building energy simulations of packages of efficiency measures using the DOE's EnergyPlus simulation software, modeling a range of different DOE climate zones for both elementary and secondary school buildings, leveraging DOE's building reference models (post-1980 construction, generally conforming to ASHRAE Standard 90.1-1989). The simulation work characterizes retrofit package impacts on performance metrics such as annual energy use, carbon emissions, and energy cost savings / ROI resulting from upgrades. Energy savings for the package will vary depending on location, existing building systems and operating characteristics. Simulations were performed for schools in ten cities representing distinct climate zones throughout the U.S., including Alaska and Hawaii. The cities and climate zones represented in the retrofit package modeling are illustrated in the following map.

Figure 1. Modeled Climate Zones and Cities



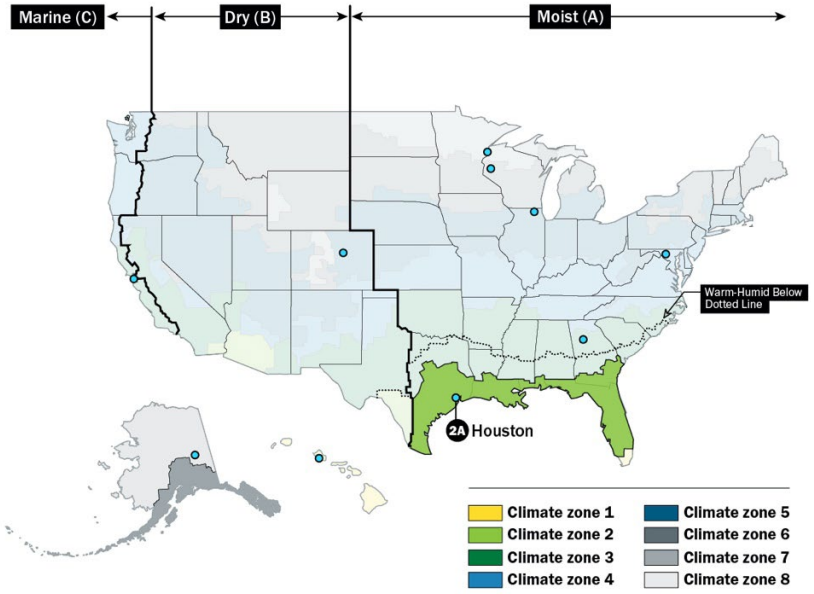
Climate Zone 1A: Honolulu



Electricity, Gas, and CO2 savings estimates per retrofit package for Climate Zone 1A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO2	Cost	Elec	Gas	CO2	Cost
1. BMS Replacement	5.2%	9.8%	5.3%	4.9%	2.1%	11.5%	2.2%	2.0%
2. Boiler Replacement	0.1%	6.4%	0.3%	0.3%	0.7%	11.4%	0.8%	0.8%
3. RTU Replacement	6.0%	9.6%	6.1%	6.4%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement	n/a (no chiller in elementary school model)				1.0%	11.2%	1.2%	1.0%
5. HVAC Controls + Lighting + IAQ	23.4%	7.1%	23.0%	21.0%	22.3%	2.5%	22.0%	21.4%
6. HVAC Equip + Controls, Envelope + IAQ	9.0%	9.7%	9.0%	10.1%	5.3%	5.8%	5.3%	7.4%
7. HVAC Equip + Controls, Lighting + IAQ	24.1%	7.7%	23.7%	22.4%	22.3%	3.1%	22.0%	21.4%
8. Partial Electrification + EE + IEQ	23.3%	35.7%	23.6%	22.3%	21.8%	41.4%	22.1%	21.8%
9. Full Electrification + EE + IEQ	27.7%	40.8%	27.9%	28.1%	25.1%	45.5%	25.4%	26.1%

Climate Zone 2A: Houston

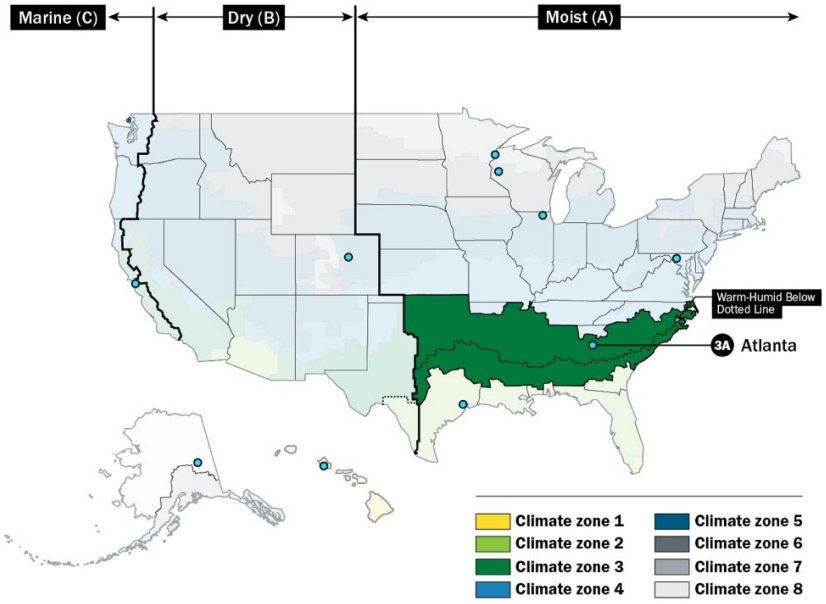


Electricity, Gas, and CO2 savings estimates per retrofit package for Climate Zone 2A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO2	Cost	Elec	Gas	CO2	Cost
1. BMS Replacement	4.8%	30.5%	5.7%	7.8%	1.4%	13.9%	1.9%	2.1%
2. Boiler Replacement	0.1%	12.0%	0.5%	0.6%	0.5%	13.9%	1.0%	1.1%
3. RTU Replacement	6.4%	28.0%	7.2%	10.0%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement	n/a (no chiller in elementary school model)				4.7%	11.5%	4.9%	5.6%
5. HVAC Controls + Lighting + IAQ	24.6%	20.6%	24.5%	24.3%	23.7%	-4.6%*	23.1%	21.3%
6. HVAC Equip + Controls, Envelope + IAQ	9.0%	28.8%	9.7%	13.9%	6.9%	15.4%	7.1%	9.0%
7. HVAC Equip + Controls, Lighting + IAQ	26.0%	23.3%	25.9%	26.5%	26.2%	0.8%	25.6%	24.6%
8. Partial Electrification + EE + IEQ	25.1%	40.7%	25.6%	26.5%	25.5%	29.1%	25.6%	24.9%
9. Full Electrification + EE + IEQ	27.6%	69.6%	29.1%	31.9%	27.3%	68.1%	28.2%	28.9%

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

Climate Zone 3A: Atlanta

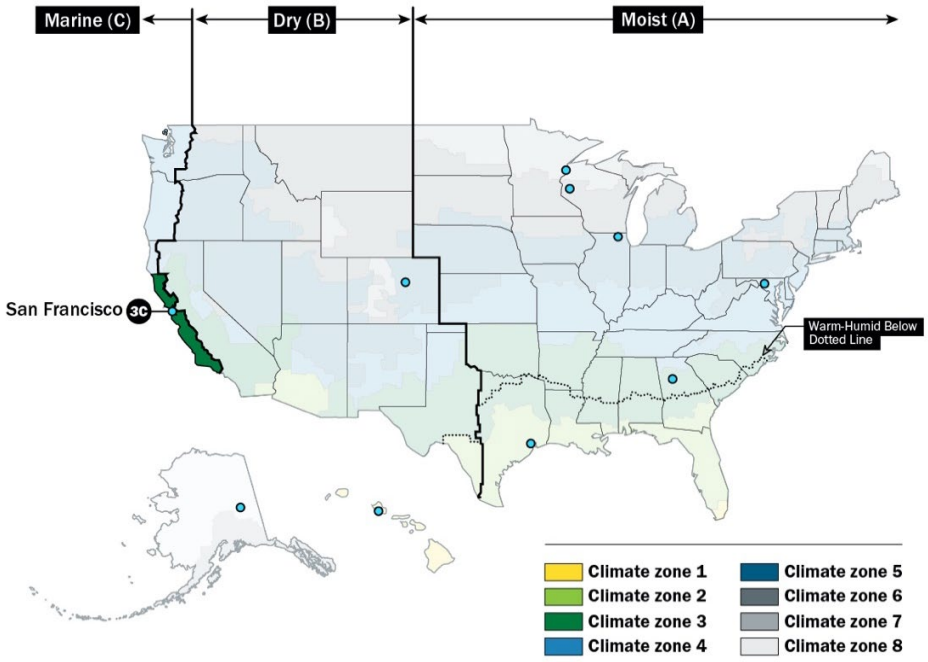


Electricity, Gas, and CO2 savings estimates per retrofit package for Climate Zone 3A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO2	Cost	Elec	Gas	CO2	Cost
1. BMS Replacement	3.6%	36.2%	6.3%	5.3%	1.1%	10.8%	2.1%	1.7%
2. Boiler Replacement	0.1%	12.2%	1.1%	0.8%	0.3%	10.7%	1.5%	1.1%
3. RTU Replacement	5.0%	31.7%	7.2%	6.2%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement	n/a (no chiller in elementary school model)				3.6%	7.2%	4.0%	3.3%
5. HVAC Controls + Lighting + IAQ	24.2%	23.0%	24.1%	23.9%	24.5%	-9.9%*	22.8%	29.2%
6. HVAC Equip + Controls, Envelope + IAQ	7.6%	34.1%	9.8%	8.6%	6.2%	17.5%	6.8%	5.2%
7. HVAC Equip + Controls, Lighting + IAQ	25.5%	27.7%	25.6%	25.2%	26.3%	-1.0%*	25.0%	30.8%
8. Partial Electrification + EE + IEQ	24.2%	38.4%	25.4%	24.7%	25.6%	17.6%	25.2%	30.8%
9. Full Electrification + EE + IEQ	25.6%	87.2%	30.4%	28.2%	26.2%	86.0%	29.0%	32.9%

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

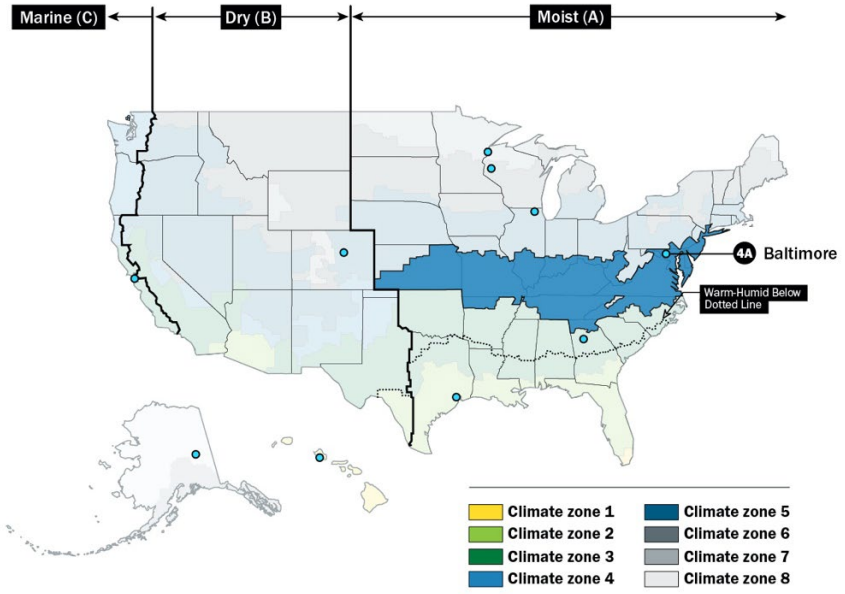
Climate Zone 3C: San Francisco



Electricity, Gas, and CO2 savings estimates per retrofit package for Climate zone 3C

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO2	Cost	Elec	Gas	CO2	Cost
1. BMS Replacement	1.5%	40.6%	7.7%	4.2%	1.2%	21.5%	5.6%	3.4%
2. Boiler Replacement	0.1%	21.0%	3.4%	1.4%	0.1%	21.0%	4.7%	2.2%
3. RTU Replacement	2.3%	37.3%	7.9%	4.9%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement	n/a (no chiller in elementary school model)				2.0%	19.6%	5.8%	4.6%
5. HVAC Controls + Lighting + IAQ	23.7%	27.0%	24.2%	23.5%	26.6%	5.8%	24.6%	28.7%
6. HVAC Equip + Controls, Envelope + IAQ	3.7%	38.1%	9.2%	6.6%	3.6%	28.4%	6.0%	9.7%
7. HVAC Equip + Controls, Lighting + IAQ	24.5%	30.3%	25.4%	24.6%	27.1%	11.4%	25.6%	29.6%
8. Partial Electrification + EE + IEQ	22.9%	44.6%	26.4%	24.1%	26.1%	38.0%	27.2%	29.5%
9. Full Electrification + EE + IEQ	21.2%	79.9%	30.6%	25.5%	26.7%	76.6%	31.6%	31.9%

Climate Zone 4A: Baltimore

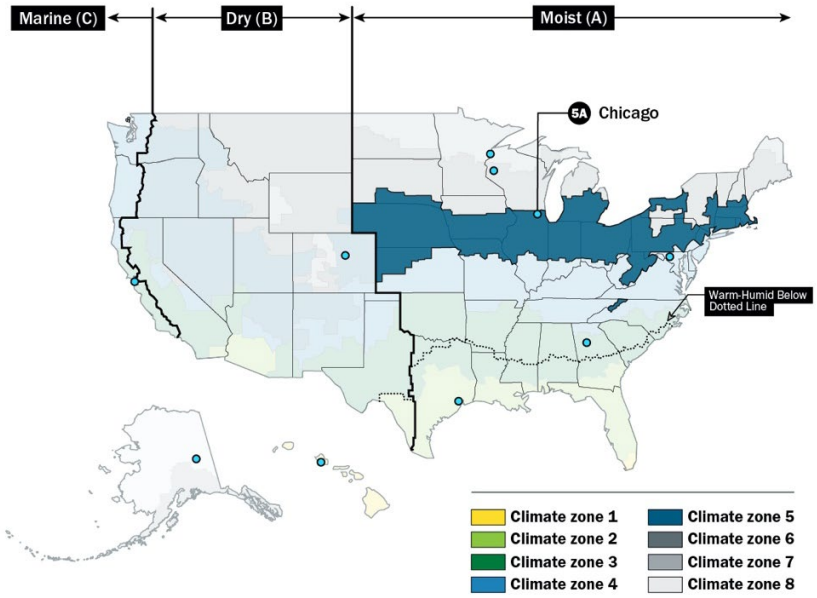


Electricity, Gas, and CO2 savings estimates per retrofit package for Climate zone 4A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO2	Cost	Elec	Gas	CO2	Cost
1. BMS Replacement	2.4%	37.4%	6.8%	9.6%	0.9%	9.1%	2.5%	1.7%
2. Boiler Replacement	0.1%	11.1%	1.5%	2.0%	0.2%	9.1%	1.8%	2.6%
3. RTU Replacement	3.6%	32.6%	7.2%	10.3%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement	n/a (no chiller in elementary school model)				2.6%	5.5%	3.2%	3.0%
5. HVAC Controls + Lighting + IAQ	24.1%	24.7%	24.2%	23.9%	25.8%	-10.9%*	23.0%	18.8%
6. HVAC Equip + Controls, Envelope + IAQ	5.0%	33.6%	8.5%	12.2%	5.2%	16.1%	6.1%	6.4%
7. HVAC Equip + Controls, Lighting + IAQ	25.1%	29.6%	25.7%	26.1%	27.1%	-1.3%*	24.9%	21.9%
8. Partial Electrification + EE + IEQ	23.7%	38.9%	25.6%	26.6%	26.2%	15.0%	25.3%	22.9%
9. Full Electrification + EE + IEQ	29.0%	87.2%	31.2%	35.6%	30.1%	86.0%	29.8%	30.7%

* 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

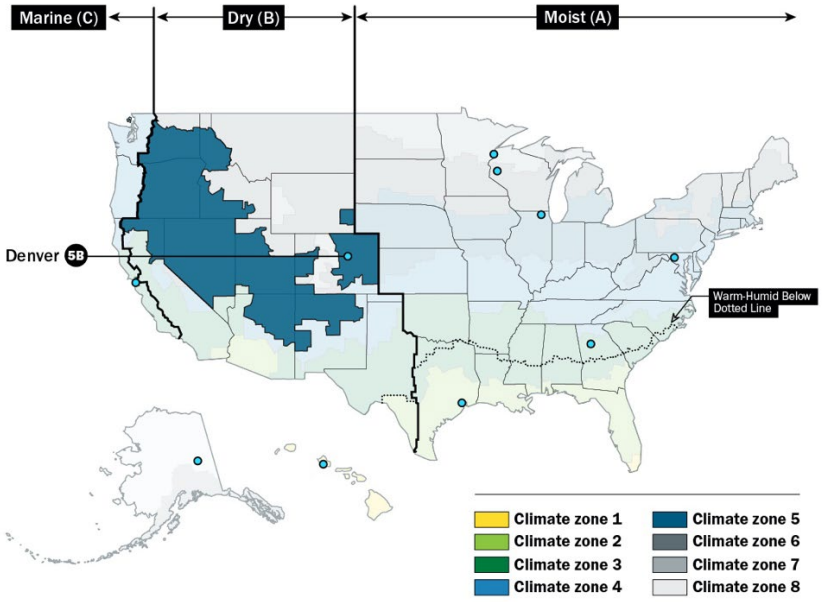


Electricity, Gas, and CO2 savings estimates per retrofit package for Climate Zone 5A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO2	Cost	Elec	Gas	CO2	Cost
1. BMS Replacement	1.9%	36.2%	5.1%	6.3%	0.8%	8.2%	1.8%	2.6%
2. Boiler Replacement	0.1%	10.7%	1.1%	1.9%	0.1%	8.1%	1.3%	2.2%
3. RTU Replacement	2.9%	30.5%	5.5%	5.6%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement	n/a (no chiller in elementary school model)				2.1%	4.0%	2.4%	1.9%
5. HVAC Controls + Lighting + IAQ	23.9%	22.8%	23.8%	23.4%	25.6%	-11.4%*	23.4%	20.9%
6. HVAC Equip + Controls, Envelope + IAQ	3.8%	30.9%	6.4%	6.1%	4.1%	14.8%	4.8%	1.7%
7. HVAC Equip + Controls, Lighting + IAQ	24.8%	28.6%	25.2%	24.7%	26.7%	-0.8%*	25.1%	22.4%
8. Partial Electrification + EE + IEQ	23.2%	35.6%	24.4%	24.6%	25.8%	11.0%	24.9%	22.8%
9. Full Electrification + EE + IEQ	29.8%	91.0%	28.1%	31.9%	30.8%	90.6%	27.0%	29.2%

* 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

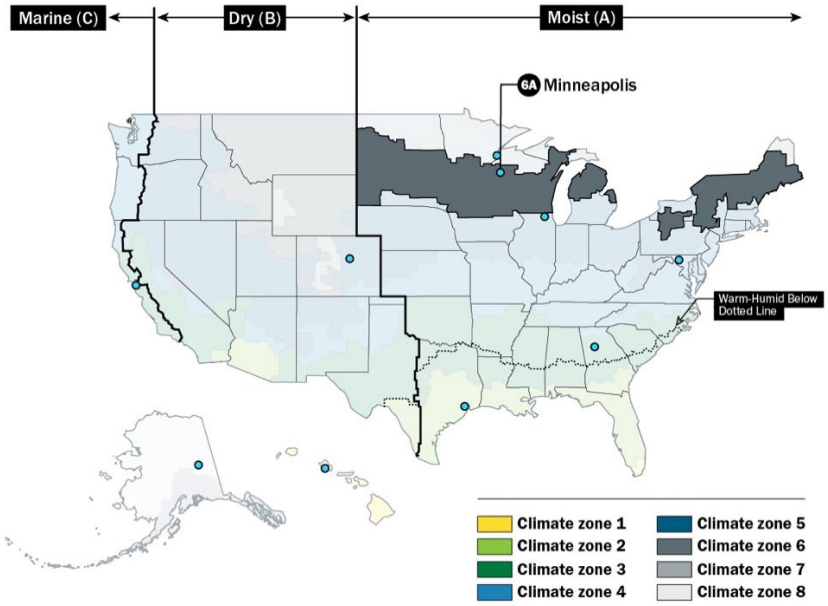


Electricity, Gas, and CO2 savings estimates per retrofit package for Climate Zone 5B

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO2	Cost	Elec	Gas	CO2	Cost
1. BMS Replacement	1.4%	37.4%	4.5%	9.1%	0.5%	9.5%	1.8%	3.5%
2. Boiler Replacement	0.1%	11.2%	1.0%	2.5%	0.1%	9.5%	1.5%	3.3%
3. RTU Replacement	2.4%	33.0%	5.1%	9.0%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement	n/a (no chiller in elementary school model)				1.4%	6.4%	2.1%	3.1%
5. HVAC Controls + Lighting + IAQ	23.9%	23.9%	23.9%	23.8%	25.9%	-13.5%*	23.8%	20.4%
6. HVAC Equip + Controls, Envelope + IAQ	3.4%	31.8%	5.8%	9.5%	3.2%	15.6%	3.9%	4.9%
7. HVAC Equip + Controls, Lighting + IAQ	24.8%	28.4%	25.1%	25.4%	26.6%	-4.1%*	25.0%	22.3%
8. Partial Electrification + EE + IEQ	23.1%	38.7%	24.4%	26.4%	25.5%	14.4%	25.0%	24.0%
9. Full Electrification + EE + IEQ	31.4%	86.7%	26.9%	35.2%	34.4%	85.4%	26.9%	32.1%

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

Climate Zone 6A: Minneapolis

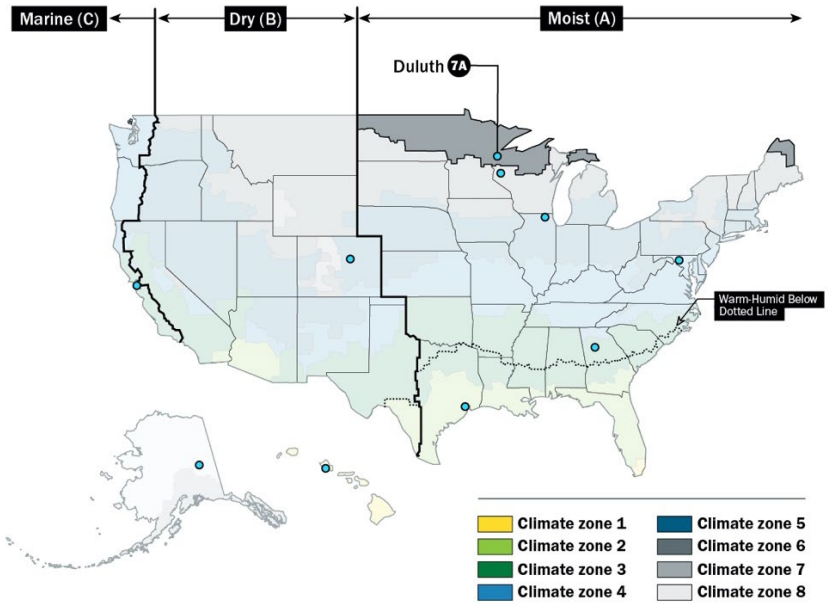


Electricity, Gas, and CO2 savings estimates per retrofit package for Climate Zone 6A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO2	Cost	Elec	Gas	CO2	Cost
1. BMS Replacement	0.9%	36.5%	6.5%	9.5%	0.4%	7.7%	2.2%	2.7%
2. Boiler Replacement	0.1%	10.2%	1.7%	2.1%	0.1%	7.7%	2.0%	2.3%
3. RTU Replacement	1.8%	30.8%	6.3%	9.6%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement	n/a (no chiller in elementary school model)				1.4%	3.8%	2.0%	3.0%
5. HVAC Controls + Lighting + IAQ	23.4%	22.4%	23.3%	23.3%	25.5%	-12.5%*	21.7%	20.1%
6. HVAC Equip + Controls, Envelope + IAQ	2.3%	30.1%	6.6%	10.2%	2.6%	13.8%	3.7%	6.9%
7. HVAC Equip + Controls, Lighting + IAQ	24.3%	28.2%	24.9%	25.6%	26.3%	-1.7%*	23.5%	23.0%
8. Partial Electrification + EE + IEQ	22.5%	35.1%	24.4%	25.6%	25.2%	10.0%	23.7%	23.7%
9. Full Electrification + EE + IEQ	20.1%	91.7%	31.2%	35.1%	21.3%	91.3%	28.3%	30.6%

* 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

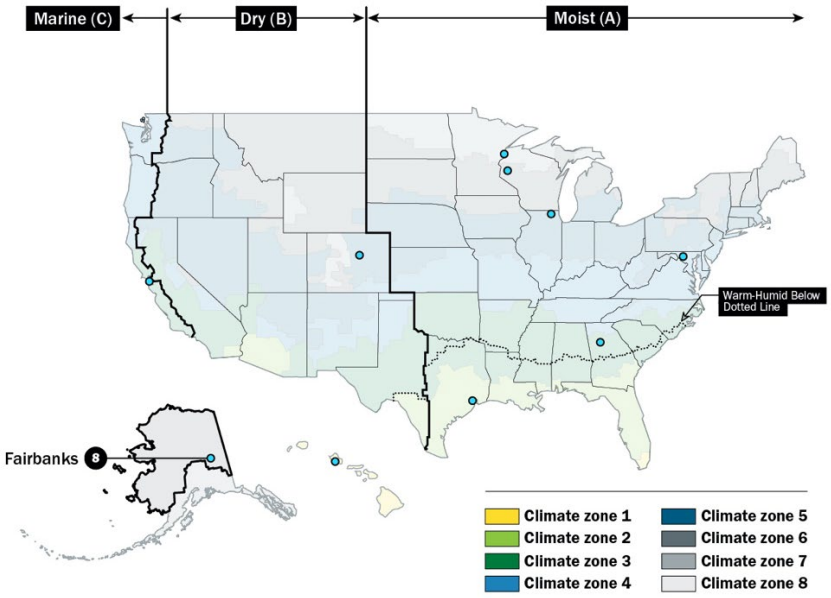


Electricity, Gas, and CO2 savings estimates per retrofit package for Climate Zone 7A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO2	Cost	Elec	Gas	CO2	Cost
1. BMS Replacement	0.4%	34.5%	7.1%	9.7%	0.4%	7.0%	2.4%	2.9%
2. Boiler Replacement	0.2%	9.5%	2.0%	2.6%	0.1%	7.0%	2.2%	2.6%
3. RTU Replacement	0.4%	28.9%	6.0%	8.5%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement	n/a (no chiller in elementary school model)				0.3%	2.8%	1.1%	1.2%
5. HVAC Controls + Lighting + IAQ	23.0%	20.2%	22.4%	22.2%	25.3%	-13.9%*	20.0%	19.2%
6. HVAC Equip + Controls, Envelope + IAQ	0.7%	27.5%	6.0%	8.6%	1.1%	12.6%	2.7%	5.7%
7. HVAC Equip + Controls, Lighting + IAQ	23.2%	26.9%	23.9%	24.2%	25.3%	-2.3%*	21.6%	21.1%
8. Partial Electrification + EE + IEQ	21.2%	32.6%	23.5%	24.2%	24.0%	7.4%	21.8%	21.9%
9. Full Electrification + EE + IEQ	n/a (package not optimized for very cold climate)							

* 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: Fairbank



Electricity, Gas, and CO2 savings estimates per retrofit package for Climate Zone 8A

Retrofit Package	Elementary School Annual Savings				Secondary School Annual Savings			
	Elec	Gas	CO2	Cost	Elec	Gas	CO2	Cost
1. BMS Replacement	0.2%	32.6%	10.9%	8.6%	0.4%	7.0%	3.4%	3.0%
2. Boiler Replacement	0.4%	9.9%	3.5%	2.8%	0.1%	7.0%	3.2%	2.6%
3. RTU Replacement	0.2%	25.6%	8.6%	7.0%	n/a (no RTUs in secondary school model)			
4. Chiller Replacement	n/a (no chiller in elementary school model)				0.2%	1.9%	0.9%	0.8%
5. HVAC Controls + Lighting + IAQ	22.6%	18.2%	21.1%	21.2%	24.5%	-9.6%*	16.1%	18.2%
6. HVAC Equip + Controls, Envelope + IAQ	0.4%	25.2%	8.6%	7.1%	0.7%	12.3%	3.5%	3.5%
7. HVAC Equip + Controls, Lighting + IAQ	22.9%	26.0%	24.0%	23.5%	24.5%	2.3%	19.0%	20.3%
8. Partial Electrification + EE + IEQ	20.8%	29.5%	23.6%	22.9%	23.2%	7.9%	19.4%	20.4%
9. Full Electrification + EE + IEQ	n/a (package not optimized for very cold climate)							

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

Appendix A – 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.

1. Energy Reduction Measurement and Verification

To assess the overall energy efficiency benefits of the project, a school or district shall assess energy impacts over the course of a 12-month period, making use of pre-retrofit energy consumption data and comparing it to post-retrofit consumption. A school or district shall 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 shall 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) as interested to understand energy performance of key systems or equipment.

Energy impacts shall be measured and evaluated separately for each fuel source (e.g. electricity [kWh] and natural gas [therms]) where applicable. Absolute and relative energy impacts shall be reported. Renewable generation is excluded from the energy efficiency metric calculation, as is electric vehicle charging. Energy impact shall 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 shall follow industry guidance such as IPMVP[3] (Option C), and ASHRAE Guideline 22. Baseline models shall be created for a representative sample of buildings and shall meet industry best practice model fit guidelines[4] 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 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* *± Non-Routine Adjustments*

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

[4] 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)

- 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)

2. Greenhouse Gas Emission Reduction Calculations

Greenhouse gas (GHG) emission reduction may occur as the result of the reduction of energy use (e.g. electricity and natural gas), through the implementation of energy efficiency measures, or through 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 delivered energy i
Cf_i is the annual average emission factor for each delivered energy i

Annual average emission factors across the U.S. are provided for electricity use in the appendix, Table E and for other fuel types in Table F.

Appendix B – 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.

1. Health Improvements

A school or district shall 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 shall be prioritized for inclusion and description because it is among the recommended strategies to mitigate risks from airborne viruses[5], and studies have also demonstrated the strongest associations with benefits to student performance and absenteeism[6]. Appendix Table D provides examples of probable IEQ improvements and the associated benefits from the sample retrofit packages. A school or district shall 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[7], CHPS[8], and IPMVP (2001)[9] to define 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 (CO2) 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 protocol for making multi-parameter measurements or conduct an occupant survey to evaluate satisfaction.

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

[6] 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

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

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

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

2. 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 shall 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 are encouraged to consider the top hazards that are 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[10].

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[11] for their location.

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

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

Appendix C – Table C. Retrofit Package Details

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	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	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 prototype Secondary School)
4. Chiller Replacement	n/a (no chiller equipment in prototype Elementary School)	This package of efficiency measures can be incorporated with a chiller replacement. In addition to a high efficiency chiller

Package	Elementary School	Secondary School
		(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 consistent with an LED retrofit indoors and outdoors as well as occupancy sensor controls on indoor and outdoor lighting, and	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-controlled ventilation (DCV). The lighting measure includes lighting power density reduction consistent with an LED retrofit indoors and outdoors as well as

Package	Elementary School	Secondary School
	daylighting controls on indoor lighting.	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 of the lighting efficiency measures.	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.
8. Partial Electrificatio n + EE + IEQ	This package combines the HVAC equipment and controls improvements of previous	This package combines the HVAC equipment and controls improvements of previous

Package	Elementary School	Secondary School
	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.	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, and the improved envelope measures (window films and cool roof). 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, and the improved envelope measures (window films and cool roof). This package also adds an energy recovery system for ventilation air.

Appendix D – Table D. Expected IEQ Improvements and Associated Benefits from Retrofit Package Measures

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 comfort being maintained; can also

Retrofit Type	Efficiency Measures and Impacts	Potential IEQ and Health Benefits
		reduce heat island effect in the vicinity

Appendix E – Table E. State Electricity Generation Output Emission Rates

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

State	Total electricity grid output emission rates (lb/MWh) CO_2e (carbon emissions)
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

State	Total electricity grid output emission rates (lb/MWh) CO_2e (carbon emissions)
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**

(eGRID2020)[12]

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

Appendix F – Table F. CO2e Emissions Factors for Fuels Burned on site[13]

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[14]	71.30
Coal (anthracite)	104.44
Coal (bituminous)	94.03
Coke	114.42
Wood	95.05

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

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