EFFICIENT AND HEALTHY SCHOOLS

Building Management System Replacement Package

Performance Requirements, Savings and Costs

Version 1.0

August 17, 2022

BERKELEY LAB

kW ENGINEERING

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Disclaimer

Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Authors

Duane Kubischta, kW Engineering
James Donson, kW Engineering
Peter Pollard, kW Engineering
Amol Shenoy, kW Engineering

Paul Mathew, Lawrence Berkeley National Laboratory
Sang Hoon Lee, Lawrence Berkeley National Laboratory

1. Introduction

Infrastructure upgrades in schools are a prime opportunity to implement energy efficiency and decarbonization measures that can reduce costs, improve indoor environmental quality, and lower greenhouse gas emissions.

School districts often have to replace their Building Management System (BMS)[1] 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 guide describes a package of complementary efficiency measures that can be combined with a building management system (BMS) replacement. These include:

- 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
- Comprehensive retro-commissioning

This guide includes information on:

- Performance requirements for energy efficiency
- Energy savings
- Implementation costs

The guide is primarily intended for school facilities staff involved with the planning, design and specification of infrastructure upgrades. It may also be useful for allied stakeholders such as designers, energy consultants and service providers.

[1] A building management system (BMS) is a common term for a control system that manages individual building systems and subsystems. It is sometimes referred to as a building control system (BCS), building automation systems (BAS), or energy management system (EMS). The core features of a BMS are: the ability to command systems and components to start and stop; and allow a user to set, adjust, and monitor setpoints.

How to use this guide:

- Read the package overview section and identify which complementary measures are in scope for your project.
- Use the performance requirements (section 2) as a template to develop project requirements and modify them as appropriate for your project. (However, note that the language here is not written as a specification that can be directly used as-is in a contractual technical document).
- The energy savings data are based on an energy simulation analysis of the DOE prototype models for primary and secondary schools. The actual savings for your site will vary based on your site characteristics. These savings data can be used for planning purposes and for presenting the value proposition to the school board and other stakeholders, prior to conducting detailed savings calculations.
- The cost data are indicative of average costs for the US. They may be used to get a "first order" estimate of the cost of the package for planning purposes, prior to conducting a more detailed cost estimate.

2. Performance Requirements

2.1 Control System

2.1.1 Functionality

The control system should provide the following minimum functionality:

- Real-time graphical viewing and control of environment
- Scheduling and override of building operations
- The scheduling interface should be capable of programming at least 12 months into the future, including routine recurring events and specific one-time events lasting up to multiple weeks.
- Collection and analysis of historical data, with a minimum 12-month retention.
- The system should be setup to automatically archive trends older than a month to a building automation system server, stored by calendar year, on a weekly basis.
- Alarm reporting, routing, messaging, and acknowledgment.
- Point database shall be organized by floor and equipment.
- Program editing.
- Transfer trend data to third-party software.
- Scheduling reports.
- Operator activity log.

2.1.2 Graphics

Each graphic is to include all control points, devices and user adjustable setpoints/ parameters associated with the system. Provide links that allow a user to logically negotiate all graphics in a hierarchical manner. Generate the following graphics and associated information as a minimum:

- Campus Map View
- Air Handlers/Roof-top Units
- Terminal Units/Thermostats
- Individual Terminal Units View
- Floor Plan View
- Tabular Views of equipment
- Chilled Water Plant
- Condenser Water Plant
- Heating Hot Water Plant
- Exhaust Fan Summary

2.1.3 Trending

- The control system is to be configured to trend all setpoints, measurements, commands, and statuses at 10 minute intervals with the capability of trending at 5 minute intervals without unnecessarily slowing the network.
- The control system is to be provided with adequate storage for 18 months of trend storage.
- The control system is to be configured to export the trend data manually via a .CSV or Microsoft Excel file (.xls or .xlsx).

2.1.4 Demand Response Support

- The control system should support load shedding upon receipt of a demand response signal using OpenADR 2.0 or another approved automated demand response standard used by the local energy utilities.
- If desired, the control system should provide the capability for an authorized user to manually initiate a load shed.
- The control system shall support at least four tiers of load shedding events.
- The control system shall support, at minimum, the following demand response strategies:
  - Zone temperature adjustments.
  - VFD speed limiting.
  - Shutting-off equipment.

2.2 Complementary Measures

2.2.1. Supply air temperature resets (for air handling units)

Implement a supply air temperature *(SAT)* reset using Trim & Respond logic, based on zone temperature cooling loops, as follows:

- Set maximum SAT setpoint to 65 °F (adjustable).
- Set minimum SAT setpoint to 57 °F (adjustable).
- Generate a temperature request when any zone cooling loop demand is 95% or above (adjustable).
- Trim the setpoint every 3 minutes (adjustable) as follows:
  - If the number of temperature requests is 0, INCREASE the SAT setpoint by 0.2 °F (adjustable).
  - If the number of temperature requests is greater than 0, DECREASE the SAT setpoint by 0.3 °F (adjustable).

2.2.2. Duct static pressure reset (for air handling units)

Implement a duct static pressure *(DSP)* reset using Trim & Respond logic, based on terminal unit damper positions, as follows:

- Set maximum DSP setpoint to 1.5 inches of water (adjustable).
- Set minimum DSP setpoint to 0.1 inches of water (adjustable).
- Generate a pressure request when any damper position is 95% open or above (adjustable).
- Trim the setpoint every 3 minutes (adjustable) as follows:
  - If the number of pressure requests is 0, DECREASE the DSP setpoint by 0.05 inches of water (adjustable).
  - If the number of pressure requests is greater than 0, INCREASE the DSP setpoint by 0.06 inches of water (adjustable).

2.1.3 Optimum start

An adaptive optimum start algorithm should commence warm-up mode. The adaptive algorithm shall compare the following:

- The minimum zone thermostat temperature reading to its warm-up setpoint, 65°F (adjustable).
- Based on the zone temperatures and the warm-up mode setpoint, the adaptive algorithm should automatically adapt the warm-up response time for the next unoccupied period.

- During both stages of warm-up mode, the economizer outside air damper (and the minimum outside air damper if applicable) should be closed and the chiller should remain off.
- At the conclusion of the morning warm-up, the control system should:
  - Reset the supply air temperature tuning loop.
  - Remove the warm-up mode minimum outside air damper and economizer outside air damper lockout.
  - Remove the warm-up mode chiller lockout.
- The optimum start warm-up time (period before occupancy required to warm-up a zone) should be limited to 3 hours (adjustable)

2.2.4. Supply fan variable flow (typically via variable frequency drives (VFD))

Select RTUs with variable flow capability, which is often standard on high efficiency RTUs, or convert constant air volume (CAV) systems to variable air volume (VAV). Fan rotational speed adjustments are the most efficient means of controlling fan flow. Variable frequency drives (VFDs) are a common and the most efficient means of controlling the fan speed. As fan speed is reduced, the airfan flow drops about proportionately; however fan power falls much faster (exponentially, to the power of about 2.4 in practice). For example, a fan slowed to 75% speed provides about 75% the airflow, but uses only about half the power of full speed operation.

Controls guidelines:

- Many RTUs have built-on controls for fan variable speed, integrated with cooling and other controls.
- For large units, the VFD and associated controls may be set by the BMS. The supply (evaporator) fan should use the VFD to vary the air volume supplied to the zone(s). If the fan serves multiple zones with terminal boxes, the fan should continuously vary the speed based on a duct static pressure setpoint and reset. If the fan serves a single zone, the fan speed should be controlled based on the current heating, cooling, or ventilation stage.

2.2.5. Variable flow chilled water pump (typically using variable frequency drives (VFDs))

Variable flow water systems have become more common with the advent of energy efficient variable flow pumps utilizing VFDs. Pump affinity laws state that pump power decreases exponentially as the speed and flow decreases. Slowing a pump by even 10% reduces its power demand by about one-quarter. Non-energy related benefits include reduced vibration and noise. Additionally, the hydraulic forces on the impeller decrease with reduced speeds, lengthening the impeller bearing and seal life.

Piping and control system design is needed. In particular, care must be taken to maintain minimum required flow through the chiller at all times. Acceptable flow range should be confirmed with the chiller's manufacturer. For a chilled water system piped as primary-only (one pump circulates water through both the chiller and the distribution system), different piping and valve options exist. For example, it may be appropriate to add a bypass pipe with bypass valve.

General best practice for a variable flow system is to actively monitor differential pressure (DP) and a sample of perimeter zone space temperatures. The pump VFD speed will be modulated to ensure all areas are satisfied. Follow these guidelines when implementing this measure:

- Chilled water pump speed needs to maintain supply-to-return differential pressure (DP) setpoint[2].
- The DP sensor needs to be installed at the most remote coil.
- The reset strategy needs to be based on valve position. The DP setpoint should be reset upwards until the valve controlling the coil that requires the highest DP is wide open. Similarly, as the valve begins to close, reset the DP down to a minimum value as set by the TAB contractor.
- Chilled water pump operation should be tied to the operation of the chiller.
  - When the chiller is on, the lead chilled water pump shall engage.
  - When the chiller is disabled, the pump shall turn off within 10 minutes of the chiller turning off.
- Valve position can be used to reset either chilled water supply temperature (CHWST) setpoint or the DP setpoint, but not both simultaneously. It would be difficult to determine if the valve is starved for the lack of pressure or enough cold water.
- Program the chilled water plant such that when the plant receives a request for maximum cooling, reset the CHWST to its minimum setpoint and DP to its maximum setpoint.
- As the chilled water load decreases, reset CHWST upwards until it reaches its maximum setpoint value and then reset the DP to its minimum value.

[2] As decided by the testing and balancing (TAB) contractor.

2.2.6. Chilled water supply temperature resets

Implement a chilled water supply temperature (CHWST) reset using Trim & Respond logic, based on chilled water valve position, as follows:

- Set maximum CHWST setpoint to 55°F (adjustable).
- Set minimum CHWST setpoint to 45°F (adjustable).
- Generate a cooling request when any chilled water valve is 90% open or above (adjustable).
- Trim the setpoint every 3 minutes (adjustable) as follows:
    - If the number of cooling requests is 0, INCREASE the CHWST setpoint by 0.5 °F (adjustable).
    - If the number of cooling requests is greater than 0, DECREASE the CHWST setpoint by 0.5 °F (adjustable).

2.2.7. Variable flow heating hot water pump (typically using variable frequency drives (VFDs))

Variable flow water systems have become more common with the advent of energy efficient variable flow pumps utilizing VFDs. Pump affinity laws state that pump power decreases exponentially as the speed and flow decreases. Slowing a pump by even 10% reduces its power demand by about one-quarter. Non-energy related benefits include reduced vibration and noise. Additionally, the hydraulic forces on the impeller decrease with reduced speeds, lengthening the impeller bearing and seal life.

Piping and control system design is needed. In particular, care must be taken to maintain minimum required flow through the boiler at all times. Acceptable flow range should be confirmed with the boiler's manufacturer.

General best practice for a variable flow system is to actively monitor differential pressure (DP) and a sample of perimeter zone space temperatures. The pump VFD speed will be modulated to ensure all areas are satisfied. Follow these requirements when implementing this measure:

- Heating hot water speed pump speed needs to maintain supply-to-return differential pressure (DP) setpoint[3].
- The DP sensor needs to be installed at the furthest coil.
- The reset strategy needs to be based on valve position. The DP setpoint should be reset upwards until the valve controlling the coil that requires the highest DP is wide open. Similarly, as the valve begins to close, reset the DP down to a minimum value as set by the TAB contractor.

[3] As decided by the testing and balancing (TAB) contractor.

- Heating hot water pump operation should be tied to the operation of the boiler.
  - When the boiler is enabled, the lead heating hot water pump shall be commanded on.
  - When the boiler is disabled, the pump shall turn off within 10 minutes of the boiler turning off.
- Valve position can be used to reset either heating hot water supply temperature (HHWST) setpoint or the DP setpoint, but not both simultaneously. It would be difficult to determine if the valve is starved for the lack of pressure or enough hot water.
  - At design heating the system operates at design DP and design HHWST.
  - As the heating hot water load declines, the heating system first resets the HHWST.
  - When the HHWST is at its minimum, the pump modulates its speed down.

2.2.8. Hot water supply temperature resets (non-condensing boilers only)

Implement a heating hot water supply temperature (HHWST) reset as follows:

- Set maximum HHWST setpoint to 180°F (adjustable).
- Set minimum HHWST setpoint to 150°F (adjustable).
- Enable the heating hot water plant at its lowest stage when the number of heating requests exceeds the number of ignored requests (default: 0) and when the outside air temperature is below the heating hot water lock-out temperature.
- Generate a heating request when any heating hot water valve is greater than 95% open (adjustable).
- Release the output signal when the most open valve falls below 10% (adjustable).
- Trim the setpoint every 3 minutes (adjustable) as follows:
  - If the number of heating requests is above 2, INCREASE the HHWST setpoint by 0.5 °F (adjustable).
  - If the number of heating requests is equal to or less than 2, DECREASE the HHWST setpoint by 0.5 °F (adjustable).

2.2.9. Comprehensive retro-commissioning

Comprehensive retro-commissioning is a worthwhile investment when replacing or upgrading a BMS. A new BMS software may offer new software capabilities. Repairs and replacement of BMS components (sensors, valves, actuators, etc.) may enable additional capabilities. The Building Commissioning Association (BCxA) offers best practices and owner resources[4] and ENERGY STAR also offers a Guide to Retro-Commissioning[5].

---

[4] https://www.bcxa.org/resources/

[5] https://www.energy.gov/eere/slsc/downloads/energy-star-guide-retro-commissioning

3. Energy and GHG Savings

Energy savings for the package will vary depending on location, existing building systems and operating characteristics. We calculated the energy savings for the package using the DOE prototype models for primary and secondary schools (Figures 1 and 2 respectively), representative of post-1980 construction, generally conforming to ASHRAE Standard 90.1-1989. Table 3 shows the key characteristics of the models.

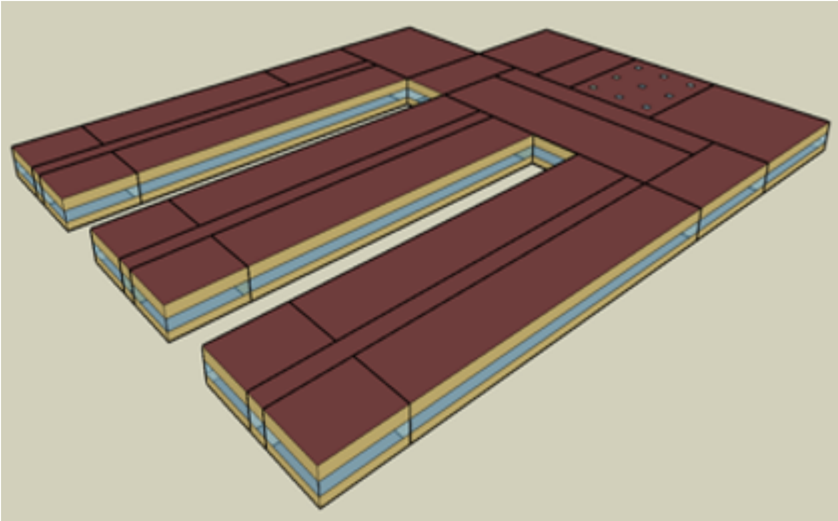

Figure 1. Primary school - DOE prototype model geometry

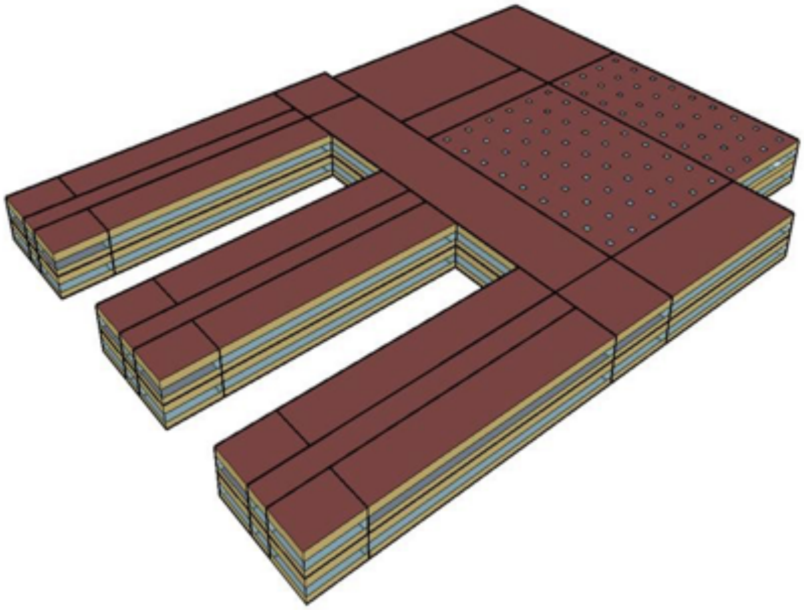

Figure 2. Secondary school - DOE prototype model geometry

Table 3. DOE prototype model characteristics

Characteristic	Primary School	Secondary School
Floor area	73,959 sq.ft	210,810 sq.ft
Number of floors	1	2
Window to wall ratio	0.35	0.33
Floor-to-ceiling height	13.1 ft	13.1 ft
Roof type	Built-up flat roof, insulation entirely above deck. Insulation varies by location	Built-up flat roof, insulation entirely above deck. Insulation varies by location
Wall type	Steel frame with batt insulation (varies by location)	Steel frame with batt insulation (varies by location)
HVAC system type	MZ VAV with hot water reheat, PSZ-AC (gym, kitchen, cafeteria)	MZ VAV with hot water reheat, PSZ-AC (gym, aux gym, auditorium, kitchen, & cafeteria)
Heating type	Boiler, gas furnace (gym, kitchen, & cafeteria)	Boiler, gas furnace(gym, aux gym, auditorium, kitchen, & cafeteria)
Cooling type	Two speed DX unit, PACU (gym, kitchen, & cafeteria)	Air cooled chiller, PACU (gym, aux gym, auditorium, kitchen, & cafeteria)
Fan control	Variable, constant (gym, aux gym, kitchen, & cafeteria)	Variable, constant (gym, aux gym, auditorium, kitchen, & cafeteria)
Service water type	Gas, storage tank	Gas, storage tank

The retrofit scenario that was modeled included implementation of all the complementary measures described earlier. The chiller-related measures only apply to the secondary school. The retro-commissioning measures assumed scheduling tune-ups and economizer repairs. It was assumed that the BMS replacement itself does not provide any savings i.e., all the energy savings are attributable to the complementary measures.

Table 4 shows the site energy, electricity, natural gas and GHG (CO2e) percentage savings for primary and secondary schools. The savings are shown for seven locations representing IECC climate zones 2A (hot humid), 3A (warm humid), 3C (warm marine), 4A (mixed humid), 5A (cool humid), 5B (cool dry), 6A (cold humid). Emissions factors for grid electricity and fuels are based on DOE guidelines, which are generally consistent with ENERGY STAR calculation methods.

Table 4. Primary school: Site energy, electricity, natural gas and GHG (CO2e) savings relative to existing building and BAU equipment replacement

	Primary School % savings				Secondary School % savings			
Location (IECC climate zone)	**Total Site Energy**	**Total Site Electricity**	**Total Site Nat. Gas**	**Total GHG**	**Total Site Energy**	**Total Site Electricity**	**Total Site Nat. Gas**	**Total GHG**
Houston, TX (2A)	11.1%	7.3%	34.4%	9.5%	3.5%	1.4%	13.9%	2.6%
Atlanta, GA (3A)	15.1%	5.1%	45.1%	11.4%	4.2%	1.1%	10.8%	3.1%
San Francisco, CA (3C)	11.7%	1.5%	44.0%	10.4%	7.7%	1.2%	21.5%	6.9%
Baltimore, MD (4A)	17.6%	3.4%	48.5%	13.6%	4.4%	1.0%	9.1%	3.6%
Chicago, IL (5A)	21.1%	2.5%	48.5%	11.5%	4.7%	0.8%	8.2%	2.9%
Denver, CO (5B)	16.8%	1.8%	48.5%	7.8%	4.6%	0.5%	9.5%	2.4%
Minneapolis, MN (6A)	22.6%	1.2%	50.3%	14.3%	4.6%	0.4%	7.7%	3.2%

4. Implementation Costs

The implementation cost for the package will depend on the size and specific characteristics of each building. The unit cost data in Appendix A may be used to aid preliminary cost estimation for implementing the package. It provides unit costs for the items included in the package. These unit cost data were used to calculate the incremental cost of the complementary measures in the package for the DOE prototype models for the seven locations mentioned earlier. The incremental energy cost savings were calculated using average electricity and natural gas prices from the Energy Information Administration[6]. Table 5 shows the simple payback of the complementary measures in the package i.e., it does not include the cost of the BMS replacement itself. Since cost data can vary widely based on site characteristics, these simple payback data below should be considered as indicative only.

[6] Using annual data for 2020 (latest complete set available as of this analysis).
Electricity prices: https://www.eia.gov/electricity/state/;
Natural gas prices: https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PCS_DMcf_a.htm

Table 7. Simple payback of the complementary measures in the BMS replacement package. Also shown are the electricity and natural gas prices used for the calculation.

Location (IECC climate zone)	Primary School Simple Payback (yrs)	Sec School Simple Payback (yrs)	Elec Price $/kWh	Gas Price $/MCF
Houston, TX (2A)	4.6	13.0	$ 0.08	$ 6.52
Atlanta, GA (3A)	4.0	10.7	$ 0.10	$ 7.71
San Francisco, CA (3C)	5.8	6.1	$ 0.18	$ 9.78
Baltimore, MD (4A)	3.2	8.0	$ 0.11	$ 10.62
Chicago, IL (5A)	3.9	10.2	$ 0.10	$ 6.84
Denver, CO (5B)	6.5	15.1	$ 0.10	$ 6.23
Minneapolis, MN (6A)	4.6	12.7	$ 0.11	$ 6.39

Note: Electricity and natural gas prices are annualized data by state, from the Energy Information Administration. The data are for 2020 (latest year for which a complete dataset was available).

Appendix A Unit Cost Data

The table below shows the unit costs for various components of the BMS package. It may be used to aid preliminary cost estimation for implementing the package. The unit costs will need to be multiplied by the size and/or number of units for each item. The table shows median (50th percentile) costs for the U.S. as well as the 5th and 95th percentile of the cost range across various U.S. locations. Note that the unit cost spreadsheet only shows items relevant to the complementary measures and assumes typical site conditions. There may be specific constraints or conditions for a given site that may require additional items (e.g., for the VFD, it includes the material and labor cost of the VFD, but not the cost of a Unistrut to rigidly mount the enclosure to a wall or beam; running conduit to the VFD, etc.).

Item	Item Cost		
	5th %ile	50th %ile	95th %ile
Optimum Start/Stop (per zone)	$38	**$40**	$43
Calibration Labor (per point)	$110	**$117**	$125
Front-End Computer w/Software	$5,810	**$6,179**	$6,623
BMS Graphics Software	$3,591	**$3,819**	$4,094
Color Graphic (ea.)	$448	**$477**	$511
VAV Controller	$769	**$817**	$876
16-point Controller (AHU)	$2,997	**$3,187**	$3,416
32-point Controller (Chiller/Boiler Plant)	$4,964	**$5,279**	$5,658
RCx Study (buildings 100,000 ft²)1	$23,790	**$25,298**	$27,118
Motor Replacement 5 hp, 1800 RPM, TEFC	$930	**$989**	$1,060
Motor Replacement 10 hp, 1800 RPM, TEFC	$1,330	**$1,414**	$1,515
Motor Replacement 15 hp, 1800 RPM, TEFC	$1,823	**$1,938**	$2,078
Motor Replacement 20 hp, 1800 RPM, TEFC	$2,801	**$2,978**	$3,193
Motor Replacement 25 hp, 1800 RPM, TEFC	$2,809	**$2,987**	$3,202
Motor Replacement 30 hp, 1800 RPM, TEFC	$3,643	**$3,874**	$4,152

All data are based on RS Means[7], except as indicated:

1. Eliot Crowe, Evan Mills, Tom Poeling, Claire Curtin, Diana Bjørnskov, Liz Fischer, Jessica Granderson, Building commissioning costs and savings across three decades and 1500 North American buildings, Energy and Buildings, Volume 227, 2020, https://doi.org/10.1016/j.enbuild.2020.110408

[7] https://www.rsmeans.com/