EFFICIENT AND HEALTHY SCHOOLS

Chiller Replacement Package

Performance Requirements, Savings and Costs

Version 1.0

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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.

This guide describes a package of efficiency measures that can be incorporated with a chiller replacement. In addition to a high efficiency chiller, the package includes several complementary measures that provide deeper savings and allied benefits.

Primary measure	High efficiency chiller (air-cooled or water-cooled)
Complementary measures	Chilled water supply temperature resets
	Variable flow chilled water pump
	Super premium efficiency motors
	Cooling tower replacement or upgrade
	BMS replacement or upgrade including controls upgrades to related HVAC systems

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.

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 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 High Efficiency Air-Cooled and Water-Cooled Chiller

2.1.1 Introduction

When deciding on a chilled water system, designers must choose between air- and water-cooled chillers. Air-cooled systems eliminate the need for a cooling tower, reducing installation and maintenance costs. However, air-cooled chillers are substantially less efficient than water-cooled models.

A chiller optimized for high full-load efficiency is appropriate for full-load operating conditions; for a chiller that will be operated at part load, a chiller optimized for high-IPLV efficiency is more appropriate. Since most schools will spend the great majority of the year operating their chilled water plant at part loads, the design team should prioritize part-load performance.

2.1.2 Guidelines

2.1.2.1 Air Cooled Chiller

Tables 1 and 2 show the recommended efficiency requirements for air and water-cooled chillers respectively. These are drawn from ASHRAE Standard 90.1, Table 6.8.1-3 Water Chilling Packages.

Table 1. Air-cooled chiller efficiency requirements.

Equipment Type	Size Category	Units	Path A (For chillers designed to operate near full load capacity)	Path B (For chillers designed to operate at part-load)
Air Cooled, with Condenser Electrically Operated	< 150 Tons	EER[1]	≥ 10.100 FL[2] ≥ 13.700 IPLV[3]	≥ 9.700 FL ≥ 15.800 IPLV
	> 150 Tons		>= 10.100 FL ≥ 14.000 IPLV	≥ 9.700 FL ≥16.100 IPLV
Air Cooled, without Condenser Electrically Operated	All Capacities		Air-cooled chillers without condensers must be rated with matching condensers and comply with the air-cooled chiller efficiency requirements.	

1.2.2.2 Water Cooled Chiller

Table 2. Water-cooled chiller efficiency requirements.

Equipment Type	Size Category	Units	Path A (For chillers designed to operate near full load capacity)	Path B (For chillers designed to operate at part-load)
Reciprocating Chiller	< 75 Tons	kW/Ton	≤ 0.750 FL ≤ 0.600 IPLV	≤ 0.780 FL ≤ 0.500 IPLV
	≥ 75 tons and < 150 tons		≤ 0.720 FL ≤ 0.560 IPLV	≤ 0.750 FL ≤ 0.490 IPLV
	≥ 150 tons and < 300 tons		<= 0.660 FL <= 0.540 IPLV	≤ 0.680 FL ≤ 0.440 IPLV
	≥ 300 tons and < 600 tons		≤ 0.610 FL ≤ 0.520 IPLV	≤ 0.625 FL ≤ 0.410 IPLV

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[1] EER - Energy efficiency ratio

[2] FL - Full Load

[3] IPLV - Integrated part load value

	≥ 600 tons		≤ 0.560 FL ≤ 0.500 IPLV	≤ 0.585 FL ≤ 0.380 IPLV
Screw Chiller	< 75 Tons	kW/Ton	≤ 0.750 FL ≤ 0.600 IPLV	≤ 0.780 FL ≤ 0.500 IPLV
	≥ 75 tons and < 150 tons		≤ 0.720 FL ≤ 0.560 IPLV	≤ 0.750 FL ≤ 0.490 IPLV
	≥ 150 tons and < 300 tons		<= 0.660 FL <= 0.540 IPLV	≤ 0.680 FL ≤ 0.440 IPLV
	≥ 300 tons and < 600 tons		≤ 0.610 FL ≤ 0.520 IPLV	≤ 0.625 FL ≤ 0.410 IPLV
	≥ 600 tons		≤ 0.560 FL ≤ 0.500 IPLV	≤ 0.585 FL ≤ 0.380 IPLV
Centrifugal Chiller	< 150 tons	kW/Ton	≤ 0.610 FL ≤ 0.550 IPLV	≤ 0.695 FL ≤ 0.440 IPLV
	≥ 150 tons and < 300 tons		≤ 0.610 FL ≤ 0.550 IPLV	≤ 0.635 FL ≤ 0.400 IPLV
	≥ 300 tons and < 400 tons		≤ 0.560 FL ≤ 0.520 IPLV	≤ 0.595 FL ≤ 0.390 IPLV
	≥ 400 tons and < 600 tons		≤ 0.560 FL ≤ 0.500 IPLV	≤ 0.585 FL ≤ 0.380 IPLV
	≥ 600 tons		≤ 0.560 FL ≤0.500 IPLV	≤ 0.585 FL ≤ 0.380 IPLV

2.2 Complementary Measures

2.2.1. 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).

2.2.2. 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[4].
- 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 should engage.
    - When the chiller is disabled, the pump should turn-off within 10 minutes of the chiller turning off.

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

- Valve position can be used to reset either 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 downwards towards its minimum value.

2.2.3. Super premium efficiency motors

When requesting motor performance quotations, request the comparison to be made in accordance with IE4 motor nameplate marking standards.

Purchase a super premium efficiency motor with nominal efficiency at or near the maximum value available within an enclosure, speed, and size class. Table 3 lists IE4's super-premium efficiency specification level.

Table 3. IE4 super-premium efficiency motor specifications. All efficiencies are in percentage (%)

Motor HP	1200 RPM	1800 RPM	3600 RPM
1	84.0	85.5	82.5
1.5	88.5	87.5	85.5
2	85.9	88.2	86.5
3	90.2	88.5	88.5
5	90.2	91.0	89.5
7.5	91.7	92.4	90.2
10	92.4	92.4	91.7
15	93.0	93.6	92.4
20	93.0	94.1	92.4
25	94.1	94.5	93.0
30	94.1	94.5	93.0
40	95.0	95.0	93.6
50	95.0	95.4	94.1

60	95.4	95.4	95.4
75	95.4	95.8	94.5
100	95.8	96.2	95.0

2.2.4. BMS replacement or upgrade including controls upgrades to related HVAC systems

Chiller replacement may also be an opportune time to consider upgrading or replacing outdated BMS systems. This affords the opportunity to improve controls across multiple HVAC systems. See the *BMS replacement package* and consider controls changes to air handling systems and boiler systems, especially if you are making a general controls upgrade.

3. Energy and GHG Savings

Energy savings for the package will vary depending on location, existing building systems and operating characteristics. Energy savings for the package was calculated using the DOE prototype model for a secondary school (Figure 1), representative of post-1980 construction, generally conforming to ASHRAE Standard 90.1-1989. Table 1 shows the key characteristics of the prototype model, representing a baseline for an existing building.

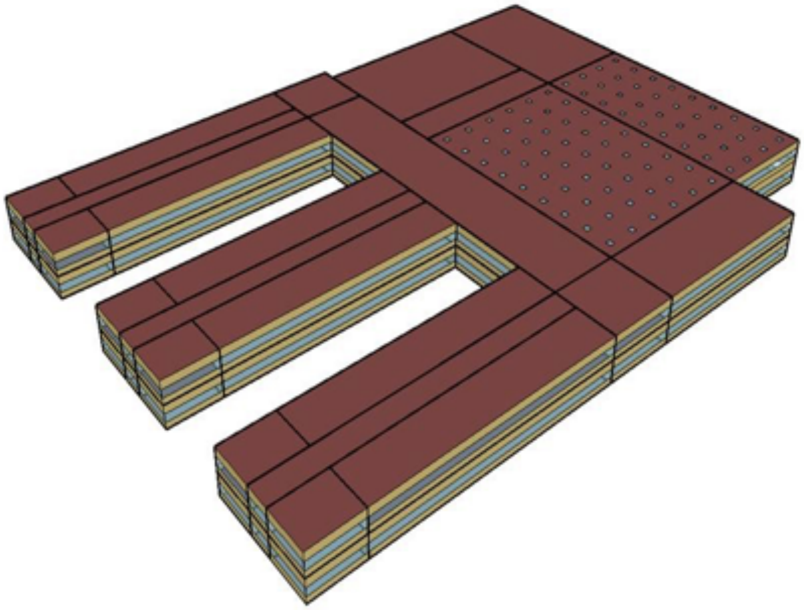

Figure 1. Secondary school - DOE prototype model geometry

Table 4. DOE prototype model characteristics

Characteristic	Secondary School
Floor area	210,810 sq.ft
Number of floors	2
Window to wall ratio	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 (varies by location)
HVAC system type	MZ VAV with hot water reheat, PSZ-AC (gym, aux gym, auditorium, kitchen, & cafeteria)
Heating type	Boiler, gas furnace (gym, aux gym, auditorium, kitchen, & cafeteria)
Cooling type	Air cooled chiller, PACU (gym, aux gym, auditorium, kitchen, & cafeteria)
Fan control	Variable, constant (gym, aux gym, auditorium, kitchen, & cafeteria)
Service water type	Gas, storage tank

The retrofit scenario that was modeled included a high efficiency chiller and the following complementary measures in the package:

- Chilled water temperature reset
- Chilled water pump VFD
- Premium efficiency motors
- BMS upgrade with optimum start, scheduling tune-up and supply air temp reset. It did not include other HVAC system controls upgrades.

Savings were also calculated relative to a “business-as-usual” (BAU) equipment replacement. The BAU replacement assumes the existing chiller is replaced with a new chiller that meets code and does not include any of the additional measures of the ISP. Therefore, the savings represent the marginal benefits of upgrading a code-compliant chiller to a higher-efficiency chiller with the additional ISP measures.

Table 5 shows the site energy, electricity, natural gas and GHG (CO2e) percentage savings relative to the two baselines, i.e., existing building and BAU equipment replacement. 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 5. Site energy, electricity, natural gas and GHG (CO2e) savings relative to existing building and BAU equipment replacement

	% Savings Relative to Existing Building Baseline				**% Savings Relative to Business-as-Usual Replacement**			
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)	5.8%	4.7%	11.5%	5.3%	2.7%	0.9%	11.5%	2.0%
Atlanta, GA (3A)	4.8%	3.6%	7.2%	4.4%	2.9%	0.8%	7.2%	2.2%
San Francisco, CA (3C)	7.5%	2.0%	19.6%	6.9%	7.0%	1.1%	19.6%	6.3%
Baltimore, MD (4A)	3.9%	2.6%	5.5%	3.6%	2.7%	0.5%	5.5%	2.1%
Chicago, IL (5A)	3.1%	2.1%	4.0%	2.7%	2.3%	0.5%	4.0%	1.5%
Denver, CO (5B)	3.7%	1.4%	6.4%	2.5%	3.1%	0.3%	6.4%	1.6%
Minneapolis, MN (6A)	2.8%	1.4%	3.8%	2.3%	2.3%	0.4%	3.8%	1.7%

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 chiller package. It provides unit costs for the items included in the chiller package. These unit cost data were used to calculate the incremental cost of the package relative to a BAU replacement for the DOE prototype model 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[5]. Table 6 shows the simple payback of the chiller package, relative to a BAU

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[5] 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

replacement. Since cost data can vary widely based on site characteristics, these simple payback data below should be considered as indicative only.

Table 7. Simple payback of the chiller package relative to a BAU replacement. Also shown are the electricity and natural gas prices used for the calculation.

Location (IECC climate zone)	Simple Payback (yrs)	Elec Price $/kWh	Gas Price $/MCF
Houston, TX (2A)	3.8	$ 0.08	$ 6.52
Atlanta, GA (3A)	2.5	$ 0.10	$ 7.71
San Francisco, CA (3C)	1.1	$ 0.18	$ 9.78
Baltimore, MD (4A)	2.2	$ 0.11	$ 10.62
Chicago, IL (5A)	3.3	$ 0.10	$ 6.84
Denver, CO (5B)	3.2	$ 0.10	$ 6.23
Minneapolis, MN (6A)	3.7	$ 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).

5. Appendix A Unit Cost Data

The table below shows the unit costs for various components of the chiller package. It may be used to aid preliminary cost estimation for implementing the chiller 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 primary and 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.).

All data are based on RS Means[6], except for the following: IE4 motor marginal material costs are based on an analysis of manufacturer suggested retail prices.

	Item Cost		
Item	**5th %ile**	**50th %ile**	**95th %ile**
High Efficiency Chiller, 153 tons, Water-Cooled, VFD Centrifugal	$520,818	**$553,832**	$593,676
High Efficiency Chiller, 153 tons, Air-Cooled	$464,820	**$494,284**	$529,844
Chilled Water Pump VFD, 25-hp, custom engineered	$8,075	**$8,587**	$9,204
Differential Pressure Sensor, Water	$892	**$949**	$1,017
Differential Pressure Sensor - Weld-on, wet-tap, 2.5" pipe, times two	$1,244	**$1,323**	$1,418
Chiller Optimization Program (each)	$1,487	**$1,581**	$1,695
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

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

Item	Item Cost		
	5th %ile	50th %ile	95th %ile
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
IE4 Motor, Super Premium Efficiency Marginal Material Cost[1]	$369	**$392**	$420
IE4 Motor, Super Premium Efficiency Marginal Material Cost[1]	$471	**$501**	$537
IE4 Motor, Super Premium Efficiency Marginal Material Cost[1]	$615	**$654**	$701
IE4 Motor, Super Premium Efficiency Marginal Material Cost[1]	$650	**$691**	$741
IE4 Motor, Super Premium Efficiency Marginal Material Cost[1]	$533	**$566**	$607
IE4 Motor, Super Premium Efficiency Marginal Material Cost[1]	$485	**$516**	$553
Balance Fan (Proxy cost for shaft-alignment analysis)	$384	**$409**	$438
Balance Pump (Proxy cost for shaft-alignment analysis)	$293	**$311**	$334

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

1. Analysis of manufacturer suggested retail prices.

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