EFFICIENT AND HEALTHY SCHOOLS

Boiler Replacement Package

Performance Requirements, Savings and Costs

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Disclaimer

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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 boiler replacement. In addition to a high efficiency boiler, the package includes several complementary measures that provide deeper savings and allied benefits.

Primary measure	High efficiency boiler
Complementary measures	Hot water supply temperature resets
	Variable flow hot water pump
	Boiler lock-outs
	Condensing boilers
	Networked thermostats
	Super premium efficiency motors

Note: School districts with decarbonization goals should first consider replacing boilers with heat pumps or other approaches that do not require fossil fuels. The package described in this document does not serve that purpose. This package is only recommended as a "last resort" for school districts that are unable to consider electrification and therefore limited to improving the efficiency of fuel-based boilers.

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 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 High Efficiency Boiler

2.1.1 Introduction

A boiler system should be capable of meeting the building's peak heating demand and also operate efficiently at part-load conditions. Selecting the right system and appropriately sizing a boiler requires knowledge of both peak demand and the load profile.

Consider specifying new boilers with the following features:

- Modulating burners: Boilers operate at part-load most of the time. To prevent excessive cycling and the losses that accompany them, specify boilers that have modulating capability. A minimum turndown ratio of 5:1 is recommended for gas-fired, hot-water boilers.
- Low mass: Boilers cycle on and off and it takes more time and energy to bring a high-mass boiler up to operating temperature. Using low-mass boilers will reduce energy consumption. In addition, some boilers can be brought online quickly, therefore avoiding the need to keep a boiler on hot standby.

- Precise air-fuel ratio control: Precise control can be accomplished by using sensor-driven actuator rather than mechanical linkages between gas input and the blower damper. Oxygen trim systems should be used on larger boilers. Oxygen trim systems monitor oxygen in the flue gas and adjust the air-fuel ratio for optimum combustion efficiency.

2.1.2 Guidelines

Table 1 shows the recommended minimum efficiency requirements for natural gas and fuel-oil boilers. These are drawn from ASHRAE Standard 90.1, Table 6.8.1-6 Gas and Oil-Fired Boilers.

Table 1. Minimum efficiency requirement for boilers.

Fuel Type	Size Category	Minimum Efficiency
Natural gas / Propane	< 300,000 Btu/h	82% AFUE[1]
	>= 300,000 Btu/h and =< 2,500,000 Btu/h	80%
	>2,500,000	82%
Fuel oil	< 300,000 Btu/h	84% AFUE
	>= 300,000 Btu/h and =< 2,500,000 Btu/h	82%
	>2,500,000	84%

[1] Annual fuel utilization efficiency

2.2 Complementary Measures

2.2.1. 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 90% 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).

2.2.2. 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 pump speed needs to maintain supply-to-return differential pressure (DP) setpoint, as set by the TAB contractor.

- 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.
- 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 should be commanded on.
  - When the boiler is disabled, the pump should turn-off within 10 minutes of the boiler turning off.
- Valve position can be used to reset either 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 reduces, the heating system first resets the HHWST downward.
  - When the HHWST is at its minimum, the pump modulates its speed down.

2.2.3. Boiler lock-outs

It is also best practice to shut off or 'lock out' a heating hot water boiler and pump when the outside air temperature (OAT) exceeds a predetermined set point. This reduces standby losses at the boiler and heating losses through the distribution systems when the building load no longer requires heating.

Typically boiler lock-out temperature can be set between 65°F - 70°F OAT. The aim of the boiler lockout is to disable the heating system once all zones are in deadband or cooling mode and are not expected to transition back into heating for a few hours.

2.2.4. Condensing boilers

Condensing boilers achieve higher efficiencies by condensing water vapor contained in flue gases. When gas is combusted in a boiler, approximately 90% of the energy contained in the fuel is converted into sensible heat (heat that causes a change in temperature) and approximately 10% is converted into latent heat (heat involved in phase change of a material). This latent heat is stored in the water vapor that is a byproduct of the combustion process.

Condensing boilers reclaim that latent heat by condensing the water vapor and transferring that heat to the incoming return water. When installing condensing boilers consider the following factors to maximize system efficiency:

- The entire system needs to be upgraded (retrofits) or designed (new construction) for condensing applications.
  - The boiler burner assembly must be rated for condensing due to the acidic exposure to flue gases.
  - The boiler flue (stack) will need to be made of stainless steel to avoid corrosion from flue gas condensate on the inner surface of the stack
  - The boiler flue condensate will be acidic and should not be discharged into the drain (neither sanitary sewers or septic systems) without first being neutralized. Most condensate systems use a vessel charged with limestone to raise the condensate pH.
- Minimize mixing within the hydronic system to keep the return water temperature to the boilers as low as possible (lower than 120°F). Higher return temperatures will mean condensation does not occur and efficiency is reduced.
  - Reduce the number of three-way valves in the system, considering the minimum flow bypass with the flow meter approach for minimum flow requirements.
  - Pipe the system for variable-flow primary instead of primary-secondary to eliminate mixing seen in the decoupler between the boiler and the system loops.
  - Design hydronic systems with wider delta-T's - target 30°F to 50°F temperature difference instead of the traditional 10°F to 20°F.
  - Lower the system temperature either by reducing both the supply and return water temperature or widen the system delta-T.
  - Be cautious when reducing system temperature due to its impact on the heating capacity of terminal units. Lowering system temperature often requires larger heating coils in terminal equipment in order to provide the same heating capacity at lower temperatures.

2.2.5. Networked thermostats

Replace existing zone level thermostats with an energy management system utilizing wireless communication with cloud-based servers for all packaged units.

- Internet programmable thermostat should be capable of modulating following setpoints:

- Temperature setpoints.
- System mode (Heat, Cool, Auto, Off).
- Fan mode (Auto, On).

- The web-based configuration of the thermostat should include following options:
  - Naming of the thermostat.
  - Grouping of the thermostat.
- The web-based app (app) should be able to control the following settings on the thermostats in real time:
  - Space temperature.
  - System mode (Heat, Auto, Off).
  - Fan mode (Auto, On).
  - Current setpoint.
  - Relay status (Heat and fan).
  - Historical trend graphs.
  - Scheduling (see below for further details).
  - Lock/Unlock entire thermostat keypad.
  - Lock/Unlock thermostats fan mode setting only.
- Web based graphical user interface (GUI)
  - The app should be able to run on any PC that uses Microsoft Edge, Safari, Chrome, Firefox, or any other web browser that meets these browsers' functionality.
  - The web-based app platform should be able to run on any Internet Accessible Smartphone and/or Tablet.
  - The app should allow up to a minimum of 100 simultaneous users/clients to access the Energy Management System.
  - Each thermostat should include a 20-year Standard subscription to the SaaS platform. The complementary first year Standard subscription should not be included in this provision.
- Schedules
  - The app should provide the user with access to setting schedules for each thermostat. Up to 12 schedule periods per day should be available for each thermostat.
  - Schedules should be available as Weekly (7-day), Daily, or Weekday/Weekend (5-2)
  - The app should provide the user with the ability to:
    - View schedules.

    - Add/modify schedules.
    - Assign the thermostat to a group schedule.
    - Delete schedules.

- Trending
  - The app should provide real-time trend information on the following parameters:
    - Space temperature.
    - Space temperature setpoint.
    - Current call for heat, and/or fan.
    - Call for economization.

2.2.6. Super premium efficiency motors

Consider following factors when replacing existing standard efficiency motors with super premium efficiency motors:

- When requesting motor performance quotations, request the comparison to be made in accordance with IE4 motor nameplate marking standards.
- When preparing specifications for the new motors, identify motor efficiency test standards to be used to determine motor performance.
- Consider standardizing on a single enclosure type (i.e., open drip-proof or totally enclosed fan-cooled) to reduce inventory size.

Purchase a super premium efficiency motor with nominal efficiency at or near the maximum value available within an enclosure, speed, and size class. Table 2 lists IE4's super premium efficiency specification level.

Table 2. 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

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.

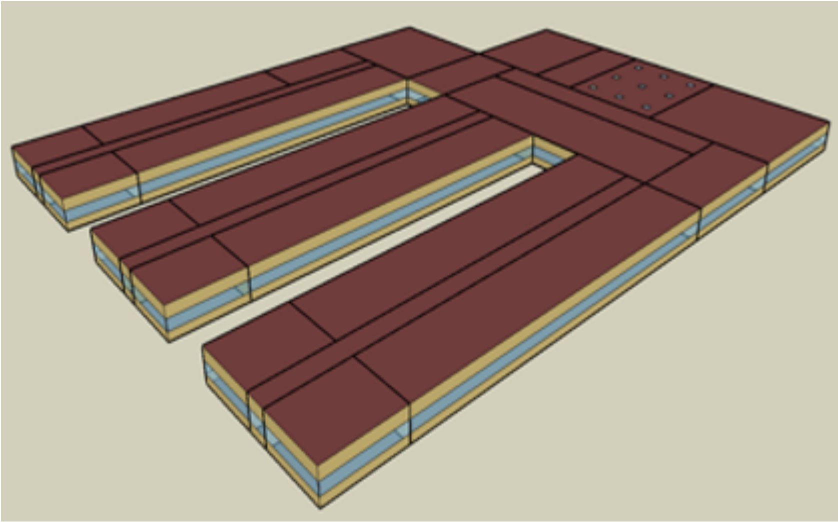

Figure 1. Primary school - DOE prototype model geometry

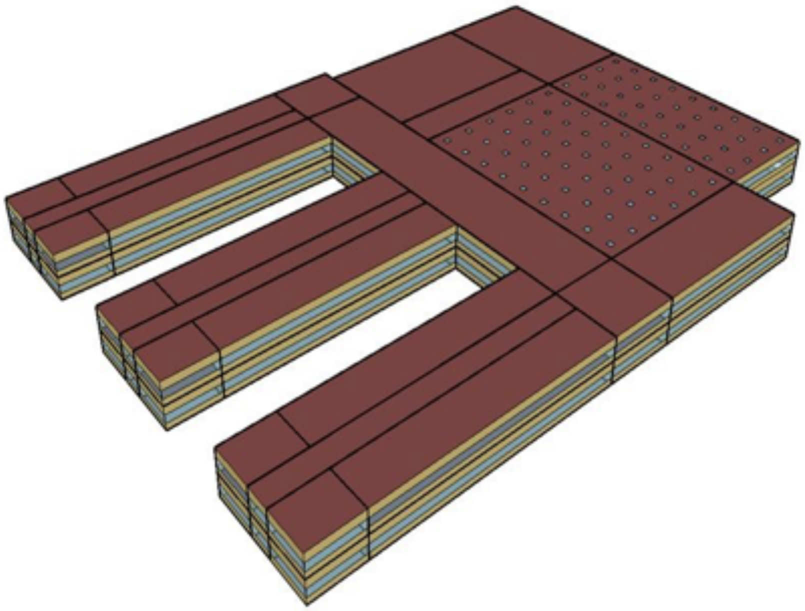

Figure 2. Secondary school - DOE prototype model geometry

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 a high efficiency boiler and the following complementary measures in the package:

- Heating hot water temperature reset
- Heating hot water pump VFD
- Boiler lockout
- Condensing boilers
- Premium efficiency motors
- Networked thermostats 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 boiler is replaced with a new boiler 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 boiler to a higher-efficiency boiler with the additional ISP measures.

Tables 4 (primary school) and 5 (secondary schools) show 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 4. Primary school: 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)	1.8%	0.1%	12.0%	1.1%	1.3%	0.1%	8.1%	0.8%

Atlanta, GA (3A)	3.1%	0.1%	12.2%	2.0%	1.7%	0.1%	6.6%	1.1%
San Francisco, CA (3C)	5.1%	0.1%	21.0%	4.5%	3.9%	0.1%	15.9%	3.4%
Baltimore, MD (4A)	3.6%	0.1%	11.1%	2.6%	1.8%	0.1%	5.4%	1.3%
Chicago, IL (5A)	4.4%	0.1%	10.7%	2.2%	1.8%	0.1%	4.3%	0.9%
Denver, CO (5B)	3.7%	0.1%	11.2%	1.5%	2.0%	0.1%	6.0%	0.9%
Minneapolis, MN (6A)	4.5%	0.1%	10.2%	2.8%	1.8%	0.1%	4.0%	1.1%

Table 5. Secondary school: 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)	2.7%	0.5%	13.9%	1.8%	2.3%	0.5%	11.4%	1.5%
Atlanta, GA (3A)	3.7%	0.3%	10.7%	2.5%	2.6%	0.3%	7.4%	1.8%
San Francisco, CA (3C)	6.7%	0.1%	21.0%	6.0%	5.9%	0.1%	18.5%	5.3%
Baltimore, MD (4A)	4.0%	0.2%	9.1%	3.0%	2.6%	0.2%	5.9%	2.0%
Chicago, IL (5A)	4.3%	0.2%	8.1%	2.4%	2.2%	0.2%	4.0%	1.2%
Denver, CO (5B)	4.4%	0.1%	9.5%	2.1%	3.1%	0.1%	6.7%	1.5%
Minneapolis, MN (6A)	4.5%	0.1%	7.7%	3.1%	2.3%	0.1%	3.8%	1.6%

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 package relative to a business-as-usual (BAU) replacement 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[2]. Table 7 shows the simple payback of the package, relative to a BAU 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 boiler package relative to a BAU replacement. 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)	21.1	3.4	$ 0.08	$ 6.52
Atlanta, GA (3A)	12.8	2.7	$ 0.10	$ 7.71
San Francisco, CA (3C)	5.6	1.5	$ 0.18	$ 9.78
Baltimore, MD (4A)	9.2	2.1	$ 0.11	$ 10.62
Chicago, IL (5A)	12.5	3.3	$ 0.10	$ 6.84
Denver, CO (5B)	15.5	3.4	$ 0.10	$ 6.23
Minneapolis, MN (6A)	14.2	3.6	$ 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).

[2] 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

5. Appendix A Unit Cost Data

The table below shows the unit costs for various components of the boiler 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 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.).

	Item Cost		
Item	5th %ile	50th %ile	95th %ile
Boiler Replacement, Non-Condensing Ancillary Costs (piping, electrical, etc.)	$28,742	**$30,564**	$32,763
Boiler, Heating Hot Water, Nat. Gas, Non-Condensing 2000 kBtu/hr output	$33,398	**$35,515**	$38,070
Boiler Replacement, Condensing Ancillary Costs (piping, electrical, etc.)	$34,588	**$36,781**	$39,427
Boiler, Heating Hot Water, Nat. Gas, Condensing 2000 kBtu/hr output	$40,190	**$42,738**	$45,812
Low ΔT HHW Coil, VAV-RH Size, 12"x24" Hot Water Coil, 2-row, 12 fins/inch, 5/8" tubing	$2,139	**$2,275**	$2,438
Low ΔT HHW Coil, Small RTU Size, 36"x24" Hot Water Coil, 4-row, 12 fins/inch, 5/8" tubing	$6,176	**$6,567**	$7,040
Boiler Optimization Program (each)	$1,121	**$1,192**	$1,278
Hot Water Pump VFD, 15-hp, custom engineered	$6,771	**$7,200**	$7,718
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
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

Item	Item Cost		
	5th %ile	50th %ile	95th %ile
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
IE4 Motor, Super Premium Efficiency Marginal Material Cost[2]	$369	**$392**	$420
IE4 Motor, Super Premium Efficiency Marginal Material Cost[2]	$471	**$501**	$537
IE4 Motor, Super Premium Efficiency Marginal Material Cost[2]	$615	**$654**	$701
IE4 Motor, Super Premium Efficiency Marginal Material Cost[2]	$650	**$691**	$741
IE4 Motor, Super Premium Efficiency Marginal Material Cost[2]	$533	**$566**	$607
IE4 Motor, Super Premium Efficiency Marginal Material Cost[2]	$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, except as indicated:

1. NREL 2014, "Condensing Boilers Evaluation: Retrofit and New Construction Applications"
2. Analysis of manufacturer suggested retail prices.