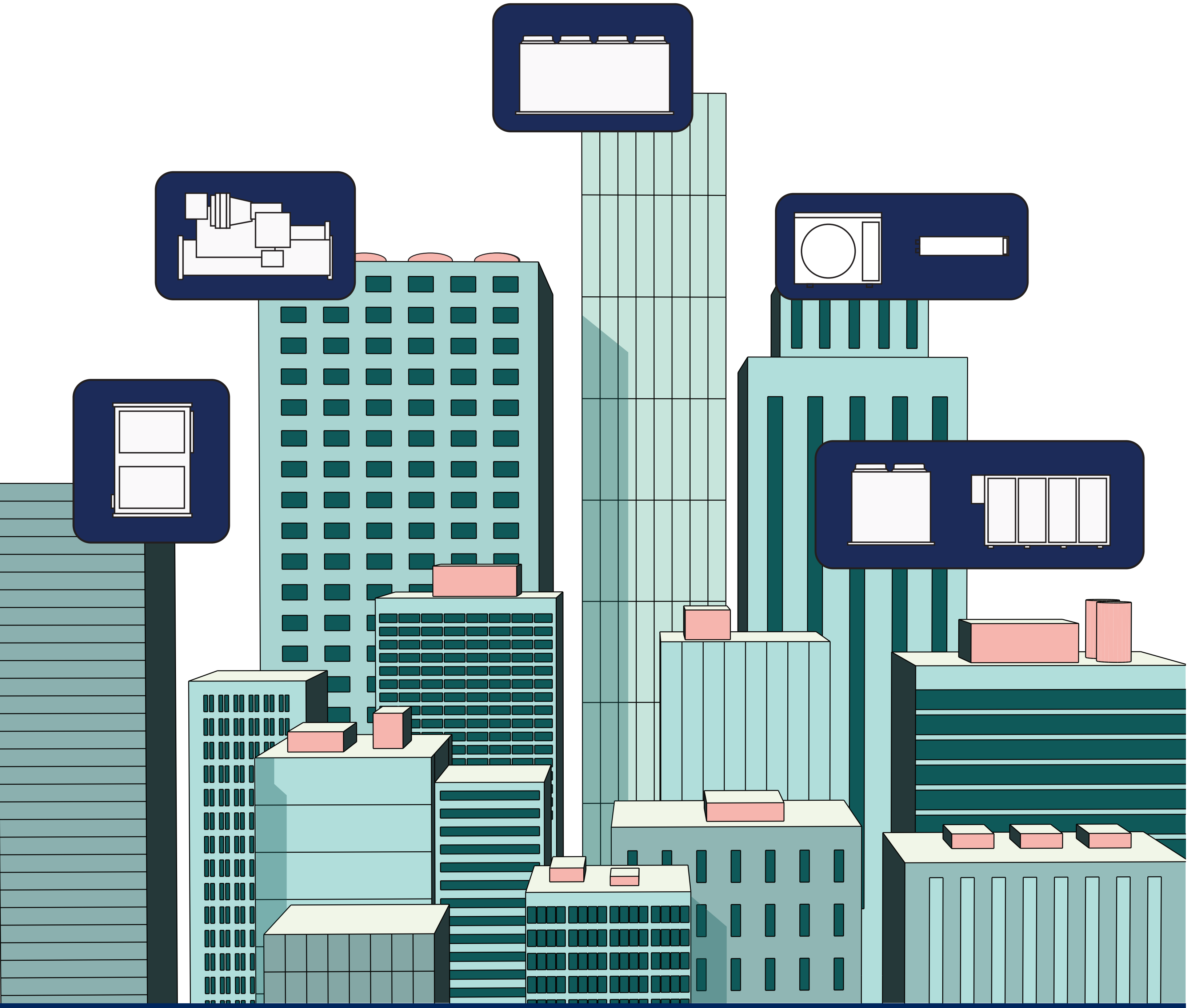
2024 LARGE BUILDING DECARBONIZATION PRICE INDEX



NEW YORK STATE | NYSERDA

Turner

SourceBlue

DISCLAIMER

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The pricing, lead times, and additional information in this report come from a combination of project procurement experience and vendor outreach. Turner Construction, SourceBlue, and the additional contributors to this pricing index shall not be held responsible if project teams find that equipment pricing/lead times on their own projects deviate from the pricing/lead times found in this index. This document is intended to provide a general overview of pricing and lead times for early-phase guidance, not to stand in as a resource for estimating, budgeting, or construction scheduling processes.

Pricing and lead times are highly subject to market forces that are beyond the control of Turner Construction / Source Blue. Influencing factors may affect pricing within the cadence of updates to this report. The authors of this report shall not be held responsible for these figures nor shall any manufacturers or engineering collaborators involved in the development of this report.

ABOUT THE AUTHORS:

Turner Construction is a North American-based, international construction services company and a leading builder in diverse market segments. The company has earned recognition for undertaking large and complex projects, fostering innovation, embracing emerging technologies, and making a difference for its clients, employees, and community. With over 11,000 employees, the company completes $17 billion of construction on 1,500 projects each year. **See page 13 for contact info.**

SourceBlue has provided clients with comprehensive supply chain services worldwide for 23 years. Their specialized equipment planners, builders, engineers, and project managers work closely with project owners and their consultants to help acquire equipment, materials, and finished products for their projects. **See page 13 for contact info.**

A NOTE FROM NYSERDA:

The Large Building Decarbonization Price Index is a collaborative effort between NYSERDA and Turner Construction. This resource will help guide the industry towards more accurate pricing and lead times for critical equipment neccesary to develop and implement decarbonization projects. The goal of the Price Index is to mitigate obstacles to advancing decarbonization projects in order to combat climate change, improve health, resiliency, and prosperity of New Yorkers, and deliver benefits equitably to all.

NYSERDA offers programs and resources to support professionals in the building sector with funding and partnership opportunities, planning guidance, and insights on the development of effective decarbonization projects.

Please contact danielle.stockman@nyserda.ny.gov for additional information on available NYSERDA programs and resources.

WELCOME

TO OUR READERS:

Welcome to the inaugural edition of the Large Building Decarbonization Price Index. As the world grapples with the urgent need to transition towards sustainable energy solutions, Turner Construction, SourceBlue, and our engineering collaborators are proud to spearhead this initiative, providing a comprehensive resource for industry professionals seeking insight into the costs associated with the decarbonization of large commercial buildings.

ABOUT THE REPORT

This report serves as a vital index, offering high-level pricing information on various types of equipment essential for electrifying large commercial buildings. From heating and cooling systems to electrical infrastructure and battery energy storage, each section of the report delves into the costs associated with different components, facilitating informed decision-making for project teams.

RESEARCH METHODOLOGY

To ensure the accuracy and reliability of our data, Turner Construction's procurement arm, SourceBlue, leverages its unparalleled buying power and extensive network within the mechanical equipment market. With a deep understanding of supply chain dynamics and national market trends, Source Blue delivers up-to-date pricing information reflective of real-time market conditions.

COLLABORATIVE EXPERTISE

In our pursuit of excellence, we have collaborated with some of the most progressive engineers in the decarbonization space. These visionary experts contribute regular technology features, highlighting emerging innovations and advancements crucial for driving sustainable change within the industry.

EMPOWERING DECISION-MAKING

While pricing may vary based on individual project requirements, this report provides project teams with a valuable head start and a level playing field for conducting conceptual pricing exercises. Our aim is to empower industry professionals with the knowledge and insights needed to navigate the complexities of decarbonization effectively.

As we embark on this journey towards a greener future, Turner Construction is committed to leading the charge in providing essential resources and fostering collaboration within the industry. We invite you to explore this report and leverage its wealth of information to drive meaningful progress towards a more sustainable built environment.

Thank you for joining us on this transformative endeavor.

Sincerely,

Colin Schless
Director of Decarbonization
Turner Construction Company

METHODOLOGY

To develop this index, Turner Construction and SourceBlue contacted vendors across the HVAC, appliance, and electrical infrastructure industry requesting pricing for pieces of equipment that met unique performance criteria. As performance capabilities can vary between similar pieces of equipment, our team took the following approach to structure and price the associated machines:

PRICE LEVELING PROCESS:

1. Developed broad categories of equipment based on their intended function.

2. Established performance specifications within each of the sub-categories to create a common performance baseline.

3. Send performance specifications to major equipment vendors and request pricing and lead times for the associated equipment.

4. Normalize pricing based on a relevant unit of capacity for each of the sub-categories. If a category was not easily translated into a unit of capacity, pricing is listed per whole component only (electric dryers, for example).

5. List price and lead time ranges from highest to lowest for each sub-category. If a piece of equipment is limited to a single manufacturer or if pricing/lead time was consistent across vendors, a single price and lead time was listed.

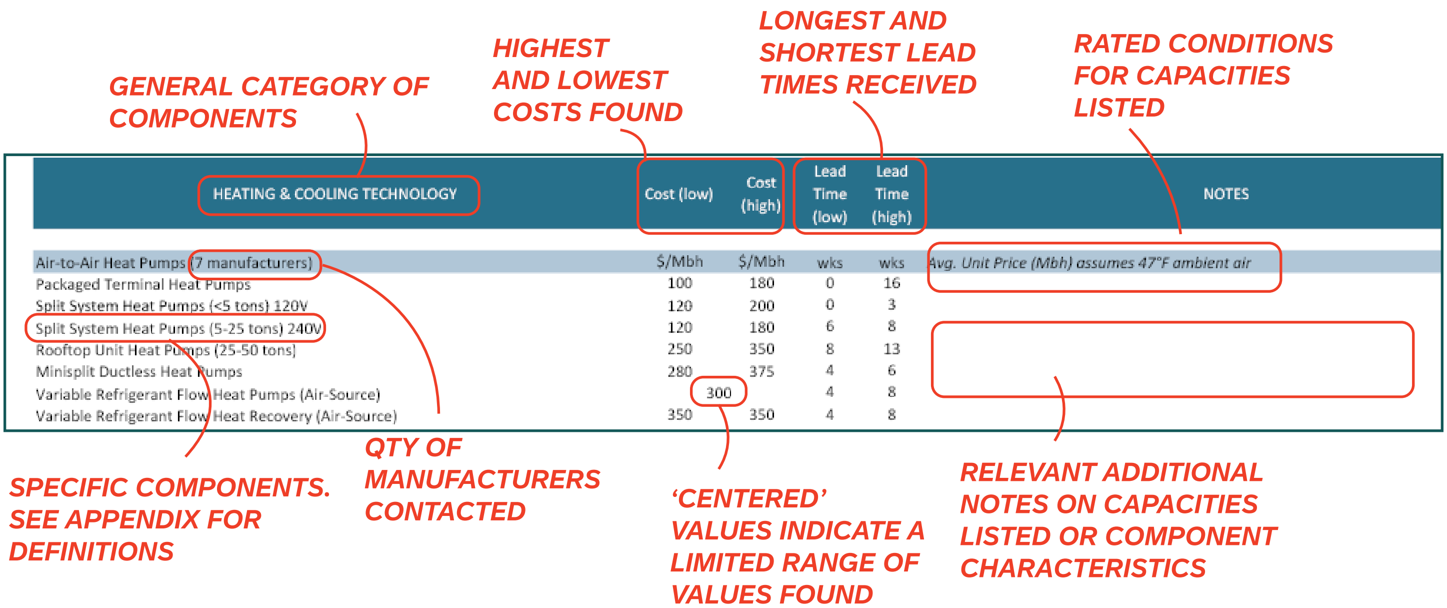
WHAT THE PRICING INCLUDES / EXCLUDES

The prices in this report represent equipment costs only. Pricing does not include mark-ups, shipping, taxes, installation costs, incentives, electrical, plumbing, architectural, or structural infrastructure.

Lead times are defined as 'manufacturing lead times' starting at release to fabrication and ending at the ship date. Lead times do not include submittal approval, order entry, and/or transit time.

Pricing and lead times will vary from project-to-project and do not assume 'bulk' discounts or unique discounts available to Turner Construction, Source Blue, or any of the contributers to this report. The pricing is intended to provide a general pricing and lead time index of the equipment outlined in the following pages.

GRAPHIC GUIDE TO THE INDEX

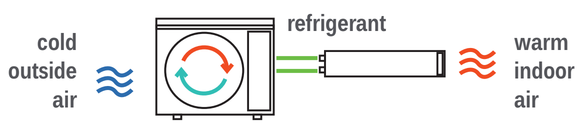


HEATING/COOLING CATEGORIES

This pricing index is organized into major equipment categories based on the sources and sinks of heat that these machines interface with, and their capabilities to do so. Terminology in the HVAC industry can be fluid, with terms like 'heat pump', 'heat recovery chiller', and 'chiller heater' often used interchangeably, sometimes inaccurately. Use this initial visual glossary to navigate the major equipment categories. More detailed definitions for the equipment within each category can be found in the comprehensive glossary at the end of this document.


Indicates Reversing Valve

AIR-TO-AIR HEAT PUMPS

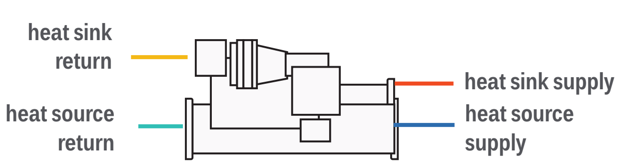


Reversible air-source heat pumps with an indoor evaporator section, connected via refrigerant. Small commercial/residential use. Alt. terms: VRF, minisplit, PTHP

WATER-TO-AIR HEAT PUMPS

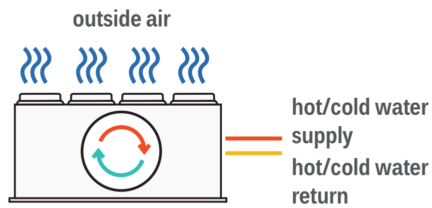
Reversible heat pumps connected to a fluid heat source/sink that can provide heated or cooled air to the space they serve. Alt. terms: water-source heat pumps.

4-PIPE WATER-TO-WATER HEAT PUMPS



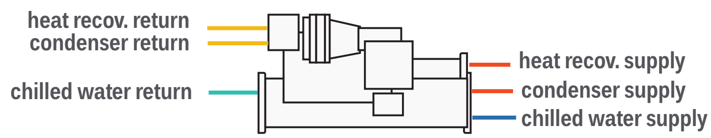
Non-reversing heat pumps transfering energy from a lake, geo loop, condenser loop, etc. to a fluid heat sink (HW loop, heat rejection loop). Alt terms: WSHP, HR chiller, Chiller

2-PIPE AIR-TO-WATER HEAT PUMPS



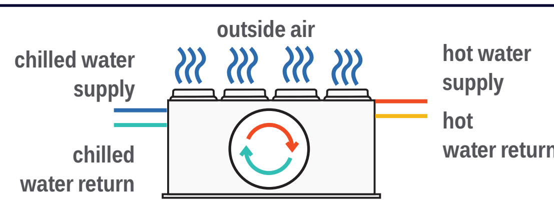
Air-Source heat pump that allows for the production of hot or cold water but does not allow for simultaneous production. Alt. terms ASHP, Ait-to-Water HP Chiller

6-PIPE WATER-COOLED HEAT RECOVERY CHILLERS



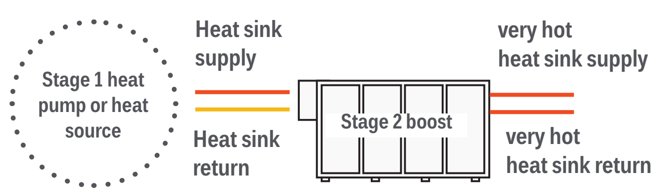
Primarily designed to cool water with a % of rejected heat used to warm water via an additional condenser bundle. Alt. terms: Water-to-water heat pump, HR Chiller

4-PIPE AIR-COOLED HEAT RECOVERY CHILLERS



Water-to-water heat pumps that simultaneously and independently produce hot and cold water, share load, and heat exchange with ambient air. Alt. terms: 4-pipe ASHP

HIGH-TEMP CASCADE HEAT PUMP SYSTEMS



Non-reversing, multi-stage, or booster heat pump systems capable of making HHW up to 200F or low-pressure steam. Various compressor types. Alt. terms: High-lift heat pump

PRICING/LEAD TIME INDEX

The pricing and lead times in these tables reflects information gathered by Source Blue and Turner Construction's estimating team. If a component is capable of providing heating and cooling, the costs referenced per unit of heating references the unit's heating capacity. **For detailed definitions of each item below, please see the glossary.**

COMMERCIAL BUILDING HEATING & COOLING TECHNOLOGY	Cost (low)	Cost (high)	Lead Time (low)	Lead Time (high)	NOTES
Air-to-Air Heat Pumps (7 manufacturers)	$/Mbh	$/Mbh	wks	wks	*Avg. Unit Price (Mbh) assumes 47°F ambient air*
Packaged Terminal Heat Pumps (PTAC)	100	180	0	16	
Split System Heat Pumps (<5 tons) 120V	120	200	0	3	
Split System Heat Pumps (5-25 tons) 240V	120	180	6	8	
Rooftop Unit Heat Pumps (25-50 tons)	250	350	8	13	
Mini-split Ductless Heat Pumps	280	375	4	6	
Variable Refrigerant Flow Heat Pumps (Air-Source VRF)	300*		4	8	
Variable Refrigerant Flow Heat Recovery (Air-Source VRF)	350	350	4	8	
Hybrid VRF	350*		16		
Water-to-Air Heat Pumps (3 manufacturers)	$/Mbh	$/Mbh	wks	wks	*Avg. Unit Price (Mbh) assumes 68°F source water temperature*
Water- Source Heat Pumps (Horizontal & Vertical)	350	450	5	8	
Water- Source Heat Pumps (console)	400	600	5	8	
Variable Refrigerant Flow Heat Pumps (Water-Source)	275*		4	16	
Variable Refrigerant Flow Heat Recovery (Water-Source)	340*		4	16	
4-Pipe Water-to Water Heat Pump (4 manufacturers)	$/Mbh	$/Mbh	wks	wks	*Avg. Unit Price (Mbh) assumes 140°F HW, 20°FΔT*
Water-to-Water Water Source Heat Pump (10 - 20T)	200*		8	10	
Water-cooled Centrifugal Chiller Heat Pump (200-600T)	100	120	30	32	
Water-cooled Rotary Screw Chiller Heat Pump (200 - 400T)	90	120	35	38	
Modular WTW HHP (30T x 10 mod, Nom. 300T)	190	200	30	40	
Modular WTW HP w integral free cooling	200	210	30	40	
2-Pipe Air-to-Water Heat Pump (5 manufacturers)	$/Mbh	$/Mbh	wks	wks	*Avg. Unit Price (Mbh) assumes 140°F HW, 20°FΔT, and 47°F OAT*
Packaged ATW HP (120 tons - 200tons)	120	150	32	34	
Modular ATW HP (Qty(10) 30-ton modules)	270*		30	32	
Modular CO2-based ATW HP	290	500	20	22	
6-Pipe Water - Cooled Heat Recovery Chillers (7 manufacturers)	$/Mbh	$/Mbh	wks	wks	*Avg. Unit Price (Mbh) assumes 140°F HW, 20°FΔT*
WC Scroll Chiller with Heat Recovery (20-75 tons)	100	120	35	40	
WC Rotary Screw Chiller with Heat Recovery (100-300 tons)	120	150	45		
WC Centrifugal Chiller with Heat Recovery (200-600 tons)	100	120	30	40	
WC Scroll Modular HR Chiller (4 Pipe)	200	300	30	40	
WC 6-pipe Unit (Geo Applications)	350	350	30	40	
4-Pipe Air- Cooled Heat Recovery Chillers (2 manufacturers)	$/Mbh	$/Mbh	wks	wks	*Avg. Unit Price (Mbh) assumes 140°F HW, 20°FΔT, and 47°F Nom Temp*
Packaged AC Scroll Chiller with HR (30 - 250 Tons)	125	150	32	35	
Packaged AC Rotary Screw Chiller with HR (60-300 tons)	150	175	35	40	
Modular ATW Pumps with HR	350	650	30	40	
Modular ATW Cooling Only with HR	300	550	30	40	
High - Temp Heat Pump Systems (3 manufacturers)	$/Mbh	$/Mbh	wks	wks	*Rated conditions vary by manuf and mystem type*
AS Cascade: 1st ASHP + 2nd Booster WSHP	384*		28		120°F EWT, 180°F LWT, 47°F ambient
Piston-Driven WTW Heat Pump	86	251	28		110°F EWT, 180°F LWT (low $/MBH) 55°F EWT, 180°F LWT (high $/MBH)
AUXILLIARY EQUIPMENT (1 manufacturer)	Cost	Unit	wks	wks	
Plate + Frame Heat Exchanger	8	$/MBh	12	16	
LARGE BUILDING DOMESTIC HOT WATER SYSTEMS (5	Cost	Unit	wks	wks	
Electric Resistance Water Heater (80- gallon)	2,200	$/80 gal	1	2	*80 gal. 16.5 KW Electric Water Heater with 316 l Stainless Steel Tank*
Combo pkg ASHP + DHW (80- gallon)	2,852	$/80 gal	12	16	
DHW Hi-temp AC-HP+ Thermal Battery	475	$/MBh	12	16	
Int. HP Boiler+ DHW Heater	2,800	$/66 gal	12	16	
Commercial ASHP WH + remote storage tanks	460	$/MBh	12	16	
Commercial WSHP WH + remote storage tanks	515	$/MBh	12	16	
Electric Res. WH: Point of Use Distributed, Tankless	8	$/MBh	12	16	
BOILERS (4 manufacturers)	Cost	Unit	wks	wks	*NOTES*
Electric Resistance Boiler (Hot Water)	$100	/HP	12	16	*Large boilers are typ. listed in horsepower. 1 HP is equal to 33.47 MBh*
High-Capacity Electrode Boiler (Steam)	$625	/HP	30	40	
Steam Heat Pump	$3,250	/HP	25	35	

* *centered values indicate a limited range of values found due to either consistent pricing or limited manufacturers*

PRICING/LEAD TIME INDEX

As the breadth of both air-handling equipment and electrical infrastructure is too broad for this index, we provided a sample of units associated with medium-to-large scale commercial buildings. **For detailed definitions of each item below, please see the glossary.**

COMMERCIAL BUILDING VENTILATION & EXHAUST EQUIPMENT	Cost	Unit	Lead Time (low)	Lead Time (high)	NOTES
DOAS + heating and/or cooling (4 manufacturers)		$	wks	wks	
DOAS w integral HP	250	$/ton	20	30	
Liquid Dessicant Dehumid	1,000	$/ton			15-ton 2000-2500 CFM 60 to 140 lb/h MRR
HRV / ERV (3 manufacturers)			wks	wks	
Catalogue HRV (100-1000 cfm, 75% Recovery+)	4.5	$/cfm	18	20	
Catalogue ERV (100-1000 cfm, 75% Recovery+)	4.75	$/cfm	18	20	
Catalogue ERV (1,000-25,000 cfm, 75% Recovery+)	7	$/cfm	18	20	
Hydronic Energy Recovery System (heat pipe/run-around)					System dependent / not generalized

COMMERCIAL COOKING TECHNOLOGY	Cost (low)	Cost (high)	Lead Time (low)	Lead Time (high)	NOTES
Commercial Electric Cooking Oven (5 manufacturers)	$6,250	$13,250	3	6	208v/240v, 1&3 Phase, Single Deck (Low), Double Deck (High)
Commercial Electric Fryer (3 manufacturers)	$2,000	$8,750	3	6	208v, 3 Phase, 1 Pot, 2 Basket, 40-50lb capacity
Commercial Induction Range (2 manufacturers)	$15,750	$22,250	4	6	120v/208v, 3 Phase, 4 Burner, 36"
Commercial Electric Combination Oven (5 manufacturers)	$18,750	$27,750	4	6	208v, 3 Phase, 10 Pan Capacity, 5 Rack, No Broil
Commercial Induction Full Size Wok Range (1 manufacturer)	$17,500 *		8		Custom option. Configurable as needed.
Commercial Chain Broiler (3 manufacturers)	$9,750	$14,750	5	6	1 phase, 208v, 10k Watt, up to 575 degrees,
Commercial Countertop Induction Hob/Wok (3 manufacturers)	$2,250	$3,500	2	6	240v,
Commercial Electric Resistance Range (3 manufacturers)	$4,750	$14,000	3	6	208v, 3 Phase, 6 Burner, 1 Oven, 36"
Commercial Electric Griddle (3 manufacturers)	$6,750	$14,250	3	6	208v, 1 phase, 3 burner, 36"

CLOTHES DRYING / LAUNDRY	Cost (low)	Cost (high)	Lead Time (low)	Lead Time (high)	NOTES
CLOTHES DRYING					
24" Condensing - Residential	950	1,200			4.1 Cu. Ft.
24" Heat Pump - Residential	1,800	2,000			4.02 Cu. Ft.
27" Electric- Commercial	1,400	1,700			7 Cu. Ft.
CLOTHES WASHING					
24" Front Load Washer - Residential	850	1,100			2.4 Cu. Ft.
27" Front Load Washer - Residential	1,600	1,800			2.26 Cu. Ft.
27" Front Load Washer - Commercial	1,400	1,700			3.42 Cu. Ft.

BLDG-BASED ELECTRICAL INFRASTRUCTURE (3 manufacturers)	Cost (low)	Cost (high)	Lead Time (low)	Lead Time (high)	NOTES
Unit Substation 13.2 kV/480 VAC, 3PH, 4 W+G, 60 Hz, 3000 amp rated, 150 kA, 150 kAIC, 5 dist. sections ea. with 3 feeder CBs, 2500 kVA Transformer.	1,055,000	1,150,000	62		
Unit Substation (Double ended) 13.2 kV/480 VAC, 3PH, 4 W+G, 60 Hz, 3000 amp rated, 150 kA, 150 kAIC, 1 tie section, 5 dist. sections ea. 3 feeder CBs, 2 X 2500 kVA Transformer.	2,110,000	2,360,000	62		The cost of electrical infrastructure does not scale well on a unit capacity basis (KVA or amperage) and is therefor reported as sized for a 'typical' medium sized commercial building. The examples provided demonstrate a hierarchy of electrical distribution equipment from substation to final transformer.
Switchboard 208 VAC, 3 PH, 4 W+G, 60 Hz, 1600 amp rated, 65 kA, 65 kAIC, 15 distribution CBs	60,000	189,000	52		
Distribution Panels, 208Y/120 VAC, 3 PH, 4 W+G, 60 Hz, 200 amp, 42 pole panelbaords.	2,400	2,700	10		
Transformer (500 kVA-2000 kVA)	25,432	69,765	8		
Transformer (50 kva-300kva)	11,540	16,705	6		

* *centered values indicate a limited range of values found due to either consistent pricing or limited manufacturers*

PRICING/LEAD TIME INDEX

Battery energy storage is a rapidly evolving technology. While standardized pricing and lead times are not available for many of today's cutting-edge technologies, we included notable items in the index so these lines can be populated as information becomes available. **For detailed definitions of each item below, please see the glossary.**

BATTERY ENERGY STORAGE SYSTEM (BESS)	Cost	Unit	Lead Time (low)	Lead Time (high)	NOTES
Lithium-Iron - Phosphate (system cost)					
Ice Storage (storage tank only)	25,000	/tank	30	40	1,655 gal storage tank
Ceramic/Heat (RONDO)	-	-	-	-	System dependent / not generalized
Iron/Air (Form Energy)	-	-	-	-	System dependent / not generalized
Compressed air or gas storage	-	-	-	-	System dependent / not generalized
Phase change materials	-	-	-	-	System dependent / not generalized

BACKUP/STANDBY POWER GENERATION (4 manufacturers)	Cost (low)	Cost (high)	Lead Time (low)	Lead Time (high)	NOTES
Standard Diesel 2000 kW, 480 VAC, 60 Hz unit in enclosure	650,000	1,845,000	60	130	
HVO (Diesel / alt fuel) 2000 kW, 480 VAC, 60 Hz unit in enclosure	650,000	2,050,000	60	130	
Hydrogen 2000 kW, 480 VAC, 60 Hz unit in enclosure	1,500,000	2,658,000	80	110	

* *centered values indicate a limited range of values found due to either consistent pricing or limited manufacturers*

TECH FEATURE

Partial Electrification and Decarbonization of High-Ventilation Buildings

Romeo Michael, Jacob Kowles,
BR+A Consulting Engineers

1. Introduction

High-ventilation buildings like hospitals and laboratories face unique hurdles in decarbonization efforts due to their significant energy consumption, driven largely by ventilation needs. These buildings require high ventilation rates to maintain safety and air quality, drawing in large volumes of outside air. In humid climates, this influx of air necessitates energy-intensive dehumidification processes. HVAC systems in these buildings must work harder to remove moisture and maintain desired indoor humidity levels. This often involves a multi-step process of cooling the air below its dew point to condense and remove moisture, and then reheating it to a comfortable temperature. Both the cooling and reheating stages contribute to substantial energy use. The key to decarbonizing these buildings is by eliminating fossil fuel consumption for heating through electrification.

Electrification involves replacing fossil fuel-based systems, primarily for heating and hot water, with electric alternatives like heat pumps. This strategy offers significant benefits, including increased energy efficiency and a reduced carbon footprint. Heat pumps are more efficient than fossil fuel systems. Additionally, transitioning from fossil fuels to electricity, especially when sourced from renewables, significantly lowers carbon emissions. However, this transition faces challenges due to the high energy demands of these buildings, which often require 24/7 operations. Integrating electric systems into existing infrastructure, especially in older buildings, can be challenging and costly. The initial investment in new equipment and installation can be significant. Increased demand from electrified buildings might necessitate upgrades to the existing electricity infrastructure.

Partial electrification offers a pragmatic path towards decarbonizing high-ventilation buildings. By strategically integrating electric technologies and optimizing the operation of existing systems, it is possible to achieve substantial emissions reductions while maintaining the necessary ventilation and operational standards. This approach advances sustainability and resilience without overburdening existing electrical infrastructure.

2. Partial Electrification

Partial electrification involves installing electric heat pumps to offset the operation of fossil fuel-based systems and maintain a hybrid approach that balances energy efficiency, reliability, and performance.

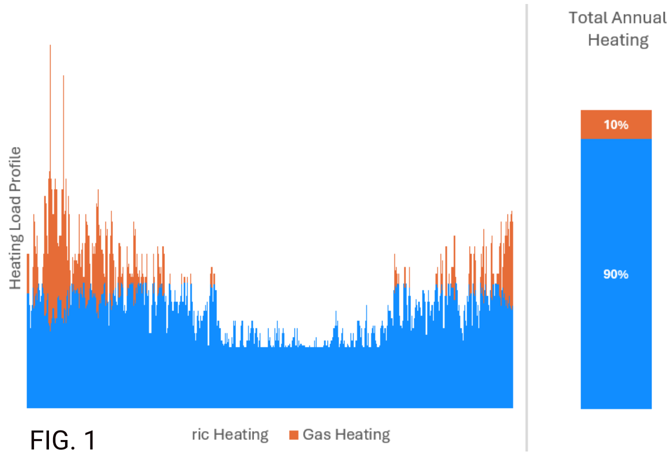


FIG. 1

The figure above shows the heating load profile of a lab building. By sizing the heat pump to cover approximately 25% of the peak heating load, it is possible to achieve about 90% of electric heating throughout the year. Strategically integrating heat pumps into the operation of existing systems, partial electrification offers a pragmatic path towards decarbonizing high-ventilation buildings. This approach enables substantial emissions reductions while minimizing initial investment costs and avoiding overburdening existing electrical infrastructure.

The graphic below illustrates the sensitivity of annual heating electric use to various sizing scenarios. It indicates that as the sizing of the heating system increases, the increase in the electrified heating load decreases. Opting for a system sized to achieve 20 to 30% of the peak heating capacity results in electrifying more than 80% of the building's heating load. However, as the system size further increases, there is a diminishing return on the electrification of annual heating.

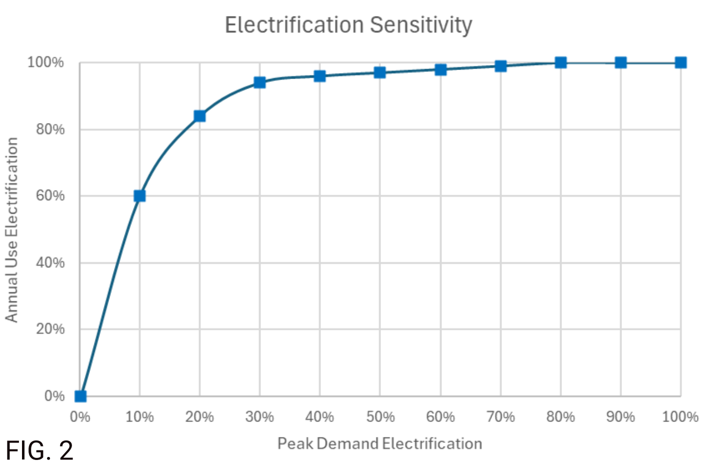


FIG. 2

3. Case Study

Our team analyzed partial electrification for multiple buildings. Table 1 pertains to a building considering the installation of a heat recovery chiller (HRCH) for a lab building as Option 1, where the HRCH can cover up to 15% of the peak heating load. With the installation of this equipment, the building is expected to achieve a 58% reduction in natural gas (NG) emissions.

As Option 2, the building is considering adding an air-to-water heat pump (AWHP) that, in addition to the HRCH, covers about 45% of the peak heating load. Under Option 2, the building is expected to achieve an 88% reduction in NG emissions.

TABLE 1

Option #	Description	Natural Gas Reduction
Base	Existing Conditions	0%
Option 1	HRCH (15% of Peak Heating)	58%
Option 2	HRCH + AWHP (45% of Peak Heating)	88%

Table 2 below displays the natural gas emissions reduction for another lab building considering the installation of an air-to-water heat pump (AWHP). Our team analyzed various equipment sizing to determine the extent of decrease in natural gas emissions. For an AWHP sized at 25% of the peak heating load, the building achieves a 72% reduction in natural gas usage. With an AWHP sized to 70% of the peak heating load, this reduction increases to 97%.

TABLE 2

Option #	Description	Natural Gas Reduction
Base	Existing Conditions	0%
Option 1	AWHP (25% of Peak Heating)	72%
Option 2	AWHP (50% of Peak Heating)	92%
Option 3	AWHP (70% of Peak Heating)	97%

The table below displays the hybrid electrification cost ($/SF) for an existing building projected to achieve at least a 90% reduction in annual fossil fuel consumption for building heating. The first three buildings considered a "Do Nothing Baseline". For these buildings, the baseline assumes that no funds are allocated to replace the existing systems, not even for in-kind replacement. The cost to electrify includes the entire cost to electrify, including the cost to replace any existing systems necessary to enable electrification. The last two buildings considered an “End of Life Replacement Baseline”. For these two buildings, the cost to electrify assumes that there is money allocated to replace the existing systems in-kind due to end of equipment life or planned renovation (excluding significant energy upgrades), allowing the electrification costs to be focused on the net premium to electrify.

TABLE 3

Building *	Cost ($/SF)
Lab 1	$ 109
Lab 2	$ 46
Lab 3	$ 71
Lab 4	$ 52
Lab 5	$ 90

*General Note: electrification costs are for heating only (excludes humidification and process).

4. Approaches to Decarbonizing Existing High-Ventilation Typologies

High-ventilation buildings require significant energy to maintain indoor air quality and environmental control, leading to high operational emissions. These buildings often rely heavily on natural gas or other fossil fuels for HVAC systems. Achieving substantial emissions reductions in these buildings necessitates innovative strategies, including load reduction, efficient systems, electric heat pumps, and both on-site and off-site renewable energy generation. The key to substantially reduce the emissions of these buildings is to eliminate fossil fuel consumption for heating. The thermometer below addresses typical electrical heating systems for different climate types. While eliminating fossil fuel in mild climates such as California is simple, doing so in Northeast regions is far more challenging. Air-source heat pumps are less reliable and operate at poor efficiency when outdoor air approaches zero degrees. That is why, for lab buildings aiming for full electrification, we consider a combination of heat recovery chillers and exhaust-source heat pump systems, supplemented by geothermal or air-source heat pumps, to achieve fossil fuel-free heating.

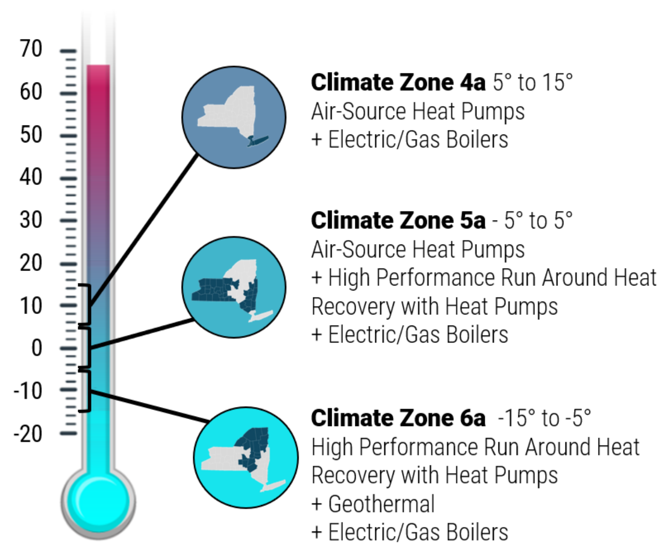


FIG. 3

5. Case Study

BR+A analyzed strategies to reduce emissions, including energy efficiency improvements and electrification options such as heat recovery chillers (HRCH), air-to-water heat pumps (AWHP), exhaust-source heat pumps (ESHP), and ground-source heat pumps (GSHP) systems. Prioritizing energy efficiency can lead to significant reductions in energy consumption, consequently lowering demand and facilitating the adoption of smaller, more economical heat pump systems during electrification. A comprehensive life cycle cost analysis can guide the selection of the most cost-effective approach.

The graphics below show the energy consumption decrease of an existing 120,000 SF lab prototype building heated by campus steam after implementing load reduction and efficiency measures in Option 1, followed by various electrification Options 2, 3a, and 3b. All the electrification options included a HRCH sized for the average simultaneous heating and cooling load. Option 2 includes an AWHP that, together with the HRCH, is sized to cover 25% of the building's peak heating load. Option 3a features an ESHP sized based on the estimated maximum energy available from the exhaust air. The exhaust source heat pump can export heating or cooling if there is no air handling unit heating demand. The remaining cooling load will be satisfied by local, water-cooled chillers and cooling towers. Option 3b combines the AWHP with the HRCH and ESHP to cover 100% of the peak heating load.

Upgrading the laboratory with either an air-source heat pump, exhaust source heat pump, or a combination is estimated to reduce the annual energy consumption significantly. This is primarily due to the heating efficiency of the exhaust source heat pump and air-source heat pump system options, which are 2-3x that of the Baseline steam boilers. Additionally, the high COP of the heat recovery chiller operating as the first stage of heating while simultaneous heating and cooling load occurs provides a significant increase in plant heating COP when compared to steam boiler operation.

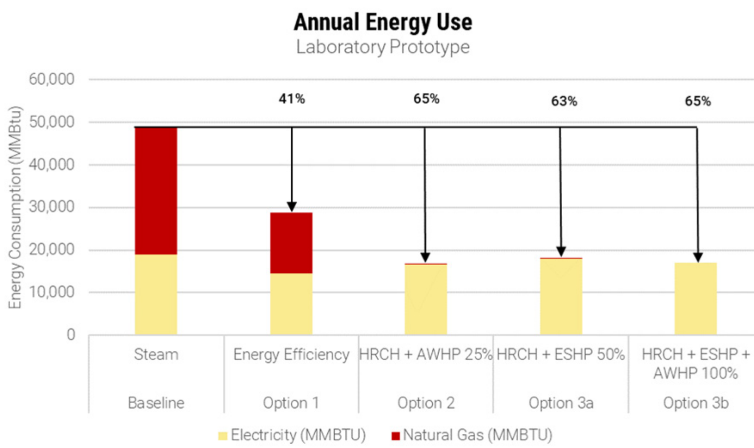


FIG. 4

6. Conclusion

Building electrification strategies hold significant promise for reducing carbon emissions and promoting sustainability. Analysis of various electrification options reveals that significant reductions in natural gas emissions can be achieved across multiple lab buildings in the northeast region. Partial electrification emerges as a pragmatic and environmentally responsible solution for decarbonizing these buildings. However, implementation may face barriers such as system costs and on-site space constraints for equipment installation. A thorough understanding of hybrid electrification costs is crucial, as it provides valuable insights into the financial implications of transitioning to more sustainable heating solutions.

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GLOSSARY

Air-to-Air Heat Pumps (7 manufacturers)	
Packaged Terminal Heat Pumps (PTAC)	Packaged Terminal Heat Pumps (PTHPs) are a decentralized air-source heat pump (ASHP) technology that can be used to heat and cool individual rooms. They are typically installed through a sleeve in the exterior wall with one side of the unit facing indoors and the other outdoors. The units blow heated or cooled air into a room to condition the space.
Split System Heat Pumps (<5 tons) 120V	Split heat pumps consist of two main components: an indoor air handler that contains an evaporator coil, and an outdoor condensing unit that contains a compressor and condenser. The outdoor condesing unit exchanges energy with the exterior environment and sends heating or cooling to the indoor evaporator coil via refrigerant housed in copper tubing. The indoor unit recirculates heated or cooled air which is distributed to various rooms through ductwork.
Split System Heat Pumps (5-25 tons) 240V	Split heat pumps consist of two main components: an indoor air handler that contains an evaporator coil, and an outdoor condensing unit that contains a compressor and condenser. The outdoor condensing unit exchanges energy with the exterior environment and sends heating or cooling to the indoor evaporator coil via refrigerant housed in copper tubing. The indoor unit recirculates heated or cooled air which is distributed to various rooms through ductwork.
Rooftop Unit Heat Pumps (25-50 tons)	Also referred to as packaged rooftop heat pumps, a rooftop unit (RTU) heat pump is a type of HVAC system that combines heating, air conditioning and air-handling all in one unit.They are often used in commercial buildings like offices, hospitals, and schools, but can also be found in residential homes. The units perform all of heating, cooling, and dehumidification functions within the unit itself and then blows conditioned air into the building via distribution ductwork or terminals connected to the unit.
Mini-split Ductless Heat Pumps	Ductless multi-split heat pumps operate similarly to split system heat pumps, with the added capability that one outdoor unit can be connected to several indoor units. This distinction allows multiple rooms to be heated or cooled without the use of ductwork. All indoor units must be in heating or cooling at the same time- the system does not have the capability to heat some rooms while cooling others.
Variable Refrigerant Flow Heat Pumps (Air-Source VRF)	Unlike multi-split or mini-split, VRF systems can handle differentiated loads by continually adjusting the flow of refrigerant to each indoor evaporator. Individual refrigerant flow and temperature control combined with inverter compressor technology minimize energy consumption. The heat pump VRF system will operate in heating or cooling mode.
Variable Refrigerant Flow Heat Recovery (Air-Source VRF)	A VRF system with heat recovery enables simultaneous operation of cooling and heating within a single refrigerant circuit. A VRF heat-recovery system can recover and redirect heat from zones in cooling mode to zones requiring heating.
Hybrid VRF	Hybrid VRF systems operate similarly to traditional VRF systems with distinction that indoor circulation is accomplished with water rather than refrigerant. An outdoor unit transfers energy to a hybrid branch controller, which exchanges heat between refrigerant and an indoor water loop. 2-pipe water loops extend to indoor fan coil units which are typically proprietary to the manufacturer. Like traditional VRF units, simultaneous heating and cooling is possible, with a typical 10% efficiency reduction for the refrigerant/water heat exchange process.

GLOSSARY

Water-to-Air Heat Pumps (3 manufacturers)	
Water- Source Heat Pumps (Horizontal & Vertical)	This category refers to smaller water-source heat pumps typically used in high-rise residential or mixed use applications. These heat pumps extract or reject heat into a geothermal closed-circuit or open well loop or a traditional tower loop system and discharge heated or cooled air into an adjacent space via a fan that draws air over a refrigerant coil. Horizontal or vertical configuration refers to the orientation of the unit. Each water-source heat pump can operate in heating or cooling mode but cannot provide heating and cooling to multiple zones at the same time.
Water- Source Heat Pumps (console)	Console water-source heat pumps work identically to the above horizontal or vertical applications, however these are floor units and are often placed under windows or against walls. These units typically include architectural encasement as they are visible in the occupied space.
Variable Refrigerant Flow Heat Pumps (Water-Source)	VRF systems can handle differentiated loads by continually adjusting the flow of refrigerant to each indoor evaporator. Individual refrigerant flow and temperature control combined with inverter compressor technology minimize energy consumption. The heat pump VRF system will operate in heating or cooling mode. Water-cooled VRF Heat Pump Systems operate similar to air-cooled VRF systems, with the exception that condenser utilizes water as a heat source versus air. Condenser water is piped from a central cooling tower or boiler to the water-cooled condensing and after heat exchange, refrigerant is piped from the condenser to each indoor unit.
Variable Refrigerant Flow Heat Recovery (Water-Source)	VRF systems can handle differentiated loads by continually adjusting the flow of refrigerant to each indoor evaporator. Individual refrigerant flow and temperature control combined with inverter compressor technology minimize energy consumption. A VRF system with heat recovery enables simultaneous operation of cooling and heating within a single refrigerant circuit. A VRF heat-recovery system can recover and redirect heat from zones in cooling mode to zones requiring heating. Water-cooled VRF Heat Pump Systems operate similar to air-cooled VRF systems, with the exception that condenser utilizes water as a heat source versus air. Condenser water is piped from the central cooling tower, boiler, or geo-exchange loop to the water-cooled condenser and after heat exchange, refrigerant is piped from the condenser to each indoor unit.
4-Pipe Water-to Water Heat Pump (4 manufacturers)	
Water-to-Water Water Source Heat Pump (10 - 20T)	Small water-to-water heat pumps transfer heat between two water flows (a source and a sink). Potential applications include spaces in tall residential and mixed use buildings where water must be 'boosted' or 'chilled' from a moderate-temperature condenser loop and sent to radiators or fan coils for space conditioning purposes.
Water-cooled Centrifugal Chiller Heat Pump (200-600T)	Water-cooled centrifugal chillers employ the vapor compression cycle as a means of extracting heat from a water-souce, and pumping that heat to a hot water loop ultimately intended for building conditioning. Typically, for heat pump applications, multiple centrifugal compressors are arranged in series to handle high-head performance requirements. Unlike the water-cooled chillers with heat recovery, these water-to-water heat pumps are intended to be operated exclusively in heating or cooling mode at any given time. Although these units are extracting heat from a source water-loop when in heat pump mode, the chilled byproduct is typically not reduced to a useful temperature.
Water-cooled Rotary Screw Chiller Heat Pump (200 - 400T)	Similar to water-cooled centrifugal chiller heat pumps, these units are intended to provide either heating or cooling at any given time, by transferring energy between two water-sources. The positive displacment screw compressor is suitable for high-head heat pump applications.
Modular WTW HHP (30T x 10 mod, Nom. 300T)	Modular water-to-water heat pumps provide a similar function to the larger heat pumps mentioned above but are delivered in standardized modules (30 tons, for example) that can be combined to form a larger unit. While these units are typically more expensive than packaged units per ton, modularity adds redundancy, expandaility, space saving, and ease of installation compared to single large units. In existing buildings, modules can be delivered to mechanical rooms and assembled onsite. Typically up to 10 modules can be combined together to operate as a larger unit. These can be configured in series or in parallell depending on functional needs.

GLOSSARY

2-Pipe Air-to-Water Heat Pump (5 manufacturers)	
Packaged ATW HP (120 tons - 200tons)	Packaged air to water heat pumps (ATW-HP) heat or chill a fluid by transfering energy between the fluid and the air using a refrigeration circuit that includes a reversing valve. The term 'packaged' refers to a single outdoor cabinet that contains all components of the heat pump chiller system including: compressors, air-cooled condenser, evaporator and controls. AWHPs utilze outdoor air as a heat sink or heat source, and are typically located outside on a roof or on the ground. The air-to-water heat pumps featured in this category are configured as two-pipe chiller-heaters. 2-pipe chillers have one refrigerant-to-water heat exchanger that can provide heating or cooling, but not simultaneously. (If simultanious heating and cooling is needed, refer to the following heat recovery chiller category.)
Modular ATW HP (Qty(10) 30-ton modules)	Modular air-to-water heat pumps serve the same function as packaged air-to-water heat pumps with the distinction that they are delivered in standardized modules (30 tons for example) that can be combined to form a large unit. While these units are typically more expensive than packaged units per ton modularity adds redundancy, expandability, and ease of installation compared to single large units. In existing buildings, modules can be delivered to mechanical rooms and assembled onsite. Typically up to 10 modules can be combined together to operate as a larger unit. These can be configured in series or in parallel depending on functional needs.
Modular CO2-based ATW HP	These modular heat pumps use CO_2 as a refrigerant, a natural, non-toxic, harmless, efficient refrigerant with 0 ozone depletion potential. By operating as a 'transcritical' refrigerant, CO_2 can achieve uniquely high temperature output. These units require 'high lift' bewteen return and supply (historically a minimum of 45F to function efficiently. Their price premium comes from the need to provide components that accomodate uniquely high pressures associated with CO_2.
6-Pipe Water - Cooled Heat Recovery Chillers (7 manufacturers)	
WC Scroll Chiller with Heat Recovery (20-75 tons)	During cooling-only operation, the chiller produces chilled water leaving the evaporator while heat from the refrigerant is dissipated by circulating water between the cooling tower and condenser or geo-exchange loop. When there is a simulataneous demand for chilled water and hot water, these chillers have the capability to operate in heat recovery mode where the recovered heat can be redirected to satisfy heating loads.
WC Rotary Screw Chiller with Heat Recovery (100-300 tons)	Provides same function as WC Scroll Heat Recovery category, but utilizes a screw compressor with a larger capacity range.
WC Centrifugal Chiller with Heat Recovery (200-600 tons)	Provides same function as WC Scroll Heat Recovery category, but utilizes a centrifugal compressor with a larger capacity range. Note this machine has functional differences from a water-cooled centrifugal chiller heat pump. *Water-cooled heat recovery chillers are specifically designed to chill water and provide a percentage of heat as warm water, while non-rerversing water-to-water Heat Pump chillers are specficially designed to heat water and provide 100% of heat as hot water. A heat recovery chiller is utilized to generate chilled water, and generates warm water as a result; a heat pump is utilized to generate hot water, that also incidentally generates cool or chilled water.*
WC Scroll Modular HR Chiller (4 Pipe)	Water-cooled scroll modular heat recovery chillers allow for simultaneous production of hot and chilled water, and come in standardized modules that can be combined to form a large unit.
WC 6-pipe Unit (Geo Applications)	A water-cooled six-pipe heat recovery chiller is typically used for geothermal applications but can be used in conjunction with a variety of heat sources/sinks (river, lake, sewer, etc.). Four of the six pipes supply and return heating/cooling to delivery points such as fan coils or radiant surfaces. The remaining two pipes run from the module's heat exchangers to a liquid-to-liquid heat exchange loop that interfaces with the aformentioned source/sink. Six pipe equipment offers superior flexibility including the sharing of thermal loads within a building and simultaneous heating and cooling.

GLOSSARY

4-Pipe Air- Cooled Heat Recovery Chillers (2 manufacturers)	
Packaged AC Scroll Chiller with HR (30 - 250 Tons)	Air cooled Heat recovery chillers are specifcally designed to chill water and provide a percentage of heat as warm water utilizing a desuperheater for heat reclaim. The recovered heat can be redirected to partially satisfy heating loads versus being rejected to the outside atmosphere. Ideal for applications that simultaneously require chilled water and tempered hot water.
Packaged AC Rotary Screw Chiller with HR (60-300 tons)	Air-cooled Heat recovery chillers are specifcally designed to chill water and provide a percentage of heat as warm water utilizing a desuperheater for heat reclaim. The recovered heat can be redirceted to partially satisfy heating loads verus being rejected to the outside atmosphere. Ideal for applications that simultaneously require chilled water and tempered hot water.
Modular ATW Pumps with HR	4-pipe modular air-to-water heat pumps go into heat recovery when in simulatneous mode.
Modular ATW Cooling Only with HR	Modular air-to-water cooling only chillers with heat recovery provide a similar function to the packaged AC scroll chillers with heat recovery mentioned above but are delivered in standardized modules (30 tons, for example) that can be combined to form a larger unit. (The "cooling only" reference means "not a heat pump" ....but...still providing heating through heat recovery.)
High - Temp Heat Pump Systems (3 manufacturers)	
AS Cascade: 1st ASHP + 2nd Booster WSHP	These sytems are comprised of two heat pumps arranged in series with the intention of producing very high water temperature (not steam solutions). The first heat pump extracts energy from the outside air and transfers it to water, heating the water to 90-110F. The second heat pump (booster) lifts the water temperature up to 160F-200F. The pricing includes the cumulative price of two heat pumps and a buffer tank, but does not include associated piping as this will be unique to the configuration of each job.
Piston-Driven WTW Heat Pump	Piston-driven compressors capable of achieving temperatures up to +248F, especially suited for industrial, district heating, or retrofit applications. The cost of these units ($/MBH) is highly dependent on the source water temperature.
VRF Cond. Unit + Cascade + HW Storage	Split type, air-to-water VRF-based heat pump water heater,for commercial applications. It is designed to produce up to 194F water and operate down to -4F. The system is comprised of a variable capacity heat pump outdoor unit, variable capacity hot water cascade booster unit and a tank sensor kit designed to be connected to a 3rd party indirect hot water tank(s)
AUXILLIARY EQUIPMENT (1 manufacturer)	
Plate + Frame Heat Exchanger	A plate and frame heat exchanger is a device that transfers heat between two fluids by using corrugated steel plates that are stacked and sealed with gaskets to create channels for the fluids to flow through. The plates are held together by a fixed plate and a loose pressure plate, compressed by tightening bolts. Most geothermal fluids used for direct use purposes contain various chemical species which can be detrimental to conventional materials of construction. Many applications include isolating geothermal fluids from indoor water loops and plate and frame heat exchangers are often the equipment of choice for this duty.
DOMESTIC HOT WATER SYSTEMS (5 manufacturers)	
Combo pkg ASHP + DHW (80- gallon)	Also referred to as a hybrid hot water heater or Package Tank-Type HP Water Heaters due to its electrric-resistance backup capability. Standalone air-source heat pump hot water heaters consist of a compressor unit packaged with a storage tank. This (traditionally residential) application allows for domestic hot water production in spaces that remain in the 40F-90F temperature range, and will cool the surrounding air.
DHW Hi-temp AC-HP+ Thermal Battery	Air source heat pump unit extracts energy from the outdoor air; instead of transferring the energy to the hydronic loop, the energy is transferred through a heat exchanger to second heat pump refrigeration loop raising the refrigerant tempearture, the heat is then transfered to the water circuit / thermal battery for DHW. Thermal Batteries can be up to four times smaller than the equivalent hot water tank because they are filled with an energy-dense phase change material.

GLOSSARY

Int. HP Boiler+ DHW Heater	Air-to-water heat pump system solution for hydronic heating, cooling, and domestic hot water. Domestic hot water is generated with indirect domestic storage tanks. These integrated units are designed to heat water for both space conditioning purposes and domestic hot water needs. To accommodate dual use, these units include an integral heat exchanger capable of 'blending down' domestic hot water for space conditioning purposes.
Commercial ASHP WH + remote storage tanks	Commercial-scale air-source domestic hot water heaters are designed to extract energy from ambient air and lift water temperatures to appropriate temperatures for domestic hot water usage. These units are designed for multi-family applications and are paired with remote storage tanks.
Commercial WSHP WH + remote storage tanks	Commercial-scale water-source domestic hot water heaters are designed to extract energy from a water loop and lift water temperatures to appropriate temperatures for domestic hot water usage. These units are designed for multi-family applications and do not include integral storage and are paired with remote storage tanks. Commercial-scale water-source domestic hot water heaters are designed to extract energy from a water loop and lift water temperatures to appropriate temperatures for domestic hot water usage. These units are designed for multi-family applications and are paired with remote storage tanks.
Electric Res. WH: Point of Use Distributed, Tankless	These small compact water heaters use electric resistance to boost water temperatures for a single application such as a kitchen sink. These are typically installed near the point of use and are geared towards minimal-use applications due to the inefficiency of electric resistance heating.
BOILERS (4 manufacturers)	
Electric Resistance Boiler (Hot Water)	Electric resistance boilers use electric resistance to generate heat. Heat output is conrolled by modulating the resistance. Of the water heating technologies reviewed for this report, these are the least efficient but take up minimal space compared to heat pump alternatives. These units are not capable of producing steam.
High-Capacity Electrode Boiler (Steam)	An electrode steam boiler is a high-voltage electric boiler that works by submerging two or three electrodes in water and connecting them to a single or three phase power supply. The current that flows between the electrodes heats the water which then vaporizes into steam.
Steam Heat Pump	Steam generating heat pumps lift heat from source water and send heat to feed water that is preheated and evaporated at the condenser. The water is sent to a steam seperator in the form of wet steam. Applications range from industrial processes to sterilization in healthcare and laboratory applications.

GLOSSARY

VENTILATION & EXHAUST EQUIPMENT	
DOAS + heating and/or cooling (4 manufacturers)	
DOAS w integral HP	Pre-engineered rooftop ventilators deliver fresh outside air to a building that is tempered and dehumidified for space comfort. This unit is ideal for 100% outdoor air, variable air volume, and single zone applications. Airflow Range: 500 - 18,000 cfm
Liquid Dessicant Dehumid	Liquid dessicant dehumidification units deliver dehumidified air without the need to reheat. These units use a non-corrosive liquid dessicant to remove moisture. Sizes are typically limited to 15 tons of cooling / 3000 cfm.
HRV / ERV (3 manufacturers)	
Catalogue HRV (100-1000 cfm, 75% Recovery+)	Dedicated outdoor air unit with the capability of transferring sensible heat from outgoing exhaust air to incoming outside air via a cross-flow or counter-flow mechanism. These units do not have the capability to recover latent heat or actively add heating/cooling to incoming air streams. This size range of HRV is most appropriate for residential, multifamily, or small commercial applications, typically in dry climates.
Catalogue ERV (100-1000 cfm, 75% Recovery+)	Dedicated outdoor air unit with the capability of transferring sensible and latent heat from outgoing exhaust air to incoming outside air via an enthalpy wheel or similar mechanism. These units do not have the capability to actively add heating/cooling to incoming air streams. This size range of ERV is most appropriate for residential, multifamily, or small commercial applications, typically in mixed/humid climates.
Catalogue ERV (1,000-25,000 cfm, 75% Recovery+)	Larger dedicated outdoor air units with the capability of transferring sensible and latent heat from outgoing exhaust air to incoming outside air. These units do not have the capability to actively add heating/cooling to incoming air streams, although this can sometimes be added at a cost premium. This size range of ERV is most appropriate for commercial applications in mixed/humid climates.
Hydronic Energy Recovery System (heat pipe/run-around)	A run-around coil heat recovery system consists of pipes to connect two coiled heat exchangers to a fluid filled loop, typically a mixture of water and an anti-freeze fluid. The system moves sensible heat from the hot side (exhaust air) to the cold side (supply air). Run-around coils are typically used in buildings where the supply and exhaust fans are far apart or the extraction air contains contaminants. Recovery is often limited to 50% for the outgoing heat. These solutions are typically customized to specific applications. Although they are generally considered less expensive than ERV or HRV solutions, this cost index does not include standardized pricing due to the custom nature of this component.