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Mini-Split Heat Pumps Multifamily Retrofit Feasibility Study

Jordan Dentz, David Podorson, and Kapil Varshney
Advanced Residential Integrated Energy Solutions (ARIES) Collaborative

May 2014

Building America
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Office of Energy Efficiency and Renewable Energy

15013 Denver West Parkway

Golden, CO 80401

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Prepared by:

Jordan Dentz, David Podorson, and Kapil Varshney

ARIES Collaborative

The Levy Partnership, Inc.

1776 Broadway, Suite 2205

New York, NY 10019

NREL Technical Monitor: Michael Gestwick

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Definitions

ACH50	Air changes per hour at 50 Pascals
ARIES	Advanced Residential Integrated Energy Solutions Building America team
BEopt®	Building Energy Optimization software
Btu	British thermal unit
COP	Coefficient of performance
EIA	U.S. Energy Information Administration
EIFS	Exterior insulation and finishing system
HSPF	Heating season performance factor
HVAC	Heating, ventilation and air conditioning
LIHEAP	Low Income Home Energy Assistance Program
LPG	Liquefied petroleum gas (propane)
MMBtu	1 million British thermal units
MSHP	Mini-split heat pump
NEEA	Northwest Energy Efficiency Alliance
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
SEER	Seasonal energy efficiency ratio
SIR	Savings-to-investment ratio

Executive Summary

Mini-split heat pumps (MSHPs) are gaining in popularity in the United States due to their high efficiency, straightforward installation, capability to provide space heating and cooling, quietness, zoning ability, and more recently, high heating capacity even at very low outdoor temperatures. These characteristics make MSHPs suitable for use as a retrofit in cold climates to replace electric resistance heating or other outmoded heating systems.

As with many promising technologies, MSHPs face technical and market hurdles. Before the technology can advance, several critical information gaps need to be addressed including: establishing the technology's costs and benefits relative to alternatives; developing objective guidance on the best applications for MSHPs (building types, existing heating, ventilation, and air conditioning systems being replaced, etc.); and providing guidance on best installation practices for the technology. This report investigates whether mini-splits can live up to their potential for one market segment: multifamily retrofits.

MSHP retrofit feasibility is analyzed for a variety of multifamily building types and characteristics. Several aspects are discussed in relation to the suitability for MSHP retrofits, including: (1) identification of technical barriers to installing MSHPs in selected building types; (2) cost with respect to competing alternatives; (3) review of collateral impacts and benefits of MSHPs, such as on electrical metering billing for space heating; and (4) market potential for MSHP retrofits in low-rise multifamily buildings, including characterization of the best applications for MSHPs.

A number of utility programs have retrofit MSHPs in both single-family and multifamily residences. Two affordable housing multifamily programs are discussed in detail. Program evaluation reports are not yet available, but interviews with program managers and participants indicate that building owners and residents are in most cases (but not all) generally satisfied with MSHPs.

The report concludes that MSHPs are a viable retrofit opportunity for certain low- to mid-rise multifamily buildings. They can be cost effective under many conditions. Successful multifamily retrofits were identified at sites in three states. All were retrofits of electric resistance heated buildings, the lowest hanging fruit.

Buildings most suitable for MSHP retrofits are those with high-cost heating fuel such as liquefied petroleum gas (propane), fuel oil and, especially, electric resistance. Buildings with natural gas service are less suitable. Coupling expensive fuels with poor thermal envelopes makes the replacement even more attractive; however, even when the envelope is substantially improved, MSHPs can be cost effective on annualized cost of energy-related expenses. Now that they are available with high heating capacities even at low outdoor temperatures, colder climates amplify the benefits of MSHPs. The simple paybacks for installing a single MSHP unit ($3,500 assumed cost) in an apartment in the New York City climate to fully offset a 30 MMBtu annual heat demand are estimated to be approximately 3.5, 4.2 and 8.3 years if replacing fuel oil, propane and electric resistance respectively.

It is easier to install MSHPs on low- to mid-rise (up to nine floors) buildings where ground and/or roof space permits mounting compressor units in relative close proximity to indoor units.

Small, open plan homes where distribution of conditioned air is easily accomplished will be more cost effective.

In Building Energy Optimization Program modeling using the New York City climate, converting from electric resistance to MSHPs saves approximately 30% of annualized energy-related costs in one sample building. Converting from oil saved about 4%. Converting from natural gas would cost about 30% more. In the Boston climate, converting from electric resistance to MSHPs is projected to save approximately 50% of annualized energy-related costs. Converting from oil saves about 3%. Converting from natural gas would cost 24% more.

For most low-rise multifamily buildings, the technical and regulatory barriers are minimal. Many buildings have been retrofitted in Maine and Connecticut without major regulatory issues. For buildings that are converting from central heating systems to individually metered MSHP systems, the utility billing change may engender regulatory barriers, especially for affordable housing. No existing conversions of this type were identified.

This report will be useful for multifamily building owners and operators and energy consultants as they consider space conditioning options, particularly in mixed and cold climates. It also may be of interest to program managers or policy makers interested in the suitability of MSHPs for multifamily buildings.

1 Problem Statement

1.1 Introduction

According to a recent U.S. Department of Energy report (DOE, 2009), more than 20% of the electricity supply in the United States is consumed by residential buildings and a large portion of that figure (40%) goes to space conditioning. Many of these buildings use electric resistance heating, which is very expensive compared to most alternatives. In addition, 7% of total oil consumption in the United States is used for space heating. The Rocky Mountain Institute recently issued a report advocating for the replacement of oil heat with mini-split heat pumps (MSHPs) in the Northeast (Matley, March 2013). MSHPs are highly efficient heating, ventilation, and air conditioning (HVAC) units (Winkler, 2011) (Christensen et. al, 2011) that are beginning to establish market share in the U.S. residential sector.

This report uses the term *mini-split heat pump* or *MSHP*. Other terms in use for MSHPs include *ductless heat pumps*, *multi-splits*, and *variable refrigerant flow heat pumps*. These terms all refer to a split-system heat pump, generally ductless, with variable-speed fan and compressor that allowing for low cycling losses, improved part load control, and enhanced humidity control (Winkler, 2011).

As an alternative to other heating and cooling technologies, MSHPs offer the following attributes:

- They provide both heating and cooling, offering a total space conditioning solution in a single device.
- Their compact size allows their use in a wide variety of applications where space is at a premium.
- They are available in small capacities (as low as 9,000 Btu/h) suitable for low-load buildings, small apartments, and individual rooms.
- They do not require ducts and therefore are suitable for spaces that lack ducts and where retrofitting a duct system is impractical.
- They do not require or interfere with windows, unlike window air conditioners and window heat pumps.
- They typically incorporate inverter-driven compressors and variable-speed fan technology, resulting in very high efficiencies of up to 27 seasonal energy efficiency ratio (SEER) and 12.5 heating season performance factor (HSPF).
- They do not require fuel other than electricity.
- A single outside compressor can be connected to numerous independently controlled air-handling units (although this tends to reduce system efficiency), facilitating highly flexible zoning of spaces and eliminating over/under-space conditioning.
- The compressor is mounted outside, reducing interior noise compared to most compact unitary air conditioning/heat pump systems.
- Many models can provide much of their heating capacity at low outdoor temperatures while retaining good efficiencies.

These attributes suggest that MSHPs are a promising technology for both new construction, where multiple units can be strategically located, and for retrofit as a replacement of old, inefficient HVAC systems where space is often at a premium. In particular, they hold promise for fulfilling an unmet need: providing a solution for replacing deteriorating or obsolete central heating systems in multifamily building stock and/or electric resistance heating systems in cold-climate building stock where other heating fuels besides electricity are not practical.

However, as with many promising emerging technologies, MSHPs face technical and market hurdles. Information gaps that need to be addressed include: establishing the technology's costs and benefits relative to alternatives; developing objective guidance on the best applications for MSHPs (building types, existing HVAC systems being replaced, etc.); and providing guidance on best installation practices for the technology. This report examines the potential opportunity for MSHP retrofits in multifamily applications by reviewing recently completed projects, discussions with industry participants, and Building Energy Optimization software (BEopt®) modeling.

1.2 Background

As of 2008 there were 27 manufacturers offering MSHPs in the United States (Table 1). Table 2 summarizes data obtained from five manufacturers on their MSHP offerings. These data indicate that MSHPs are available in various capacities, their cooling and heating efficiencies are high, and they are quiet while running. All these units are split-system heat pumps with an inverter-driven, variable speed compressor which helps them to control space temperature precisely and is responsible for their high efficiency at a wide operating capacity range. Their advanced electronic control systems detect changes in room temperature and automatically adjust the compressor speed and electronic linear expansion valve position for precise capacity control. Zoning is possible; a single compressor can be connected with multiple individual indoor units and each indoor unit can be controlled separately based on the temperature requirement in that zone. There exists, however, a wide range of efficiencies among MSHPs, and pricing is often reflective of these differences.

Table 1. Manufacturers Offering MSHPs in the United States in 2008 (some may have units built for them by third parties) (Pratt, 2008)

No.	Manufacturer	No.	Manufacturer	No.	Manufacturer
1	Amcor	10	LG	19	General Electric
2	Americare	11	Mitsubishi	20	Goodman
3	Carrier	12	Pace Air	21	Haier
4	Daikin	13	Panasonic	22	Heil
5	DeLonghi	14	Samsung	23	Hitachi
6	EML/RetroAire	15	Sanyo	24	Toshiba
7	Fedders	16	Single Zone	25	Trane/US Standard
8	Friedrich	17	Soleus	26	Unionaire
9	Fujitsu	18	Thermal Zone	27	York

Table 2. Comparison of Typical Manufacturer Reported Data

Types	Capacity (Cooling)	Capacity (Heating)	SEER	HSPF	Zones	Noise Level (Decibel)
Wall-Mounted	9,000–30,000	9,000–32,000	13–26	8.2–11	1	20–60
Small Ceiling-Mounted (Cassette)	8,800–42,000	10,900–45,000	14–21	8.5–11.5	1	30–50
Large Ceiling-Mounted	24,000–42,000	26,000–45,000	14–17	8.5–11	1	40–50
Universal Floor/Ceiling	17,800–22,200	21,500–24,000	15–16	8.5	1	35–47
Multizone (Wall-Mounted, Cassette, Slim-Duct)	18,000–62,000	20,000–62,000	17–18	8.9–9.8	2–8	30–50

Winkler (Winkler, 2011) presented laboratory test results for two MSHPs using a field test protocol for mini-split systems developed by Cristensen et al. (Christensen et. al, 2011). Winkler's research aimed to confirm and expand on data reported by MSHP manufacturers so that the cost and performance characteristics of MSHPs can be accurately compared with conventional systems. He tested both units under a wide range of outdoor and indoor temperatures at various compressor and fan speeds. In addition, cycling performance for each unit was tested under both heating and cooling modes of operation. His experimental test data aligned with manufacturer-reported values. Both systems tested outperformed two-stage, high SEER forced air systems under low and intermediate loads, but under peak loads tested at slightly lower coefficients of performance (COPs). Winkler also measures heating COPs of the Mitsubish FE12NA at low outdoor temperatures. In the –10°F to 3°F range, he observed COPs of 1.33–1.84 at 53%–72% of rated heating capacity. In the 15°–33°F range, he observed COPs of 1.75–2.5 at 72%–132% of rated heating capacity.

Mitsubish claims that its 9,000- and 12,000-Btu Hyper Heat Performance models provide full capacity heating at 5°F outside air temperature and the 18,000-Btu model provides 73% capacity at -13°F outside air temperature (Mitsubishi Electric US, Inc., 2012).

Ecotope (Ecotope, 2009) tested a Fujitsu MSHP for more than 3.5 years and the analysis showed that similar total energy savings were achieved each year of the study. The most important conclusion was the consistency of the MSHP performance for the entire period of testing. This finding suggests that the technology is robust.

The Northwest Energy Efficiency Alliance (NEEA, 2009) conducted telephone interviews of households that purchased MSHPs through a program whose target was to install MSHPs in single-family homes with resistance heating as the primary heating source, general population households, utility personnel involved in the MSHP program, and MSHP manufacturers/ distributors and installers. NEEA interviewed 30 utilities, 31 contractors, 10 manufacturing and/or distribution firms, and 300 homeowners. The survey results showed that 57% of the homeowners wanted an MSHP because of its efficiency and 17% because it was ductless. Participant satisfaction was high: almost 90% of surveyed participants have had their overall expectations met, and 96% use their new MSHPs for primary heating. The report also provides current data on the MSHP market in the Northwest.

A sampling of energy efficiency programs across the United States identified several incentives and programs targeted specifically to encourage MSHPs. Many states offer good incentives for installing MSHPs (NEEP, July 2013); all were either in New England or the Northwest. A summary of programs identified is shown in Table 3. Note that other programs that provide incentives for high efficiency heat pumps or air conditioners for which MSHPs may qualify are not included on this list; only programs specifically calling for MSHPs (or as they are sometimes referred to, ductless heat pumps) are included.

Table 3. MSHP Incentive Programs

Program	Eligibility	Description
NW Ductless Heat Pump Project (About Northwest Ductless, 2013)	Single and multifamily homes with electric heat	Launched in 2008; more than 200 utility programs across Washington, Oregon, Idaho, and Montana; rebates range from \$200 to \$2,670, with \$1,000 to \$1,500 most common.
Efficiency Maine Low Income Electric Heat Multifamily Weatherization Program (Efficiency Maine, 2013)	Electric or natural gas heat (in practice only electric properties receive MSHPs); ≥ 66% of tenants Low Income Home Energy Assistance Program (LIHEAP)-eligible	Pays 100% of an energy audit and cost-effective energy efficiency improvements. No caps. Includes other weatherization measures.
Energize Connecticut (Connecticut Light & Power, 2013)	Single and multifamily; owned or rented; any heat type; new or existing homes	\$250 per system; ENERGY STAR®-qualified units
Belmont Municipal Light Utility (Mancinelli, 2013)	Electric or natural gas heat; requires home energy assessment	\$200 rebate since November 2012; 3 indoor units minimum
Bangor Hydro Electric (Bangor Hydro Electric Company) and Maine Public Service	Owner-occupied residential or small commercial; use oil, propane (LPG), electric resistance or kerosene as primary heat; spend at least \$1,400 on heat annually; estimated energy savings covers installed cost over 5 years.	HSPF rating of ≥ 10. \$600 rebate with optional on-bill financing.

A number of recent multifamily retrofits were identified and are described in Section 3 of this report. Most of the retrofits were participants in state efficiency programs in Connecticut and Maine; one was a weatherization effort in Illinois. All projects were intended to offset electric resistance heat. No studies or examples of MSHPs replacing fossil fuel heating systems in multifamily buildings were found.

1.3 Relevance to Building America's Goals

This project addresses a large stock of existing housing in mixed, marine, and cold climates. There are approximately 19 million occupied housing units with electric resistance space heating as their primary heat source in mixed, marine, and cold climates (American Housing Survey for the United States, 2005) (U.S. Energy Information Administration, 2009). In addition to electrically heated homes, an unknown (but significant) number of multifamily buildings with outmoded central systems (such as one-pipe steam) may be good candidates for MSHP retrofits.

In addition to the market potential described above, this project addresses the following Building America Implementation Standing Technical Committee milestone:

"Deliver market ready space conditioning systems that save 30% cooling energy savings relative to current (2012) SEER 16 systems, while maintaining adequate [relative humidity] and providing ventilation consistent with BA best practice guideline" (NREL, 2012).

While MSHPs do not provide ventilation as described in the milestone, they can be significantly more efficient than SEER 16 and ductless varieties, avoiding distribution inefficiencies associated with duct leakage and thermal losses.

1.4 Research Questions

This report assesses the potential benefits and costs of MSHPs by addressing the following questions:

1. What characteristics impact the potential for MSHP retrofits (i.e., what buildings are most suitable for MHSP retrofits and why)?
2. What is the relative cost effectiveness of MSHP retrofits by building type and climate compared to competing alternatives, including maintaining or upgrading obsolete, inefficient space conditioning systems?
3. What are the major technical and regulatory barriers to installing MSHPs in multifamily buildings?
4. Are MSHP retrofits cost effective in common types of low-rise multifamily buildings?

These questions were addressed by the following methods:

1. A literature review of technical reports on MSHP performance, manufacturer information, program evaluations, case studies, and any other MSHP information related to MSHP retrofits in the United States.
2. Interviews with manufacturers, distributors, contractors, building owners and managers, and energy efficiency program administrators, regarding applicability and experience with MSHP retrofits in mixed and cold climates in the United States.

3. Modeling to analyze the cost effectiveness of MSHP retrofits compared to alternative retrofits or maintaining existing systems in a variety of climates for selected building types.

2 Modeling

2.1 Energy Cost Analysis

An analysis was performed to estimate the heating and cooling costs and energy use for a typical apartment in a multifamily building (hot water or steam heat), comparing MSHPs to a variety of other fuels. The apartment is assumed to have an annual heating demand of 30 MMBtu (based on data for a moderately insulated midsize apartment in climate zone 4). Fuel costs were taken from the U.S. Energy Information Administration (EIA) for New York State ($0.17/kWh, $1.23/therm gas, $2.89/gal oil) (U.S. Energy Information Administration); typical heating plant efficiencies for existing equipment were used and were derated by an estimated distribution efficiency for central hot water and steam heating systems in the oil and natural gas case (based in part on overheating data collected as part of earlier ARIES research (Dentz, Varshney, & Henderson, Overheating in Hot Water and Steam Heated Multifamily Buildings, 2013). The MSHP plant efficiency used was 250%, a conservative value given the typical HSPF values of 8.2 to 11 for these units.

The annual cost to heat the apartment is lowest for natural gas, followed closely by the MSHP, with oil, LPG, and electric resistance being approximately 2–3 times the cost (Table 4). EIA's electricity and natural gas costs were nearly identical to average 2012 New York State heating season costs published by the New York State Energy Research and Development Authority (NYSERDA); however EIA's oil costs are significantly lower: $2.89 compared to NYSERDA's $4.01 (NYSERDA, 2013). If NYSERDA's higher costs were used, the annual cost to heat the apartment would be $1,264 rather than $911.

Table 4. Heating Energy Cost Calculations for a Typical Apartment

Heating	#2 Heating Oil	Natural Gas	LPG	Electricity (Resistance)	Electricity (MSHP)
Fuel Unit	Gallon	1000 ft^3	Gallon	kWh	kWh
Cost per Fuel Unit (BEopt NYS Average)	$2.89	$13.32	$3.08	$0.17	$0.17
Btu per Unit of Fuel	140,000	1,020,000	91,500	3,412	3,412
Cost per MMBtu	$20.64	$13.06	$33.63	$49.68	$49.68
Efficiency Plant	80%	85%	85%	100%	250%
Efficiency Distribution	85%	90%	90%	100%	100%
Efficiency Total	68%	77%	76.5%	100%	~250%
Cost per Useful MMBtu	$30.36	$17.08	$43.95	$49.68	$19.87
MMBtu Annual Heat Demand per Apartment	30	30	30	30	30
Site Energy Required for Heating (MMBtu)	44	39	39	30	12
Source Energy Required for Heating (MMBtu) (U.S. Environmental Protection Agency, 2013)	44	41	39	94	38
Annual Heating Cost per Apartment	$911	$512	$1,319	$1,490	$596

A similar analysis was conducted for cooling season, comparing room air conditioners to MSHPs (Table 5). Cooling cost is inversely proportional to cooling efficiency, which results in an approximate 60% reduction in cooling cost for MSHPs. Because room air conditioners are commonly controlled by turning them on and off as needed rather than with set point control and continuous operation (Lovins, 1992), a fixed number of hours of cooling was assumed for the season (3 hours per day × 90 days per year). Note that because MSHPs are quieter than traditional room air conditioners they may be used more frequently, resulting in less than the $109 savings indicated.

Table 5. Cooling Energy Cost Calculations for a Typical Apartment

Cooling	Window or Sleeve Air Conditioner	MSHP
Fuel Unit	kWh	kWh
Cost per Fuel Unit	$0.17	$0.17
Btu per Fuel Unit	3,412	3,412
Cost per MMBtu	$50	$50
SEER	9 (EER of 8.5)	22
MMBtu Cooling per kWh	9	22
Cost per MBtu Cooling	$0.019	$0.0077
MMBtu/h Capacity per Equipment (Room)	12	12
Cost per Hour of Operation	$0.227	$0.093
Hours Cooling per Year (3 units)	810	810
Cooling Cost per Year	$184	$75

The total annual cost of the site energy required for heating and cooling for each fuel type is compared to MSHPs in Table 6. For this apartment, and for EIA New York average energy prices, converting to MSHPs for space conditioning would reduce heating and cooling energy bills by more than half for all fuels except for natural gas, which would be similar in cost to MSHPs.

Table 6. Space Conditioning Site Energy Savings Using MSHP Compared to Alternatives

Heating Fuel	MSHP Savings ($)	MSHP Savings (%)
#2 Heating Oil-Fired Boiler	$424	39%
Natural Gas-Fired Boiler	$25	4%
Electric Resistance Baseboard	$1003	60%
LPG-Fired Boiler	$832	55%

The number of homes using major fuel types for primary space heating in very cold, cold, and mixed humid U.S. climates is provided in Figure 1. More than 40% of homes in these climates could save substantial amounts on heating bills by converting to high efficiency MSHPs, according to this analysis.

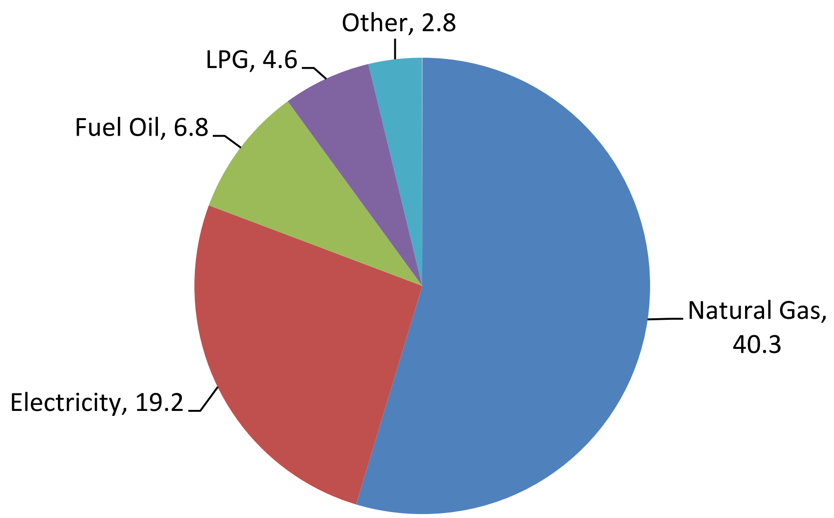


Figure 1. Number of homes in millions using fuel for primary space heating in very cold, cold, and mixed-humid U.S. climates (Office of Energy Consumption and Efficiency Statistics, 2010)

2.2 BEopt Modeling—Annualized Energy-Related Costs

BEopt version 2.0 was used to predict annualized energy-related costs and source energy consumption for a three-story, 11-unit building. Because BEopt is not intended to model entire multiunit buildings, the 5,925-ft^2 building was modeled as a single large home (Figure 2). This was a reasonable assumption because the building has a single boiler and only space heating and envelope measures were varied in the analysis. The numbers of bedrooms, bathrooms, and appliances were increased to simulate the larger internal gains of an 11-unit building.

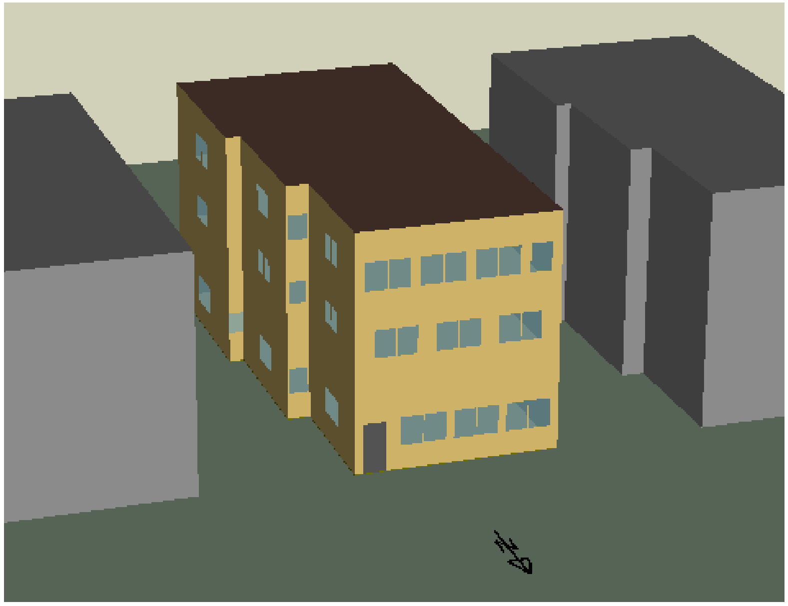


Figure 2. BEopt model geometry

Energy use and economics were estimated for an MSHP retrofit in place of oil, natural gas, conventional through-the-wall (sleeve) heat pump, and electric resistance heat in two locations: New York City and Boston. Before the retrofit analysis was conducted, the model was calibrated using existing heating fuel bills for the oil-heated building. The model was adjusted to be within 1% of the actual oil consumption by changing the heating set point to 76°F, a reasonable approximation of the average temperature in a hot water or steam heated multifamily building during the heating season (Dentz, Varshney, & Henderson, 2013), and by multiplying the miscellaneous gas, electric, and hot water loads in BEopt by a factor of 2, 2, and 12, respectively. Miscellaneous loads are those not specifically defined in the appliance section, including gas fireplaces, electric plug loads, and sink/shower hot water use.

Because BEopt does not currently model MSHPs, the closest approximation (central variable-speed heat pump without ducts) was used on the advice of BEopt developers. The performance of the variable-speed heat pump was left unchanged: SEER 22 and HSPF 10. These values are slightly conservative when compared to MSHP testing data from NREL (Winkler, 2011). Additional modeling assumptions are shown in Table 7 and Table 8.

Table 7. BEopt Assumptions

	#2 Heating Oil	Natural Gas	Electricity (Resistance)	Electricity (Through-the-Wall Heat Pump)	Electricity (MSHP)
Fuel Unit	Gallon	1000 ft^3	kWh	kWh	kWh
Cost per Fuel Unit NY (BEopt NYS Average)	$2.89	$13.32	$0.17	$0.17	$0.17
Cost per Fuel Unit MA (BEopt MA Average)	$2.85	$12.32	$.017	$0.17	$0.17
Heating Equipment Cost	$16.32/kBtu $1,934 installation $1,150 removal	$21.19/kBtu $1,934 installation $1,150 removal	$16.24/kBtu $21.96/kBtu installation $8.09/kBtu removal	$800 × 11 units	$3,500 × 11 units (installed cost)
Heating Equipment Lifetime	25 years	25 years	20 years	10 years	16 years
Efficiency Heating Plant	80%	85%	100%	7.7 HSPF % to 40°F), resistance below 40°F	10 HSPF to 0°F, resistance below 0°F
Efficiency Heating Distribution	85%	90%	100%	100%	100%
Efficiency Cooling	13 SEER	13 SEER	13 SEER	13 SEER	22 SEER
Cooling Equipment Cost	$400 × 11 units	$400 × 11 units	$400 × 11 units	n/a	n/a
Cooling Equipment Lifetime	10 years	10 years	10 years	n/a	16 years

Table 8. BEopt Default Economic Modeling Inputs

Economic Variable	Modeling Input
Project Analysis Period	30 years
Inflation Rate	3%
Discount Rate (Real)	3%
Loan Period	5 years
Loan Interest Rate	7%
Fuel Escalation Rate	0%

The annualized energy-related costs for three scenarios (converting to heat pumps from electric resistance, oil, and natural gas), each in two climates (New York and Boston), are presented in the following figures. Note that BEopt includes fan/pump energy with heat pump equipment because it assumes a central system with forced air distribution. This energy would not be expended with point-source systems and so BEopt slightly overestimates the energy expense for these options.

Converting from electric resistance to MSHPs or conventional heat pumps is shown in Figure 3 and Figure 4. Both options show annualized energy-related expense savings on the order of 30% with MSHPs providing 41% source energy savings compared to conventional heat pump source energy savings of 33%. Both Boston and New York showed the same energy savings percentage, but in the base case Boston showed 11% more energy consumption.

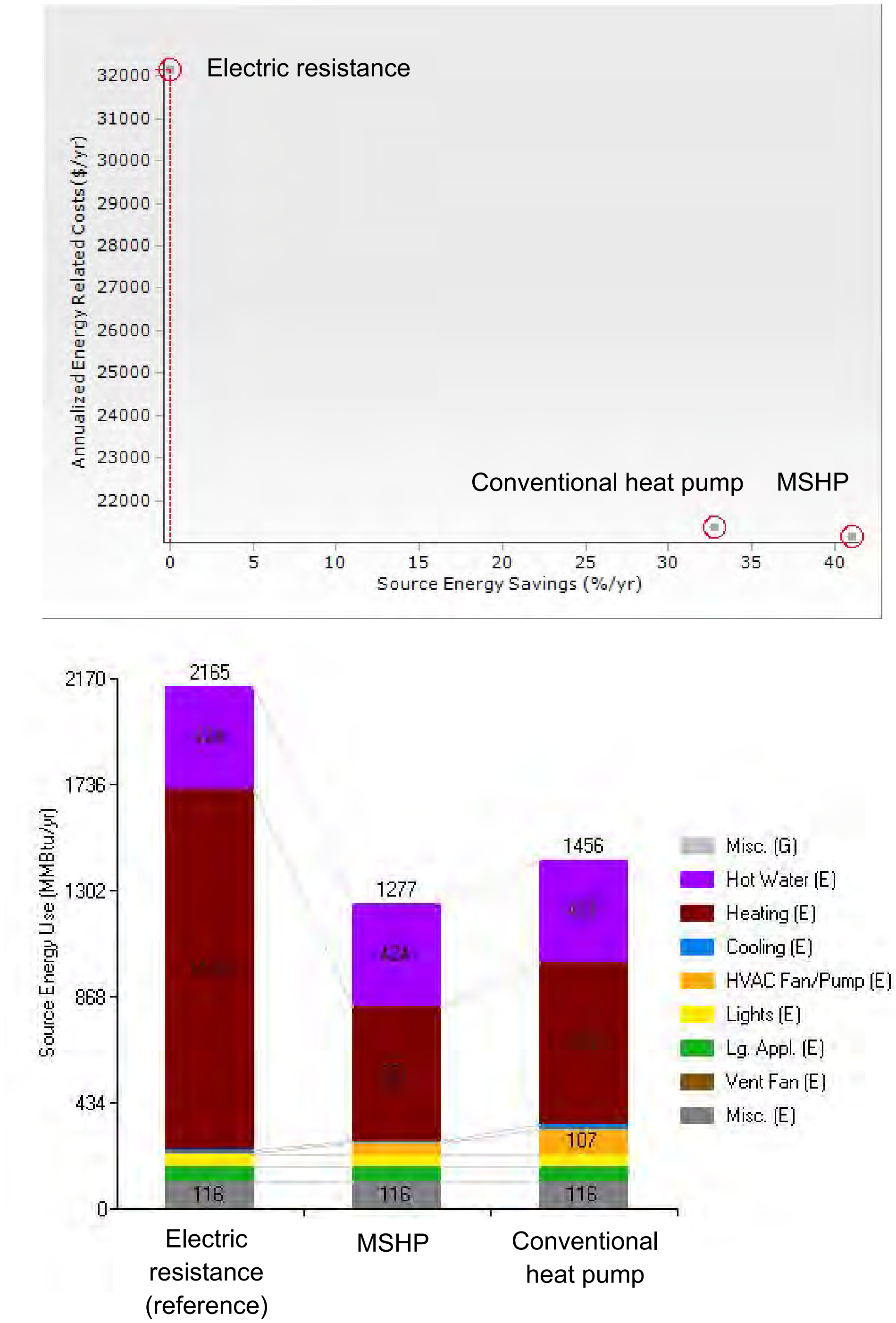


Figure 3. BEopt output comparing electric resistance, MSHPs, and conventional heat pump—New York

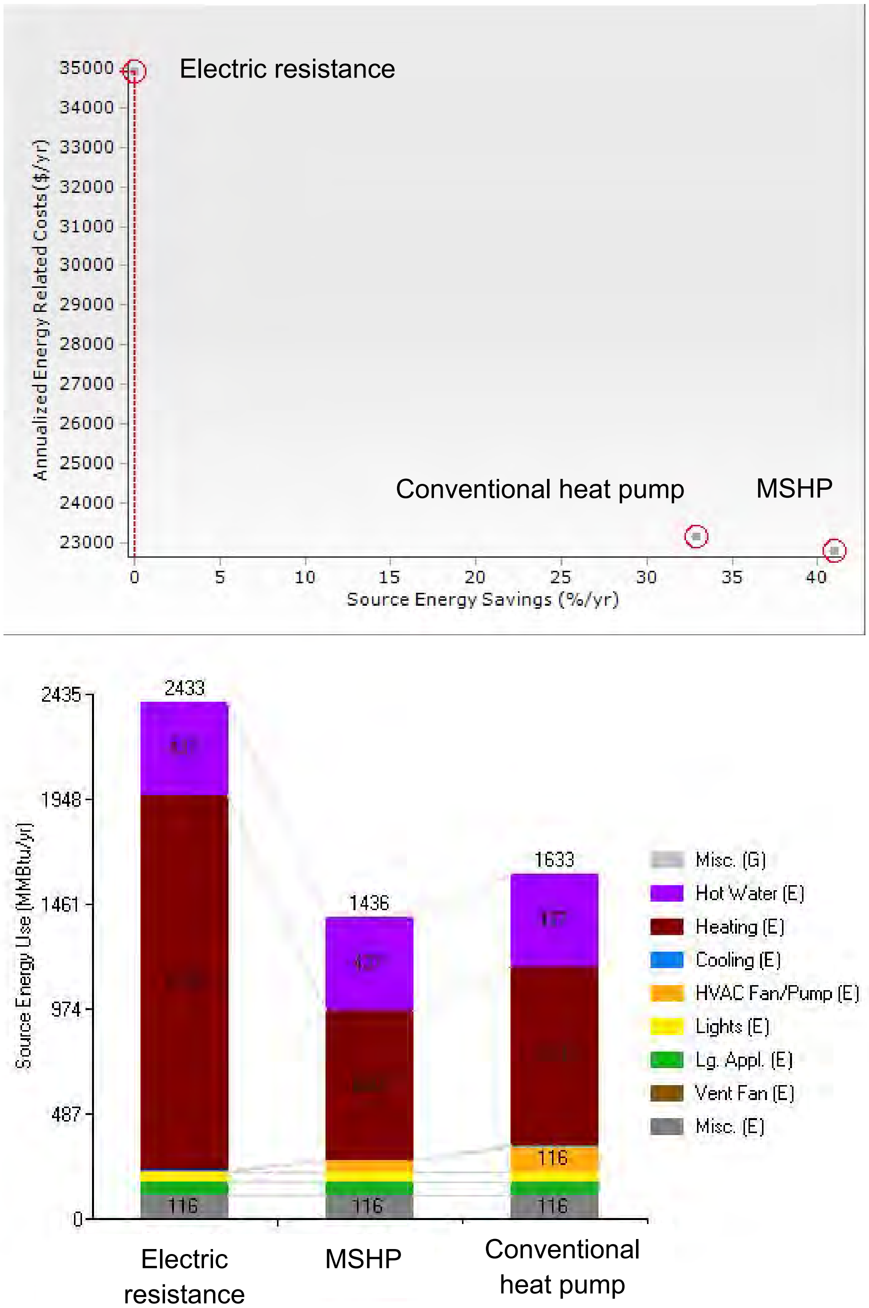


Figure 4. BEopt output comparing electric resistance, MSHPs, and conventional heat pumps—Boston

Converting from oil to MSHPs or conventional heat pumps is shown in Figure 5 and Figure 6. Water heating in this case is also by oil. Both heat pump options reduce annualized energy-related expenses by about 2%–6% in this example, with the MSHP having lower source energy requirements. New York showed a greater percentage reduction in energy consumption than Boston in this case, saving 6% as opposed to 2% for Boston. Energy consumption was greater for conventional heat pumps than with oil for both cities.

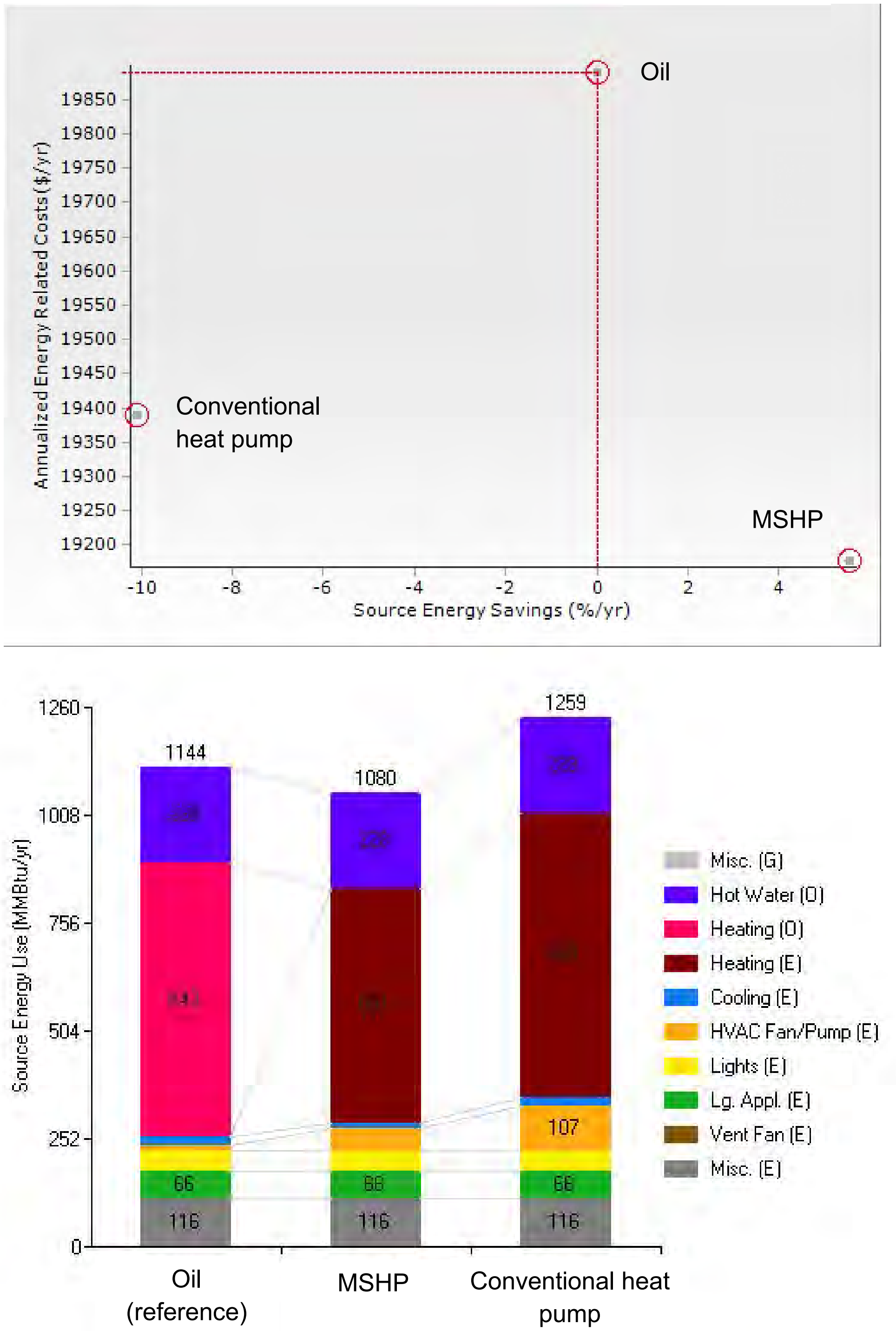


Figure 5. BEopt output comparing oil, MSHPs, and conventional heat pump—New York

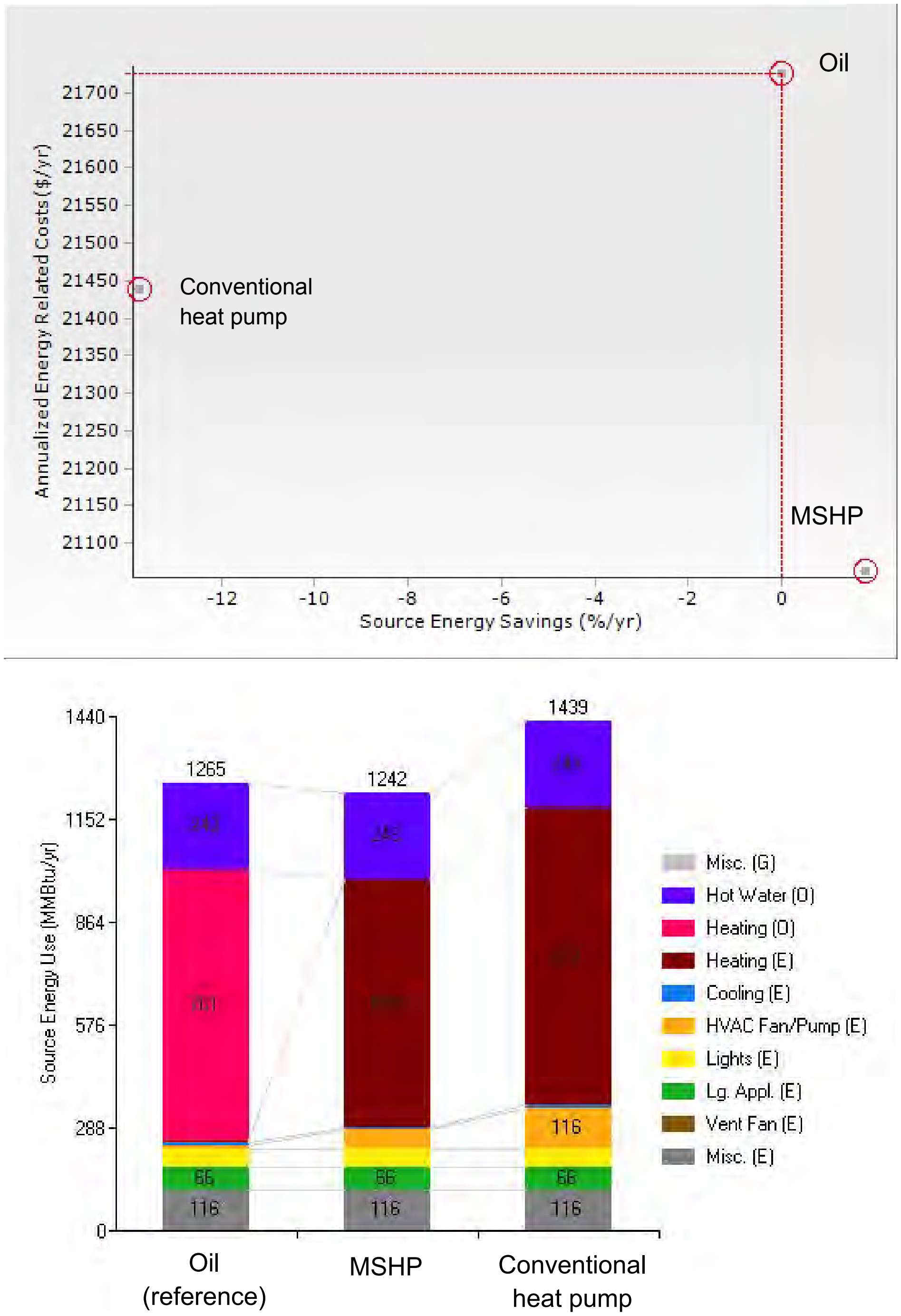


Figure 6. BEopt output comparing oil, MSHPs, and conventional heat pump—Boston

Converting from natural gas to MSHPs or conventional heat pumps is shown in Figure 7 and Figure 8. Unsurprisingly, gas is the lowest cost option indicating that this would not be a cost-effective conversion. Water heating in this case is by natural gas. New York saw an energy savings of 2% by converting from natural gas to MSHPs, but Boston saw a net energy consumption increase of 2%. Both climates saw an approximately 16% increase in energy consumption by switching to conventional heat pumps. It should be noted that conventional heat pumps work effectively down to 40°F. Below 40°F, heating is provided by electric resistance coils built into the conventional heat pump unit.

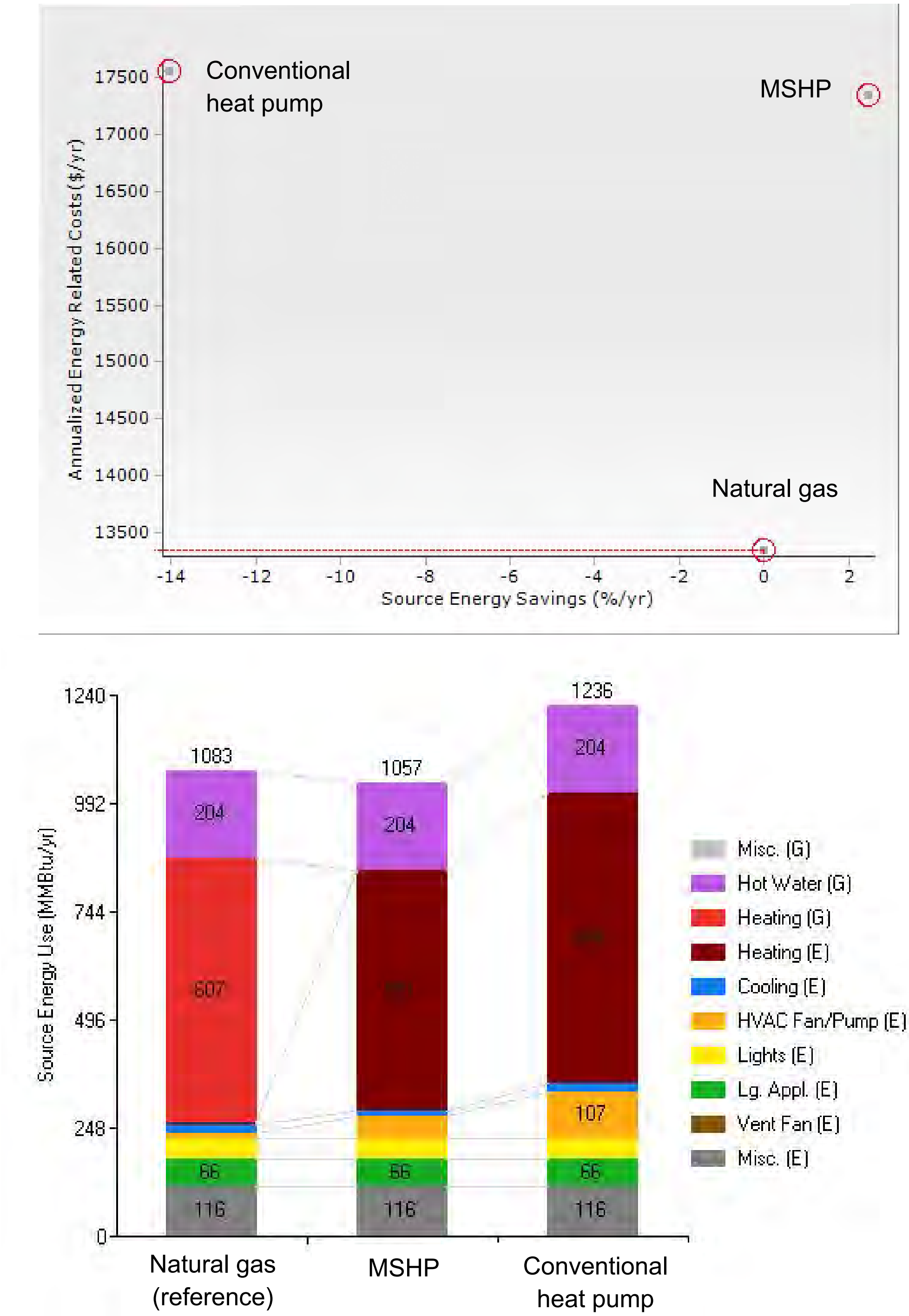


Figure 7. BEopt output comparing natural gas, MSHPs, and conventional heat pump—New York

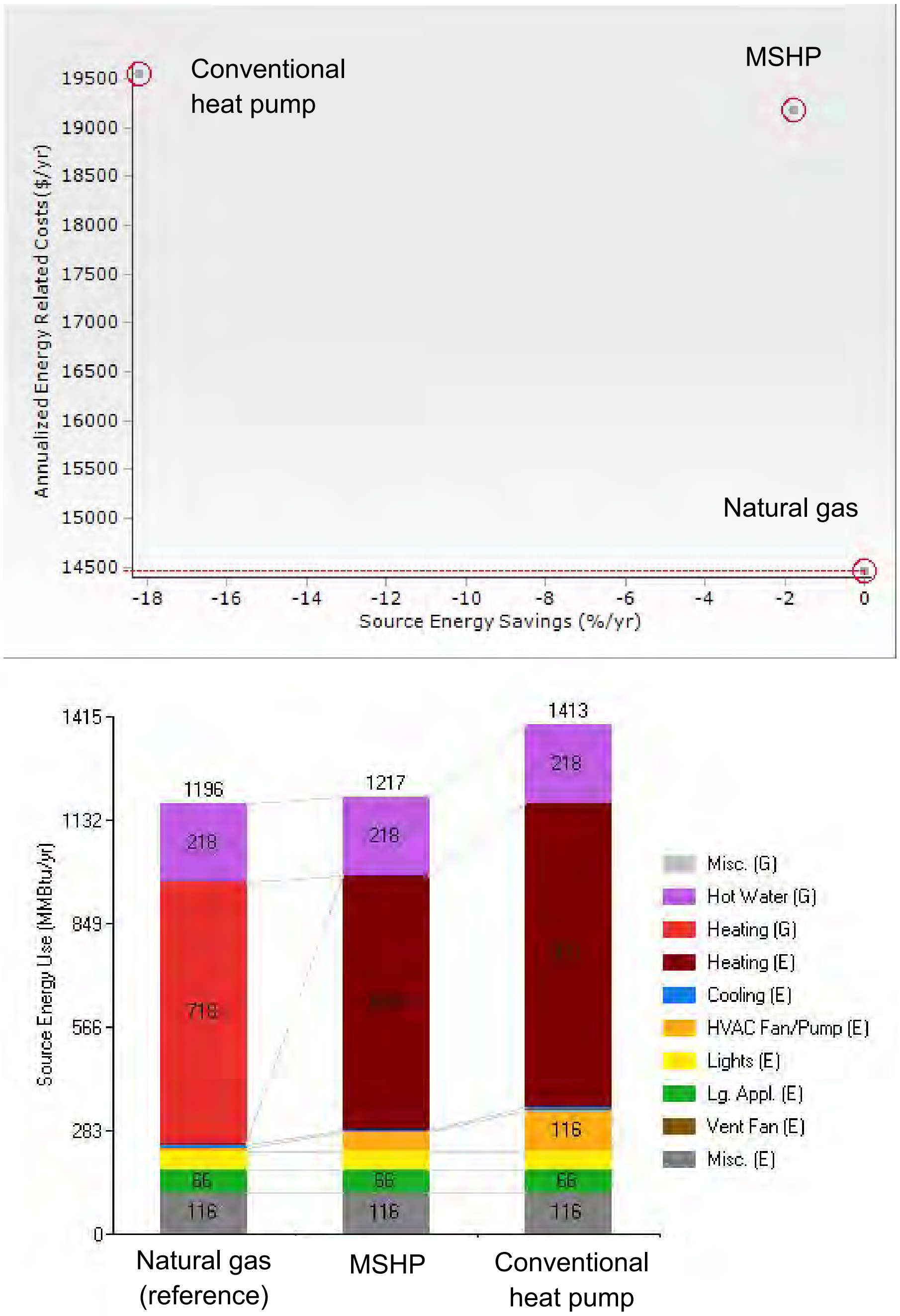
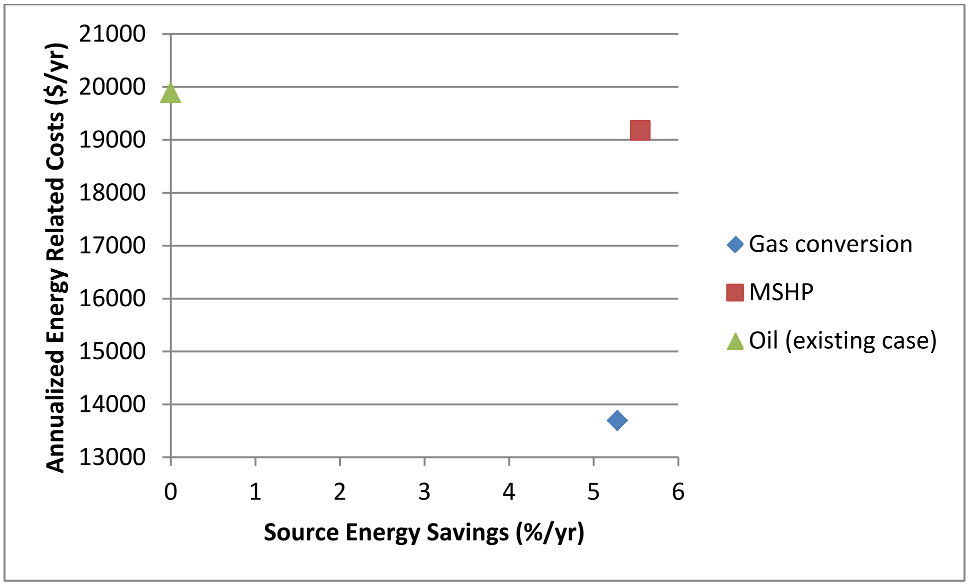


Figure 8. BEopt output comparing natural gas, MSHPs, and conventional heat pump—Boston

A further comparison was made of converting the oil-heated building to either MSHPs or to natural gas (assuming gas service is available), but that a new natural gas boiler would be installed at a cost of $11,563 and have a lifetime of 25 years (Figure 9 and Figure 10). The cost was determined by adding $3,000 to the BEopt defaults for installation of a new boiler ($1,000 for installing a gas line from the street to the building, $500 for the piping from the meter to the boiler, $750 for lining the chimney with a corrosive-resistant material, and $750 for the removal of the oil tank) (Perez, 2011) (Marks, Should You Convert from Oil to Gas Heating?, 2009)

(Marks, Converting to a Gas Furnace from an Oil Furnace, 2010). In both the New York and Boston cases, natural gas has a lower annualized energy-related cost indicating that MSHPs would not be the most cost-effective solution in this scenario.



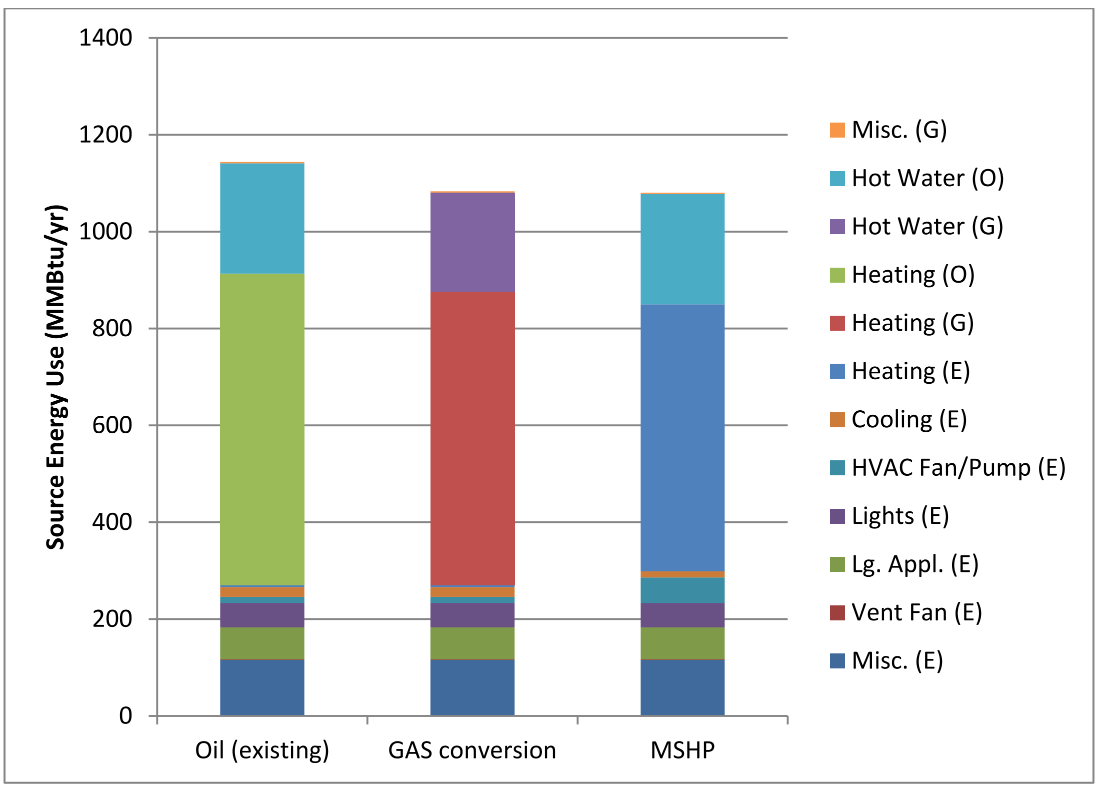
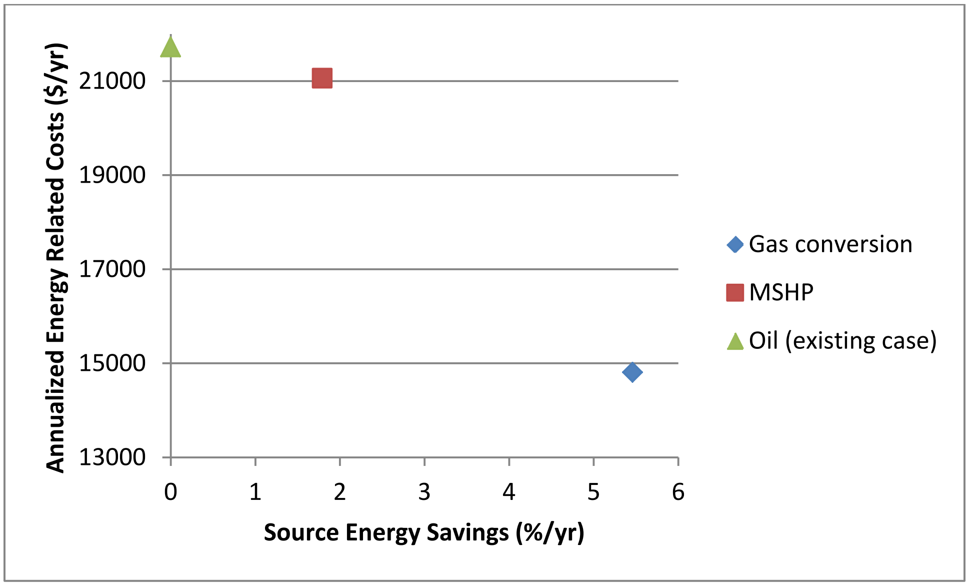


Figure 9. BEopt output for converting oil to natural gas or MSHPs—New York



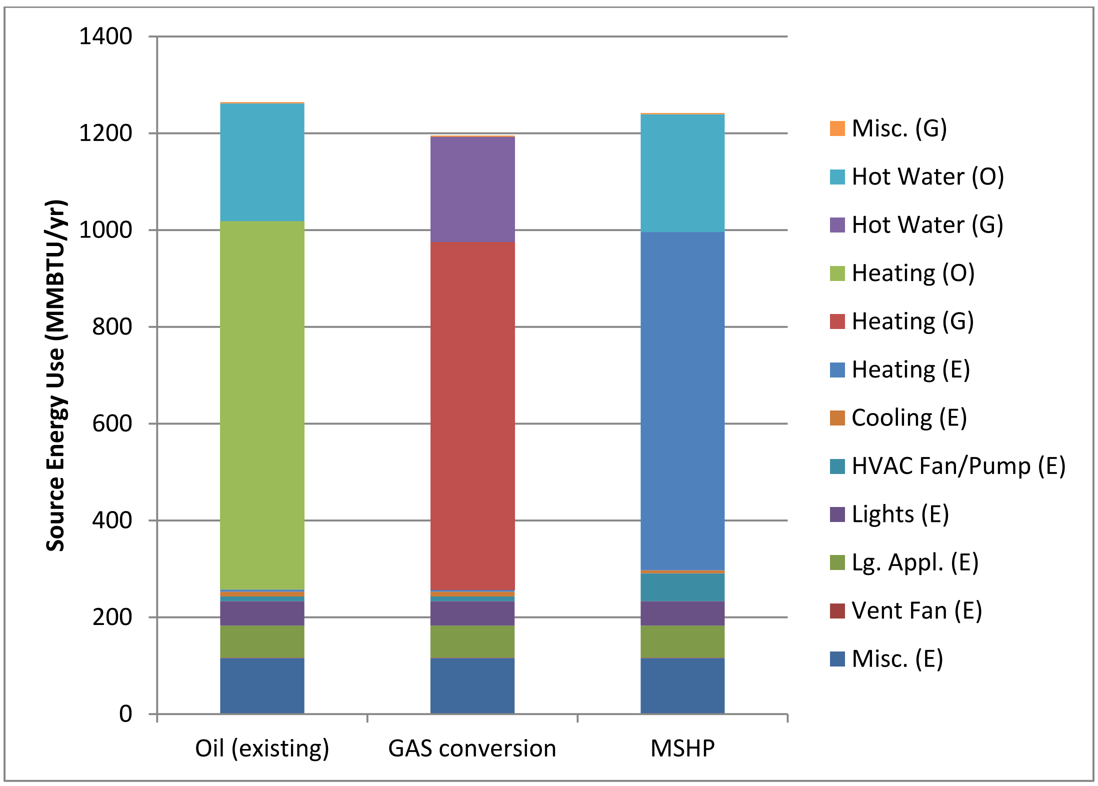


Figure 10. BEopt output for converting oil to natural gas or MSHPs—Boston

The impacts of envelope improvements on the results of the above BEopt analysis were explored for one case: oil-heated building in a mixed-humid climate (New York City). Three levels of enclosure air sealing were tested in combination with three other thermal enclosure improvements: 4 in. or 8 in. of exterior insulation (EIFS) and upgraded windows (from double-glazed air fill with metal frames, U = 0.76, to double-glazed argon fill low-e, U = 0.34). The specific improvement combinations evaluated are described in Table 9. Each was run with central oil-fired hydronic heating or with an MSHP retrofit. Costs for the EIFS were obtained from a local provider ($15/ft^2 for 4 in. and $17/ft^2 for 8 in.). BEopt values were used for windows.

Table 9. Envelope Improvements for BEopt modeling

Envelope leakage	Baseline	Add 4 in. EIFS	Add 4 in. EIFS and New Windows	Add 8 in. EIFS and New Windows
14 ACH50	✓			
10 ACH50	✓	✓	✓	✓
6 ACH50	✓	✓	✓	✓
3 ACH50	✓	✓	✓	✓

As heating and cooling loads decreased due to envelope improvements, lower equipment costs (obtained from contractor interviews) were used for MSHPs (11 units are present in the modeled building) reflecting smaller size units (Table 10). Boiler costs (for end of life replacement) were automatically adjusted by BEopt. Through-the-wall air conditioners for the reference case were maintained at $400 each for all cases.

Table 10. BEopt Default Economic Modeling Inputs

MSHP Rates Capacity	Cost
24,000 Btu/h	$3,500
18,000 Btu/h	$3,150
12,000 Btu/h	$2,400
9,000 Btu/h	$2,250

The annualized energy-related costs and source energy savings for the 13 scenarios are presented in Figure 11 and Figure 12. Figure 11 illustrates the points grouped by level of air sealing. Within each air sealing group is an upper (oil) and lower (MSHP) series of points (connected by dashed lines). As air sealing improves, the margin of savings of MSHP compared to oil decreases, although even at 3 ACH50, an MSHP retrofit has a lower annualized energy cost for this example. Note that if MSHP sizing (and therefore costs) had not been reduced as loads decreased, this relationship would have been inverted at the lowest ACH level, illustrating the importance of proper equipment sizing.

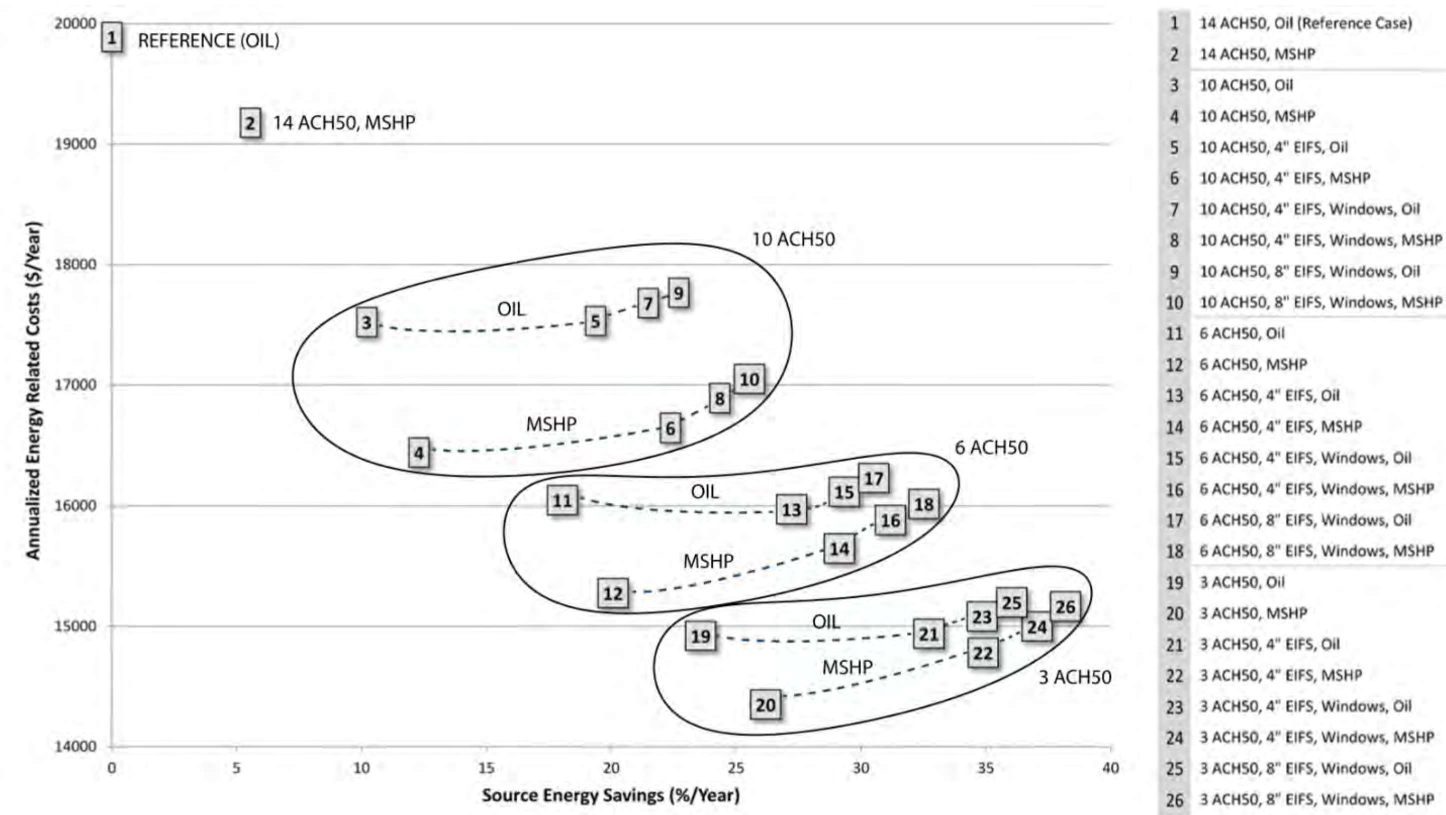


Figure 11. BEopt output comparing envelope improvements—air sealing

Figure 12 repeats the same plot, but groups the points according to envelope improvements. The leftmost group of points represents air sealing only, followed by 4 in. EIFS, 4 in. EIFS with new windows, and finally 8 in. EIFS with new windows. The lowest annualized cost of the options examined was the 3 ACH50 with MSHPs and no other envelope improvements. Oil at 3 ACH50 has a lower annualized cost than most other points.

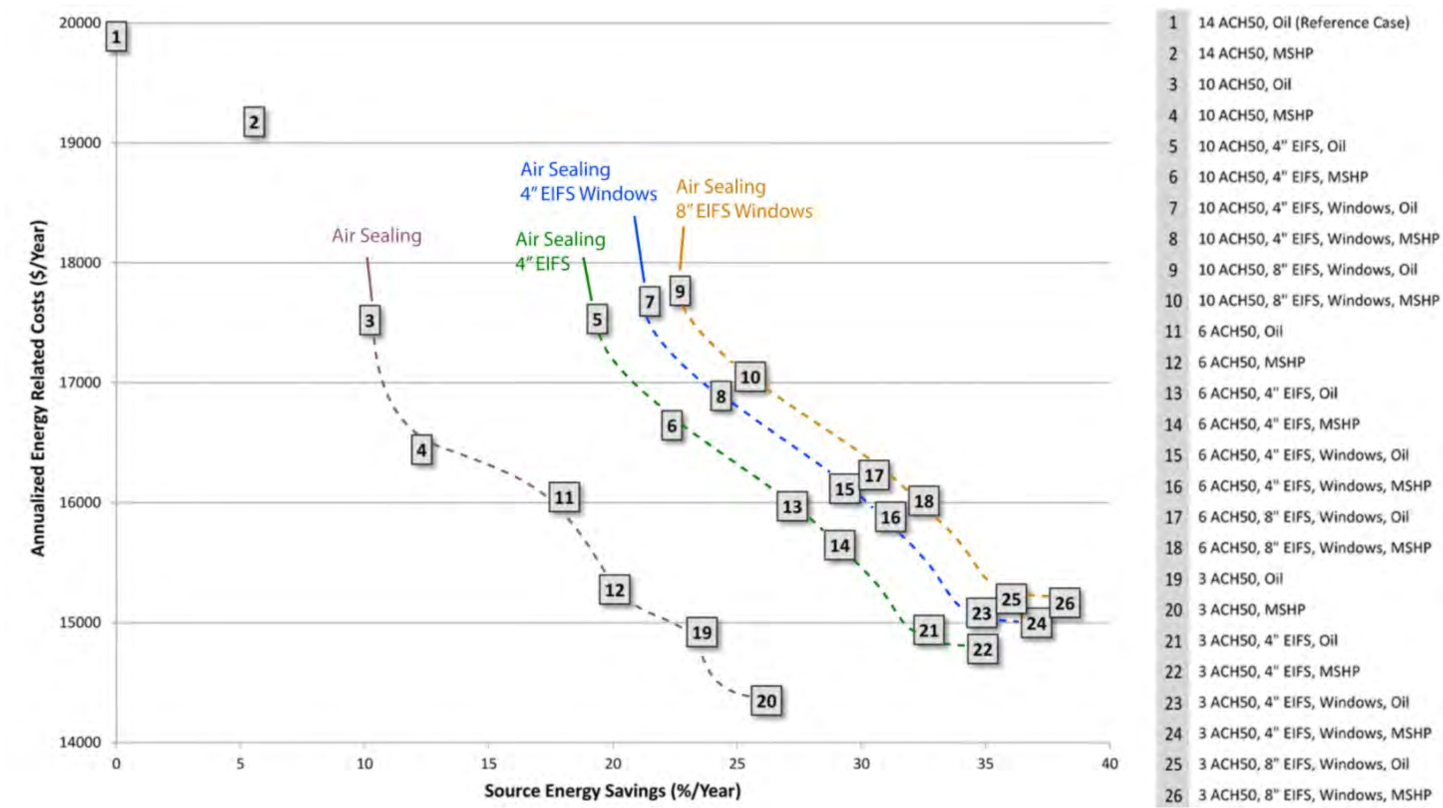


Figure 12. BEopt output comparing envelope improvements—insulation and windows

The above is not intended to be a comprehensive engineering analysis. It provides a preliminary estimate of the cost effectiveness of MSHP retrofits in typical low-rise multifamily buildings. Site-specific energy modeling would be required to predict the impacts of such a retrofit on other building types or on another specific building. The BEopt modeling provides a more in-depth look at various scenarios compared to the simplified energy cost modeling. Both methods resulted in similar heating source energy impacts of MSHP conversion as seen in Table 11.

Table 11. Comparison of Source Energy Savings

Source Heating Energy Savings of MSHP Compared to:	Simplified Energy Cost Modeling	BEopt Modeling
#2 Heating Oil	14%	14%
Natural Gas	7%	9%
Electric Resistance	60%	63%

3 Retrofit Examples

No published reports describing retrofits of MSHPs in multifamily buildings in mixed or cold climates were found. However, a number of examples were identified and are described below. This information is gathered from interviews with program and project participants.

3.1 Efficiency Maine

Efficiency Maine's Low Income Multifamily Weatherization Program began providing incentives for installation of MSHPs in January 2012. The information included here was obtained from interviews with Efficiency Maine (Meyer, 2013), Conservation Services Group (Gifford, 2013), and C&C Realty Management (Moeykens, 2013).

The program pays 100% of the cost of an energy audit plus cost-effective energy efficiency improvements without caps. To be eligible for MSHPs, properties must be heated with electricity and at least 66% of tenants must be LIHEAP-eligible. LIHEAP participation is not required. In addition to MSHPs, other measures—most commonly air sealing and attic insulation—are included in the program. Approximately 600 MSHPs have been installed. Many sites, but not all, also include envelope improvements. An energy audit and utility bill analysis are used to estimate savings-to-investment ratio (SIR) for each measure. Measures that receive an SIR of 1.1 or higher may be funded. Not all residences achieve the minimum SIR for MSHPs; some do not because they are small apartments that do not consume enough electricity to warrant the investment. Additionally, some owners were not interested in heat pumps because of aesthetics (they objected to the outdoor compressors or line sets) or a lack of confidence in the technology.

Most of the apartments included in the Maine program were one-bedroom units, with a few two-bedroom units. All were in one- or two-story buildings. In addition to electric resistance baseboard heat, they often had window air conditioners. The energy audits assumed that 75%–80% of the heat load would be satisfied by the MSHPs with a COP of 3.0. The baseline case assumed no air conditioning, and the post-retrofit case assumed 100% air conditioning (effectively imposing an energy penalty). The overall program SIR averaged about 1.75–2.0.

One wall-mounted, 9,000 Btu/h single-head unit (manufacturer rated HSPF 12.5, yielding an approximate rated COP of 3.7) was installed per apartment. There was no additional distribution provided to bedrooms. Compressors were set on the ground. Existing baseboard resistance heat was left in place and residents were instructed to not use it unless necessary. A future program will evaluate compliance with these instructions.

The program budgeted for $4,500 per MSHP unit. After a learning curve and increase in qualified contractors, the average cost became $2,229 per unit ($1,041 for equipment and $1,188 for labor).

The program manager reported very few problems and only three broken units to date (two due to abuse; one failure). The lack of resident feedback is interpreted to be positive (no news is good news). There have been some problems, resulting in minor modifications to the process:

- **Ice from melt water:** The biggest issue was that compressors located under roof drip edges had freeze problems when roof melt water dripped on them. The program is now installing a custom aluminum cover to protect units from water.

- **Ice from rain:** Compressors can cause local freezing temperatures when it is raining and the outdoor air temperatures are in the 30s°F (units will shut off when they get ice to protect themselves). The covers will also help to prevent this problem.
- **Indoor unit cover:** A delicate plastic cover on indoor unit rises when there is a call for heat. This cover can be installed incorrectly, preventing the unit from operating.
- **Controls:** The standard controls are far more complex than what residents were accustomed to with electric resistance heaters. The program switched from the standard remote control to a simpler wall-mounted thermostat also provided by the manufacturer.
- **Usability:** Residents found the user manual difficult to understand. A simple one-page "quick start" guide would be helpful according to program administrators.

One major benefit of the MSHPs is reduced annual maintenance because they eliminate the need to seasonally install and remove (and store) window air conditioners, formerly the responsibility of property management. Compared to this task, the required MSHP filter cleaning is less burdensome. While there is no direct monetary benefit to property owners (residents pay utilities) as a result of the retrofit, the retrofit property has higher property value and is more desirable to prospective tenants. Aesthetics is a large factor in decision making: while the addition of outdoor compressors and line sets is a negative, the elimination of window air conditioners is a positive.

C&C Realty Management manages approximately 1,000 affordable housing units (one- to two-bedrooms each) in about 25 developments in central Maine, many of which participated in the Efficiency Maine retrofit program. The communities consist of one- and two-story wood frame multifamily buildings. Initially C&C was leery about installing MSHPs for cold climate heating. However, its property owner clients were interested in the program because of its potential to reduce resident turnover. While residents of these affordable housing properties receive utility allowances from the state, they are sometimes unable to pay the steep wintertime bills. Failure to pay these bills can result in utility cutoffs and eviction. While lowering their utility bills will not lower their total annual out-of-pocket housing costs (except in the short term while allowances are readjusted over 1.5–2 years), it will smooth out what would normally be large seasonal fluctuations. C&C has had very positive resident feedback overall. Education has been important because the operation of the units differs from what residents were previously familiar with. C&C does not have data on continued use of the resistance heaters. Its scheduled maintenance to clean filters will add a minor cost to its management fee.

3.2 Connecticut Energy Efficiency Fund

The Connecticut Energy Efficiency Fund Home Energy Solutions—Income-Eligible program installed 3,576 MSHP units at 51 sites in 2011 in partnership with the Connecticut Department of Social Services, leveraging American Recovery and Reinvestment Act funds. The information included here was obtained from interviews with Connecticut Energy Efficiency Fund (Bugbee, 2013) and Wethersfield Housing Authority (Forcier, 2013).

According to the program annual report, "Energy-efficient ductless heat pumps, with their small footprint and easy installation, are well suited to offset electric baseboard heating consumption usually found in public housing properties and can typically save residents 25% to 50% percent on their heating bill" (Energy Efficiency Board, 2012). The program provided a package of measures including the MSHPs and basic weatherization at no cost to property owners.

Most properties were public housing agencies. Most buildings were single story with electric resistance heat. Most apartments were studios or one-bedroom units, but there also were a few larger units. Most apartments previously had window or through-the-wall air conditioners. Through-the-wall sleeves were sealed as part of the retrofits.

Community action agencies (weatherization agencies) conducted audits and calculated SIRs, and an engineer developed specifications for each project. The community action agency solicited three bids per project. Mostly single-head systems were installed; however, sometimes two-head systems with a single outdoor unit were used in one-bedroom apartments. Costs for heat pumps were $3,000–$4,000 per apartment, including installation. Existing resistance heating remained in place.

According to program staff, resident feedback regarding the MSHPs is positive, including among elderly residents. Educational kickoff meetings were conducted at each community where residents were encouraged to turn off resistance heating. Simply setting the resistance heater to a lower set point on the theory that it would not turn on unless the MSHP could not meet the load did not work as intended. When the resistance heater did turn on, it would remain on. Anecdotal reports indicated that it would override the heat pump and savings would not be achieved.

Installation challenges that were noted included that it was difficult to get lines to second floor units (about 15% of units), and a code compliance issue arose with respect to the drip pans and condensate pumps.

The Wethersfield Housing Authority administers state, federal and local housing programs for income-eligible individuals, families, those aged 62 and older and adults who are 100% disabled. The authority operates three elderly housing communities and two family housing communities. Rents are based on a percentage of income, or base rent, whichever is higher. They participated in the Home Energy Solutions—Income-Eligible program, retrofitting 112 electric resistance heated units with MSHPs. While the residents have not had significant complaints, as the property owner and operator, the housing authority has some misgivings. Additional costs that it cannot recoup through increased rents include labor for regular filter cleaning, annual weatherization of outdoor units, and repairs of complicated equipment. During a blizzard in 2013 they had to advise residents to not use their heat pumps (and to use resistance heaters instead) until they could clear snow from all compressor units. They also had bad experiences with one unit that was defective and one that was destroyed by an insect infestation. Utility costs are passed through to the state or federal programs, but the additional maintenance costs are not. Furthermore, while they have no funds to replace failed heat pumps, because the utility program sealed up the pre-existing air conditioner sleeves, residents will be forced to resort to window units for cooling should the MSHPs fail.

Another housing agency in Sharon, Connecticut that participated in the Connecticut program is very satisfied with the MSHPs after one season, anticipating 25%–50% heating energy savings for the residents (Davies, 2013).

3.3 B.C.M.W. Community Services

B.C.M.W. Community Services is a weatherization agency in Centralia, Illinois (4,568 heating degree day base 65, and 14,114 cooling degree day base 74). The agency installed MSHPs under a low-income multifamily weatherization project in a development known as the Library Apartments. The three-story building contains studios, one-bedroom, and two-bedroom apartments under a common attic. The existing concrete exterior and interior walls contained no insulation. Residents (who pay their own utility bills) were using plug-in electric space heaters and one to two window air conditioners per apartment. An SIR of 4 to 5 was calculated for the installation of SEER 16, 8.0 HSPF MSHPs. Twenty-three systems were installed in July 2011 for an equipment cost of $1,300 for single-head and $1,500 for dual-head systems. Installation labor was one day per system for a crew of two. Typical installation was one head in the living room, one in the master bedroom, and none in the second bedroom (if one existed). Doors were undercut to provide some airflow to second bedrooms. All pre-existing heating equipment was removed. Other measures included:

- Vinyl, argon-filled windows (four to six per apartment) replaced single-pane metal.
- ENERGY STAR exterior doors replaced hollow core doors.
- Open concrete masonry unit cavities in exterior walls were filled with injection foam.
- R-49 insulation was added to the previously uninsulated attic.

According to the contractor, anecdotal feedback from six to eight residents is very positive; utility bills were reduced by $150–$275 per month per apartment; the landlord is pleased and cleans filters every 2–3 months (Pryor, 2013).

4 Discussion

This section summarizes a number of issues and information regarding MSHP multifamily retrofits gleaned from the projects described above and other sources.

- **Technical barriers:** There are a few technical barriers to the use of MSHPs in multifamily retrofits; they largely relate to the placement and location of the outdoor compressor unit and its proximity to the indoor evaporator unit. For small capacity units (up to 2 tons) that are most likely to be used for apartments, the vertical distance between the indoor and outdoor units typically should be shorter than 50 feet and the refrigerant pipe should be shorter than 60 feet. Larger capacity units allow longer vertical and overall distances. Therefore, maintaining proximity for low-rise housing is generally not an issue if ground space is available. However, for units up to 2 tons, building heights above about nine floors will require intermediate locations for compressor placement, either on balconies, intermediate setbacks, or mounted to exterior walls. Mounting on exterior walls may require additional structural engineering and potentially be aesthetically objectionable. Also, future maintenance costs must be considered for difficult to access locations. Fortunately, both indoor and outdoor units run relatively quietly, therefore the units can be mounted near windows without noise problems, assuming the windows are closed.
- **Building code compliance:** Building codes may limit where outdoor compressors may be placed with respect to lot lines and exterior attachment to buildings. No other building code issues are known.
- **Utility billing:** The MSHP retrofits identified during this research were all electric resistance heated buildings that converted to heat pumps and therefore did not involve fuel switching. If buildings with central heating systems (typically gas or oil fired) are converted to MSHPs, then changes to the way space heating is paid for may result. Public Utility Commission regulations may apply to situations where central heating (paid for commonly or by the building owner) is replaced with electric heating metered to the apartment owner or renter. If the building owner wishes to, or is required to continue paying for space heating, then extensive electrical work may be needed to install the indoor evaporator units on circuits separate from the apartment circuits. Another variation on utility billing is when a large outdoor compressor serves indoor units in multiple apartments (e.g., Mitsubishi's City Multi system): the compressor energy can be paid for centrally, and the indoor units' energy paid for by each respective apartment.
- **Peak electricity demand:** MSHPs have the potential to reduce peak electricity demand by 40%–60% as compared to electric resistance heated buildings during both heating and cooling seasons (assuming the buildings already have cooling—if not, they will increase summer electricity demand and energy consumption). Converting from fossil fuel heating to MSHPs will increase winter kilowatt peaks, but reduce summer kilowatt peaks, assuming the property has pre-existing cooling.
- **Occupant comfort:** Changing space conditioning systems to MSPHs entails a number of comfort considerations. Changing from central steam heating provides a higher level of thermal control to occupants where before there may have been none. It has the potential

to eliminate overheating, but introduces some fan noise in place of possible radiator knocking and hissing. Changing from hot water heating to MSHPs may offer improved control depending on the condition of the existing heating system. Central steam and hot water systems have been observed to consistently overheat apartments in multifamily buildings (Dentz, Varshney, & Henderson, 2013), something that MSHPs under resident control could avoid. Changing from electric resistance heating provides better mixing of air to distribute heat, potentially improves control via programming and setback opportunities, but adds fan noise. Changing from room air conditioners generally provides more cooling capacity at a lower cost, has lower fan noise and provides better mixing of air and humidity control. One advantage of MSHPs is that one compressor can be connected with multiple indoor units and each indoor unit can be controlled separately depending on the need. This provides true zoning and can optimize comfort by room, although efficiencies are typically lower for multi-head systems. If MSHPs are not installed in every room, then comfort may be adversely affected in unserved rooms—this is discussed further under **Distribution** below.

- **General satisfaction:** Anecdotal reports from interviews with building and program managers indicate that overall, residents are pleased with MSHPs where they have replaced electric resistance heating and room air conditioners (or have been installed in apartments without pre-existing cooling). There has been a learning curve as residents become accustomed to different controls. The populations involved in the retrofits identified were low income and/or elderly, but there is no reason to believe that these findings would differ with other building population types. Note that many of these retrofits included weatherization of envelopes, which also may have affected satisfaction and comfort. Also note that the retrofits researched were all small apartments with typically one bedroom. Larger apartments may require additional indoor evaporators and/or other means of distributing conditioned air.
- **Distribution:** Ensuring adequate distribution of conditioned air from point-source MSHPs in retrofits is a balance between additional indoor units (at significant cost), envelope improvements and other means of air distribution. None of the multifamily retrofit projects investigated used distribution techniques other than door undercuts. With the exception of the studio apartments in the Connecticut program, all units had at least one bedroom without an MSHP evaporator, meaning these rooms were reliant on passive distribution of space conditioning unless residents activated the electric baseboard heat that was left in place (except for the Illinois project) (Table 12). Anecdotal reports indicate this has not been an issue; however, savings data have not been analyzed yet.

Table 12. Summary of Retrofit Project Data

	Connecticut	Maine	Illinois
Apartment Type	Studio and 1 bedroom	1 and 2 bedrooms	1 and 2 bedrooms
Number of Indoor Units per Apartment	1	1	1 or 2
Backup Heating	Yes	Yes	No

- **Occupant health and safety:** The superior control of MSHPs will reduce overheating, if any, that can create unhealthy, low-humidity environments. MSHPs also do not have exposed high temperature components in the living spaces (e.g., steam pipes, radiators, electric heating elements) that are potential hazards. The addition of cooling where it may not have previously existed can be a health benefit, particularly for the elderly.
- **System reliability:** One benefit of MSHPs compared to central systems is that having independent, distributed heating equipment avoids situations where the entire building must be shut off for maintenance or repairs, an occasional occurrence with central steam or hot water heat. However, there is limited experience in the United States related to the reliability of MSHPs in heating mode in cold climates. The Ecotope study (Ecotope, 2009) showed robust performance over 3 years. Cold climate experience from Maine and Connecticut is limited to 1–2 years, but the program evaluation reports have not yet been prepared. This will be important to track, especially given the limited funds available for equipment maintenance and the fact that existing resistance heaters were left in place: what percent of the heat pumps will still be operating at high efficiency in 5 or 10 years?
- **Equipment durability:** Hydronic and steam systems are generally quite durable. Electric resistance heaters are virtually maintenance free and if in need of replacement are very inexpensive. MSHPs are more sensitive to physical damage, require regular filter cleanings, and have a major component (the compressor) outdoors where it is exposed to the elements and possible intentional or accidental damage. This is an additional burden on building staff and a potential expense for owners. If the building owner is not receiving the benefit of energy savings, then he or she may be incurring additional unrecompensed costs for repairs. For public housing agencies that are reimbursed for utility bills by the state or federal government (or whose residents are), it may be hard to justify additional repair and maintenance expense, even if the equipment is installed at no cost and it benefits the public.
- **Equipment maintenance:** MSHPs require more maintenance compared to electric heating elements, which require little or no attention for many years. By contrast, MSHPs have many fragile parts (including fins on outdoor units, moving mechanical parts, plastic housing and fins on indoor units, condensate pump, and tubing). This is of concern to building owners, but not enough data are available to determine the long-term cost. MSHP maintenance requires a different skill set than does maintenance of steam and hydronic systems. This may require outside service personnel whereas the in-unit equipment (e.g., radiators) of steam and hydronic systems often can be serviced by building staff. Because MSHPs would be distributed throughout the building, maintenance may require access to apartments, rooftop, balcony, or exterior wall locations. The only regular maintenance required by MSHPs is filter cleaning.
- **Costs:** The Maine program, which began in 2012, budgeted $4,500 per MSHP unit. The average cost dropped over time to $2,229 per unit ($1,041 for equipment and $1,188 for labor). In Connecticut, the program paid approximately $3,000–$4,000 per unit starting in 2011. The Illinois project paid (for equipment only) $1,300 for single-head and $1,500 for dual-head systems in 2011. A survey was conducted by ARIES in 2012 of contractors on Long Island, New York to estimate current installed costs of MSHPs in a typical retrofit situation. Costs were obtained for the installation of single systems (i.e., a single-

family home) and for multiple systems (i.e., multiunit development). All units had SEERs from 17.5 to 23 and HSPF from 9.5 to 11. The results are shown in Table 13.

Table 13. MSHP Costs

Contractor	Configuration	Installed Cost (Multiple Systems)	Installed Cost (One System)
1	9,000 Btu (one head)	$2,100	
	12,000 Btu (one head)	$2,300	
	18,000 Btu (one head)	$2,800	
	18,000 Btu (two 9k heads)	$4,200	
	24,000 Btu (two 9k and one 7k head)	$5,000–$6,500	
2	9,000 Btu (one head)	$2,250	$2,550–$3,050
	12,000 Btu (one head)	$2,400	$2,650–$3,150
	18,000 Btu (one head)	$3,150	$3,150–$3,650
	18,000 Btu (two 9k heads)	$3,650	$3,950–$4,350
3	9,000 Btu (one head)	$2,577	
	12,000 Btu (one head)	$2,711	
	18,000 Btu (one head)	$3,257	

5 Conclusion

MSHPs are a viable retrofit opportunity for low- to mid-rise multifamily buildings. They are cost effective under many conditions. Successful multifamily retrofits were identified in three states, although they were all retrofits of buildings with electric resistance heating, the lowest hanging fruit. The following summarizes the answers to the specific research questions addressed in this report:

1. What are the characteristics that impact the potential for MSHP retrofits (i.e., what buildings are most suitable for MHSP retrofits and why)?

Buildings most suitable for MSHP retrofits are those with high-cost heating fuel such as LPG, fuel oil, and electric resistance. Electric resistance is by far the most suitable for retrofit. Buildings where natural gas service exists are less suitable because the current cost of that fuel is low and natural gas appliances are efficient. Coupling expensive fuels with poor thermal envelopes makes the building even more suitable; however, even when the envelope is substantially improved, MSHPs can be cost effective on annualized cost of energy-related expenses. Colder climates amplify the benefits of MSHPs, now that they are available with high heating capacities even at low outdoor temperatures. It is easier to install MSHPs on low- to mid-rise (up to nine floors) buildings where ground and/or roof space permits mounting compressor units in relative close proximity to indoor units. Small, open plan homes where distribution of conditioned air is simple will be more cost effective.

2. What is the relative cost effectiveness of MSHP retrofits by building type and climate compared to competing alternatives, including maintaining or upgrading obsolete, inefficient space conditioning systems (e.g., one-pipe steam with 30-year-old boilers and room air conditioners; electric resistance heating with room air conditioners)?

In the New York climate, converting from electric resistance to MSHPs saved approximately 30% of annualized energy-related costs in the example building modeled with BEopt. Converting from oil saved about 4%. Converting from natural gas would cost about 30% more. In the Boston climate, converting from electric resistance to MSHPs saved approximately 50% of annualized energy-related costs in the BEopt model. Converting from oil saved about 3%. Converting from natural gas would cost 24% more.

3. What are the major technical and regulatory barriers to installing MSHPs in multifamily buildings?

For most low-rise multifamily buildings, the technical and regulatory barriers are minimal. Many buildings have been retrofitted in Maine and Connecticut without major regulatory issues. For buildings that are converting from central heating systems to individually metered MSHP systems, the utility billing change may engender regulatory barriers especially for affordable housing. No existing conversions of this type were identified.

4. Are MSHP retrofits cost effective in common types of low-rise multifamily buildings?

Modeling indicates that MSHP retrofits are highly cost effective for buildings currently heated with electric resistance, if the property managers are able to accommodate a potentially slight increase in maintenance costs. MSHP retrofits are moderately cost effective for oil (and likely LPG) buildings with poor thermal envelopes in mixed and colder climates.

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