CADMUS

E4THE FUTURE

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

MASSACHUSETTS CLEAN ENERGY CENTER

U.S. DEPARTMENT OF ENERGY

Final Report

Residential ccASHP Building Electrification Study

June 3, 2022

Cadmus Project Team

- **Neil Veilleux:** Principal Investigator
- **Christie Amero, PE:** Project Manager
- **John Walczyk:** Technical Advisor
- **Jeremy Koo:** Technical Advisor
- **Mark Janett:** Customer Survey and Contractor Interview Task Lead
- **Nathan Hinkle:** Data Analysis Lead
- **Anne Greening (Acadia Consulting Group):** Home Performance Contractor and Customer Interview Lead

Project Advisory Committee

- **Project Funders**
  - **E4TheFuture:** Steve Cowell, President
  - **MassCEC:** Meg Howard, Program Manager
  - **NYSERDA:** Victoria Engel-Fowles, Project Manager
  - **DOE Building Technologies Office & PNNL:** Monica Neukomm, Ed Vineyard, Cheryn Metzger
- **Stakeholders**
  - **Eversource:** Peter Klint, Program Manager
  - **National Grid:** Stephen Lasher, Principal Engineer
  - **NEEP:** David Lis, Director of Technology & Market Solutions
- **Technical Advisors**
  - **Coughlin & Associates Energy Consulting:** Tom Coughlin, Principal
  - **Bruce Harley Energy Consulting:** Bruce Harley, Principal
  - **Performance Systems Development:** Greg Thomas, Chief Strategy & Technology Officer

Contents

Study Background

Drivers of the Study

Carbon reduction targets require transformation of the built environment.

Widespread electrification is essential to achieve carbon neutral buildings.

A concerted policy push is necessary to deploy whole-home (or primary heating) electrification.

Drivers of the Study

- **Carbon reduction targets in the Northeast require transformation of the built environment.**
  - Massachusetts seeks 50% GHG reductions by 2030 and 85% by 2050.
  - New York seeks 40% GHG reductions by 2030 and 85% by 2050.
  - Direct emissions from fossil fuel combustion for space and water heating in buildings account for approximately 30% of emissions.
- **Achieving carbon neutral buildings requires:**
  - Widespread electrification of thermal loads.
  - Improved thermal performance of building envelopes.
  - Ability to store and/or shift energy use and interaction with the electric grid.
  - Supply of energy loads from zero emissions resources.
- **However, across the Northeast, most building thermal loads are served by fossil fuels (oil, gas or propane).**
  - Use of heat pumps (electrification) is increasing, though primarily for supplemental loads.
  - Greater adoption of whole home heat pumps—or heat pumps serving as the primary heating source (90% of thermal load or more)—is necessary to decarbonize building stock.

Whole-Home or Primary with Backup ASHP Deployment Barriers

A range of barriers inhibit adoption of whole home (or primary) electrification. This study focused primarily on **real or perceived technology and performance risk**.

Technology & performance risk

- Poor technology performance on coldest days of year
- Poor comfort for building occupants

Financial

- High upfront costs
- Poor return on investment
- Inadequate access to capital

Marketing & awareness

- Lack of customer awareness
- Insufficient marketing and sales from contractors

Supply chain

- Lack of training for contractors
- Undersupply of contractors

Decision-making

- Split incentives (landlord-tenant)
- Misaligned priorities

Scope of Work

Residential (1-4 family) building electrification

Assess **cold climate** air source heat pump performance in **NY + MA**

Whole-home and **primary** w/ backup heat pump configs

Quantitative Research	Qualitative Research
Program database review identify trends and eligible sites for study	Literature review sales, design, installation best practices
Online surveys with customers (n=628) customer satisfaction and usage behavior	Stakeholder interviews (n=4) understand electrification priorities
Site visits + metered data collection (n=43) overall energy use, performance, fossil fuel displacement	Heat pump contractor interviews (n=19) design, marketing, installation
Customer billing analysis (n=84) comparison to previous heating fuel usage	

Key Objectives of the Study

1. Are ccASHP systems meeting home comfort needs?
2. Are ccASHPs efficiently delivering heating and cooling?
3. How does performance differ between whole-home and primary with backup applications?
4. What are the grid impacts of ccASHP market scale up?
5. What continued challenges with customer and contractor experience need to be addressed to scale the market?

IMPORTANT CAVEAT: This in-depth research study focused on a small sample of homes in MA and NY. We did not select the participant sample to be statistically significant or representative of the population. Findings and conclusions from this study are intended to provide an indication of potential operational trends. We recommend additional data collection for a broader sample to draw firm conclusions about ccASHP operation in the Northeast.

Objective 1: Are ccASHP systems meeting home comfort needs?

CADMUS

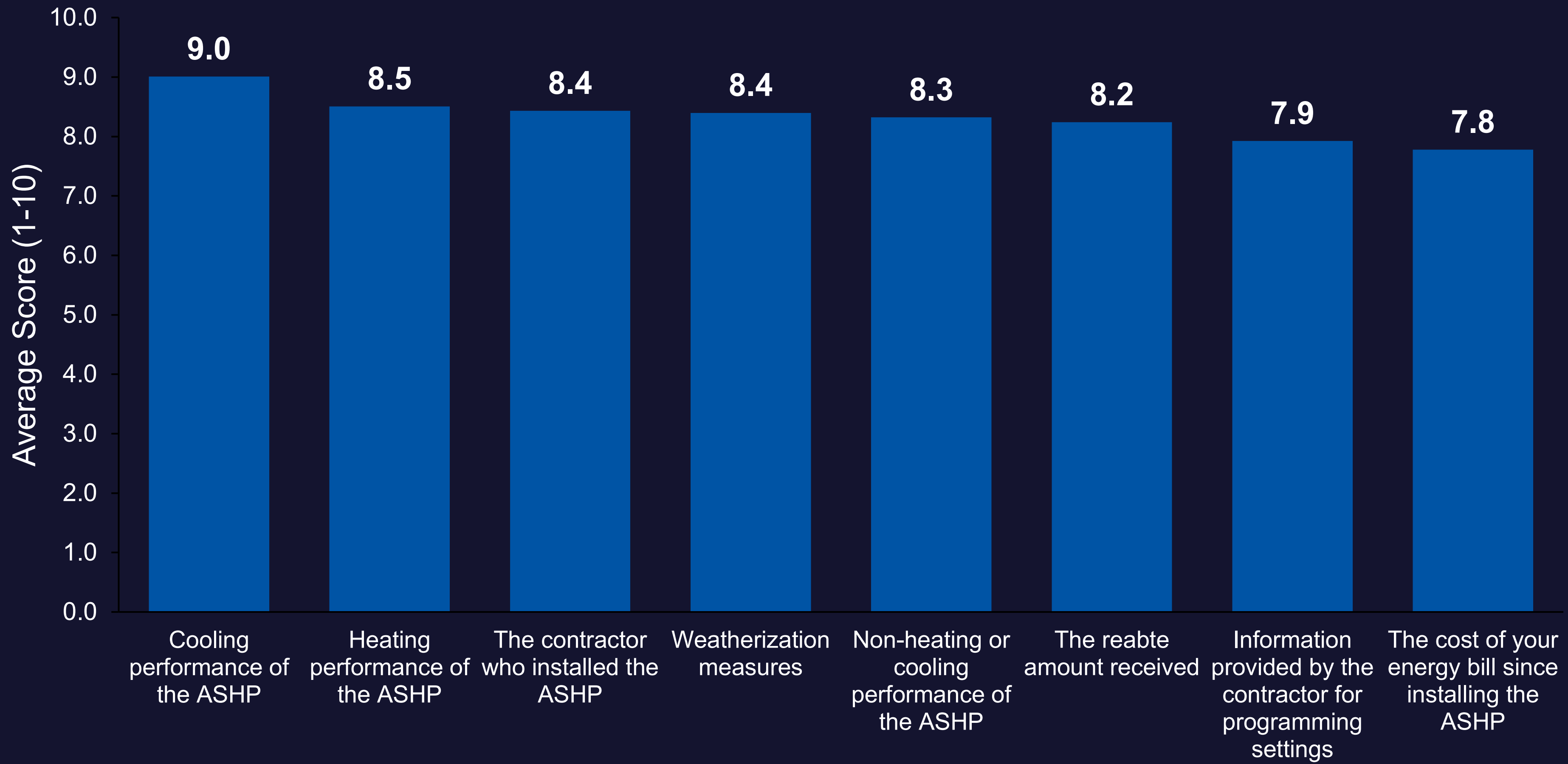
Customer Survey Key Findings

- Customers primarily installed ASHPs to **increase home comfort** and **save money on energy bills**. Customers with a whole-home configuration are especially likely to be motivated by energy savings.
- **Word-of-mouth** was the most common way that customers learned about ASHPs and found their contractor.

- **Weatherization upgrades** were usually completed at the same time as **ASHP installations**. This was especially true among those that had an energy audit completed, typically through the Mass Save program.
- Contractors were a key knowledge conduit, as **contractors are how most customers learned how to use their ASHP**.

- Performance issues were uncommon with ASHPs and nearly all customers reported lower bills.
- Customers were **highly satisfied with heating and cooling performance** (8.5/10 for heating and 9.0/10 for cooling).
- These factors lead to an **extremely high likelihood to recommend an ASHP** to others (whole-home = 8.9/10 would recommend; primary w/ backup = 9.3/10)

Customer Satisfaction



In general customers reported an **extremely high likelihood to recommend an ASHP** to others, with slightly lower likelihood for customers with whole-home systems (whole-home = 8.9/10 would recommend; primary w/ backup = 9.3/10).

Participant Interview Key Findings

Of the 43 sampled metering sites, 42 participated in follow up phone interviews. Respondents were happy with comfort, cost, and removing fossil fuels during the heating season and even more satisfied with cooling performance. **32 of the 42 reported being 'very satisfied'** with their heat pump in the past year, 3 'satisfied,' and 7 'somewhat satisfied.'

Very Satisfied

- Improved comfort and temperature maintenance (n=10)
- Working well and did what we wanted it to (n=9)
- Costs less to run (n=9)
- No fossil fuels, reducing carbon footprint (n=7)
- Extremely efficient (n=4)
- Better than old system (n=4)
- Easy to use (n=3)
- Changes temperature quickly (n=2)
- Quiet and clean (n=2)
- Dehumidify function (n=2)
- 'Free' electricity from solar PV (n=2)
- Don't have to haul as much firewood (n=1)

Satisfied and Somewhat Satisfied

- Distribution of heat to specific rooms is not always consistent (n=3)
- Requires more attention than previous system (n=2)
- System is oversized, so some rooms get too hot and cool too fast, need separate dehumidifiers (n=1)
- Repeated breakdown of one outdoor unit (n=1)
- Outdoor unit is too loud (n=1)
- Settings get screwed up and fan is consistently on (n=1)
- Doesn't stay warm as long and doesn't heat enough when its cold outside (n=1)

Blower Door Test Results

According to the National Association for State Community Services Programs,[1] homes with ACH50 values <5 are considered tight, moderate is between 5 and 10 ACH50, and leaky is >10 ACH50 (where ACH50 is the measured CFM at 50 Pa normalized for conditioned building volume).

On average, the participating homes would fall into the **'moderate'** category based on the results of the blower door tests.

However, this was a small sample of homes, and many variables factor into home leakiness, including the type and quality of existing and new insulation, home age, and test conditions.

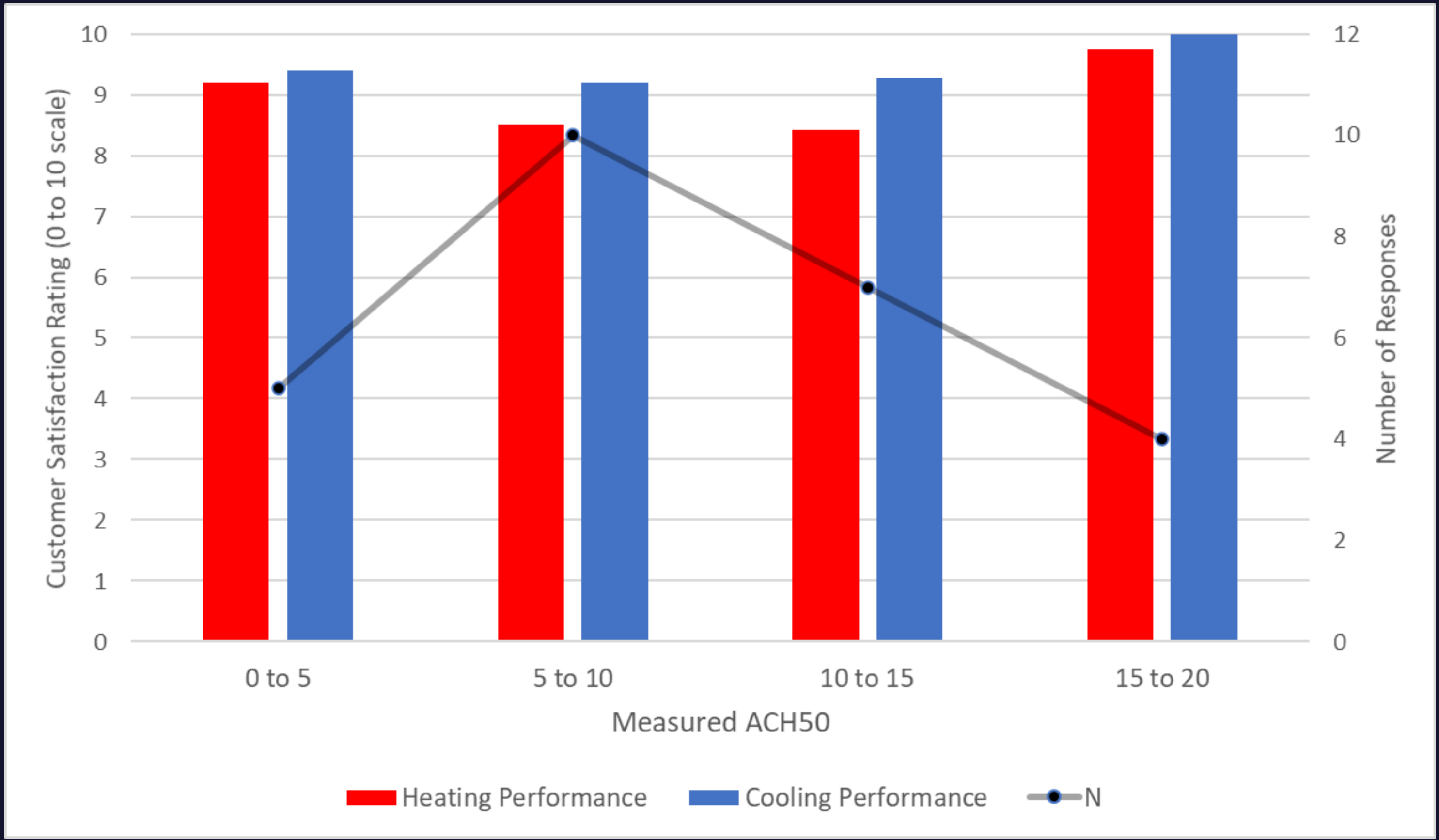
Home Weatherization Upgrade	Number of Homes[2]	Measured Airflow, CFM		Equivalent Leakage Area, ELA	Approximate ACH50
		50 Pa	25 Pa		
No change/existing	8	2,889	1,848	160.6	9.5
Pre-ASHP Installation	18	2,521	1,775	140.1	9.1
During ASHP Installation	4	2,567	1,429	142.8	10.1
Post-ASHP Installation	4	1,928	1,138	107.0	8.5
Overall	**34**	**2,543**	**1,676**	**141.4**	**9.2**

[1] National Association for State Community Services Programs. Blower Door Testing. Accessed February 2022. https://nascsp.org/wp-content/uploads/2018/02/van-der-meer_blower-door-testing.pdf

[2] Cadmus conducted blower door tests or collected contractor blower door test reports for 34 of the 43 sites.

Comparison of Home Leakiness and Comfort Satisfaction

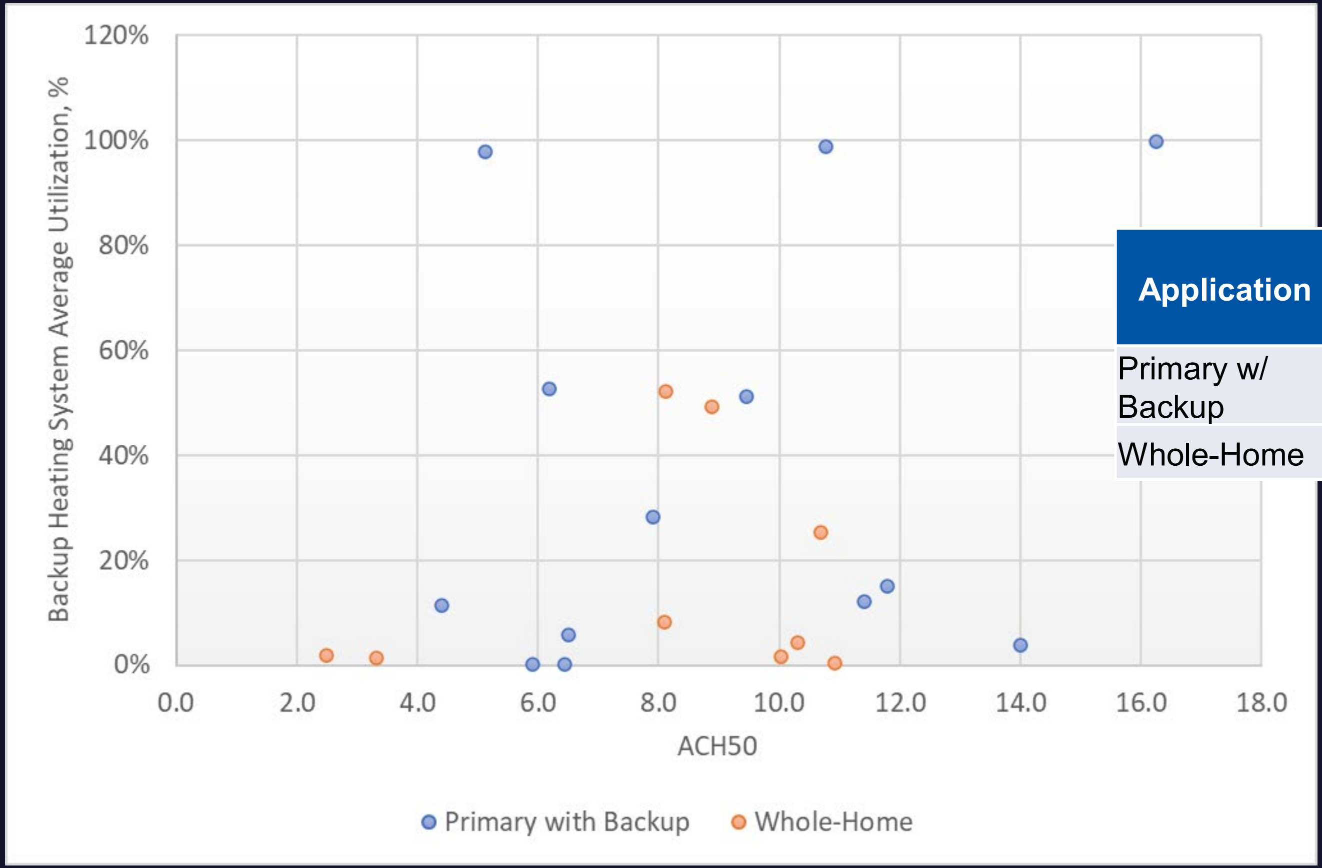
Cadmus compared participating customer survey responses with measured home insulation levels from onsite blower door tests in ACH50. On average, participants reported **very high satisfaction levels with heating and cooling performance, regardless of measured leakiness.** The lowest individual satisfaction score was a ‘5’ from a home with a 12.5 ACH50.



CADMUS

Comparison of Backup Fuel System Usage and Leakiness[1]

We compared leakiness to backup fuel system utilization for 22 homes where both data points were available. The results of this limited sample show that primary with backup homes had **much higher backup fuel utilization** and slightly **higher leakiness (10% higher)** than whole-home sites.



Application	Number of Sites	Average Backup Utilization[1]	ACH50
Primary w/ Backup	13	37%	8.9
Whole-Home	9	16%	8.1

[1] Where there were multiple backup fuel systems at one site, this plot reflects the system with the highest utilization.

Objective 2: Are ccASHP systems efficiently delivering heating and cooling?

CADMUS

Heat Pump Energy Use Intensity

Whole-home heating applications were **23% more** energy intensive than primary with backup applications. On average, the ASHP heating energy use intensity (EUI) is **almost 10 times higher** than the ASHP cooling EUI.

Application	Conditioned Area, sq. ft	Number of Homes	Heating		Cooling	
			Total Avg. ASHP System Energy Use, kWh	EUI, kWh/sq. ft.	Total Avg. ASHP System Energy Use, kWh	EUI, kWh/sq. ft.
Primary w/ Backup	500 to 1,000	1	4,018	4.46	765	0.38
	1,000 to 1,500	3	3,889	3.14	348	0.23
	1,500 to 2,000	6	3,154	1.64	326	0.17
	2,000 to 2,500	5	4,589	1.89	434	0.25
	2,500 to 3,000	3	7,143	2.51	206	0.14
	3,000 to 3,500	1	7,268	2.27	125	0.06
	3,500 to 4,000	1	6,244	1.73	2,330	0.78
Primary w/ Backup	**-**	**20**	**4,625**	**2.24**	**450**	**0.23**
Whole-Home	500 to 1,000	1	3,603	3.60	340	0.26
	1,000 to 1,500	8	3,882	2.73	563	0.29
	1,500 to 2,000	8	4,336	2.41	462	0.24
	2,000 to 2,500	4	8,433	3.60	665	0.38
	2,500 to 3,000	1	11,802	3.93	1,704	1.22
	3,000 to 3,500	1	454	0.15	101	0.04
Whole-Home	**-**	**23**	**5,015**	**2.75**	**565**	**0.31**
Overall	**-**	**43**	**4,833**	**2.51**	**512**	**0.27**

CADMUS

Heating Season Utilization per Outdoor Unit

ASHP systems used as the sole-source of heating were in-use 68% of metered hours during the heating season. Primary with backup systems were used 48% of the time. **Whole-home systems operated 42% more often than primary with backup systems**, on average.

Application	System Type	Number of Outdoor Units	Average Utilization
Primary with Backup	Single-zone, Ductless, Wall	8	36%
	Single-zone, Ducted, "Compact Ducted"	1	6%
	Single-zone, Ducted, Centrally Ducted	9	39%
	Multi-zone, Ductless	18	60%
	Overall	**35**	**48%**
Whole-Home	Single-zone, Ductless, Wall	11	73%
	Single-zone, Ductless, Floor	1	80%
	Single-zone, Ductless, Ceiling	1	61%
	Single-zone Ducted, Centrally Ducted	6	43%
	Multi-zone, Ductless	16	74%
	Multi-zone, Ducted	1	49%
	Multi-zone, Mix of Ductless and Ducted	1	98%
	Overall	**38**	**68%**
Overall		**73**	**58%**

Cooling Season Utilization per Outdoor Unit

Average cooling season utilization per outdoor unit was **56% less** than heating season utilization. Again, systems installed in whole-home applications were used **more than primary with backup systems (13% more)**, but overall average utilization was only 26%.

This result indicates that these participants may be using their ASHP systems primarily for heating, rather than cooling.

Application	System Type	Number of Outdoor Units	Average Utilization
Primary with Backup	Single-zone, Ductless, Wall	8	18%
	Single-zone, Ducted, "Compact Ducted"	1	0.1%
	Single-zone, Ducted, Centrally Ducted	8	29%
	Multi-zone, Ductless	18	26%
	Overall	**35**	**24%**
Whole-Home	Single-zone, Ductless, Wall	11	20%
	Single-zone, Ductless, Floor	1	3%
	Single-zone, Ductless, Ceiling	1	42%
	Single-zone Ducted, Centrally Ducted	6	26%
	Multi-zone, Ductless	16	33%
	Multi-zone, Ducted	1	55%
	Multi-zone, Mix of Ductless and Ducted	1	9%
	Overall	**37**	**27%**
Total		**72**	**26%**

Comparison of Heating Performance by System Type and Indoor Heads

Ductless multi-zone systems with more than three indoor heads (some with branch-box control) had the lowest average seasonal heating performance during the metering period. Anecdotal feedback from the advisory committee and Cadmus' experience indicate that the more zones a multi-zone system serves, the higher the likelihood that some zones may be oversized, causing a greater differential between actual load and capacity.

In contrast, ductless single-zone systems had the highest measured performance.

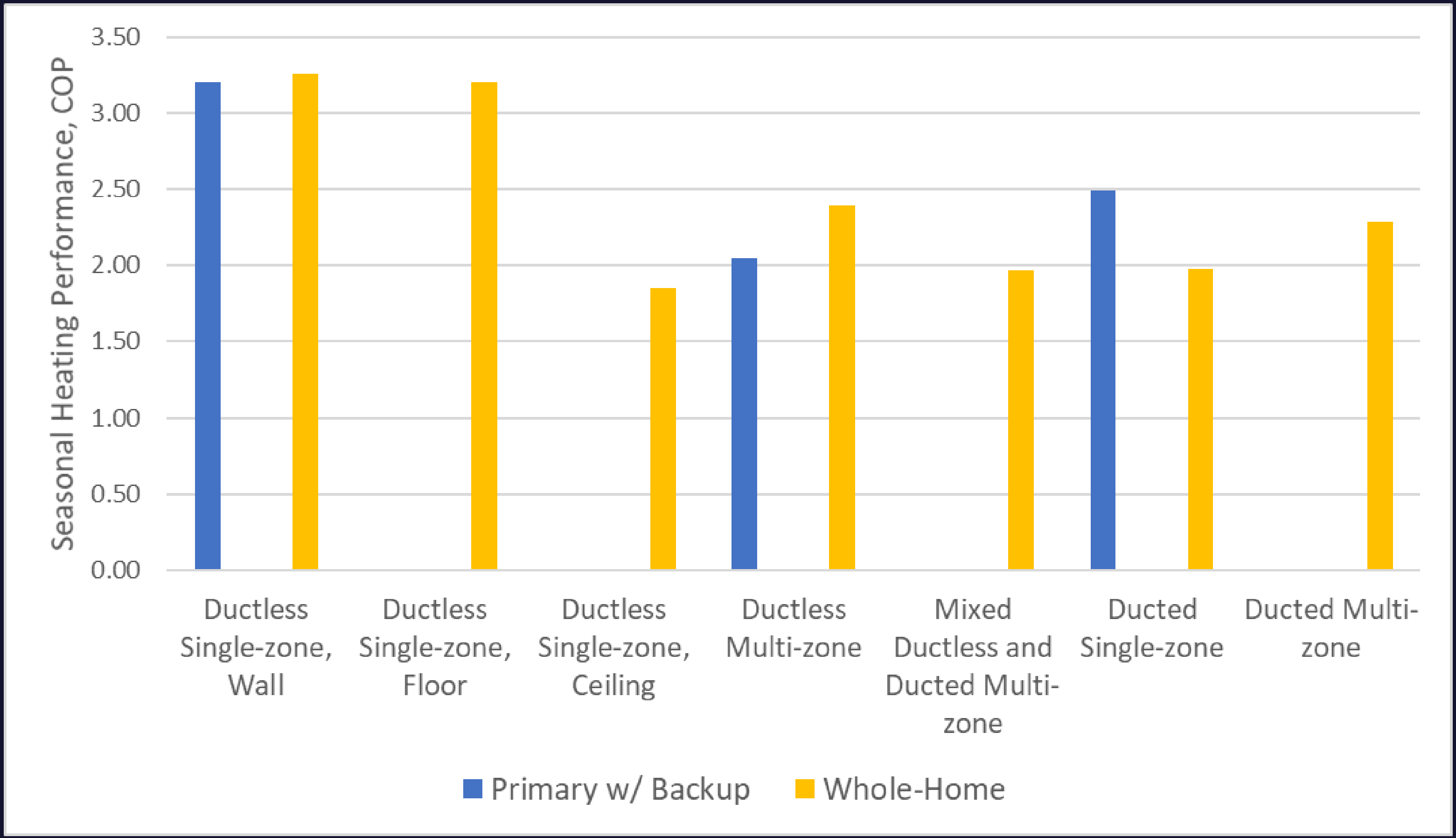
System Type	Description	Number of Indoor Heads	Number of Outdoor Units	Average Utilization, %	Average Seasonal Heating Performance, sCOP
Ductless	Single-zone, Wall	1	19	57%	3.23
	Single-zone, Ceiling	1	1	61%	1.85
	Single-zone, Floor	1	1	80%	3.20
	Multi-zone	2	15	66%	2.24
	Multi-zone	3	13	72%	2.57
	Multi-zone	4	3	45%	**1.12**
	Multi-zone	5	3	70%	**1.52**
Mixed	Multi-zone Mix of Non-ducted and Ducted	3	1	98%	1.97
Ducted[1]	Single-zone, Central	1	15	41%	2.25
	Single-zone, Compact	1	1	6%	N/A
	Multi-zone	2	1	49%	2.29
Individual Outdoor Unit			**73**	**58%**	**2.50**
Overall Site-Level			**43**	**-**	**2.34**

CADMUS

Comparison of Measured Seasonal Heating Performance by System Type

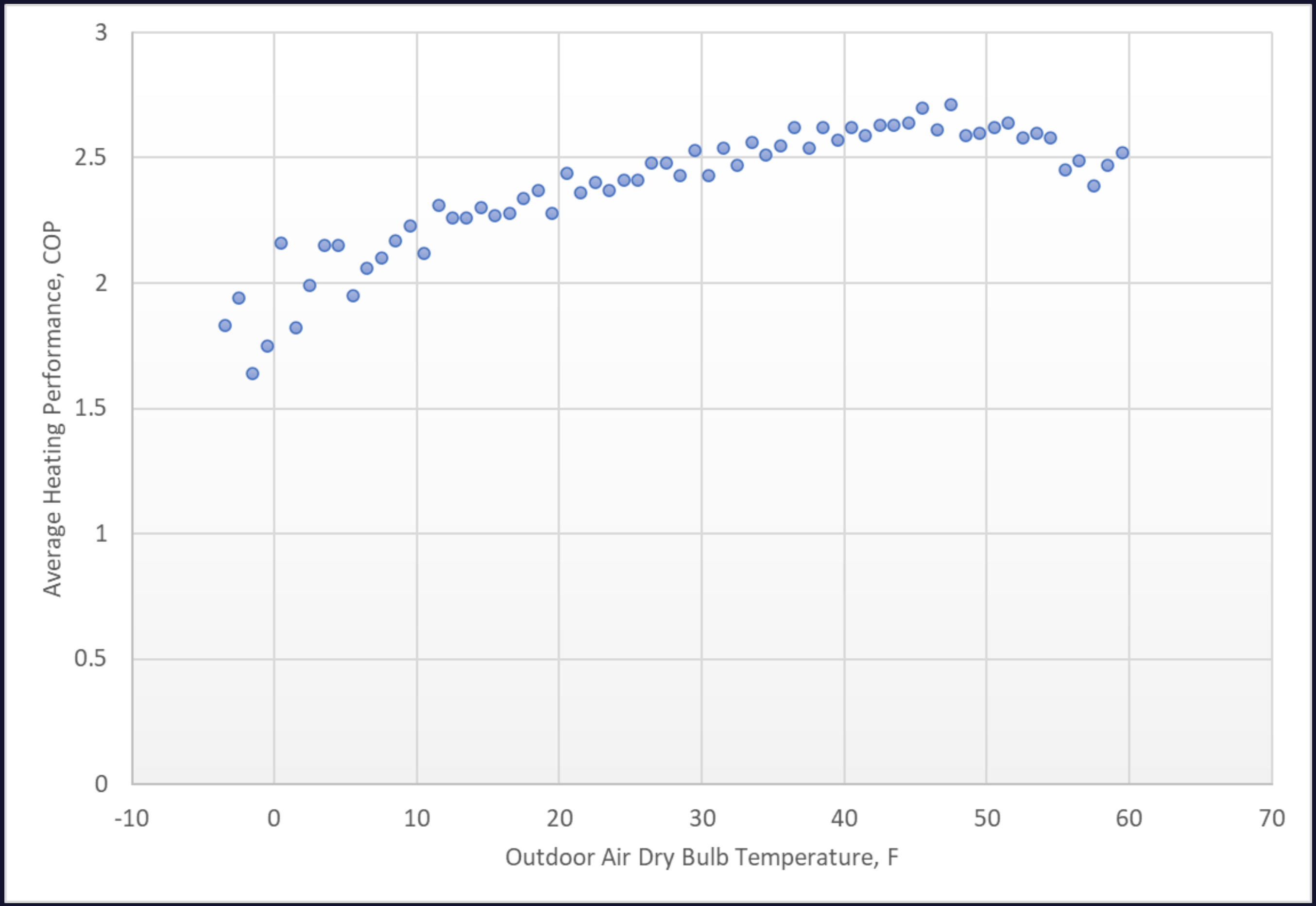
Ductless, single-zone, wall and floor-mounted systems had the highest metered average seasonal heating performance in both applications.

Ducted systems in primary with backup applications performed better than in whole-home applications, likely due in part to being utilized for heating less often during the coldest times of the year.



Average Heating Performance[1] by Outdoor Air Temperature Bin

As expected, the overall average heating performance for the sampled homes peaked between 40-50°F, with a pronounced drop at 10°F.



[1] Heat pump performance shown does not include intervals when electric resistance was used. The actual performance for the five ducted systems with ER is expected to be lower.

CADMUS

Measured Heating Load Comparisons

- Cadmus calculated space heating load using metered indoor unit supply and return temperatures and fan airflow.
- We calculated the average measured heating load during cold outdoor air conditions between 0-15°F and during a seven-hour ‘cold snap’ for each state.
- The ‘cold snap’ was defined as 12 AM to 7 AM on January 31st for MA sites and February 12th for NY sites. The average cold snap temperature for MA sites was 4.3°F and the average cold snap temperature for NY sites was 8.3°F.
- The next two slides compare the calculated space heating load during these two conditions to the installed system maximum capacity based on NEEP test procedures at 5°F, contractor design load, and Cadmus’ Manual J heating load.
- When reviewing this data, please note the following:
  - The average design temperature for the 24 Massachusetts sites is 5.2°F and 1.8°F for New York sites.
  - 2020/2021 was a mild winter and the ‘cold snap’ load may be underestimating peak load. While the average temperature for MA sites was close to design conditions, there was no prolonged period at design conditions during this winter.
  - The ‘cold snap’ load calculation includes intervals when the system was not delivering heat (0 Btu/hr). The instantaneous peak load is expected to be higher.

Comparison of Contractor Heating Load to Measured Heating Load[1]

Compared to the average measured heating load during cold outdoor air temperatures (0 to 15F) and extreme cold snaps, **contractors do not appear to be under-sizing systems.** Cadmus' Manual J heating load, which incorporates blower door test results, may be overstating the actual load. Oversized systems will result in higher upfront costs and potential performance issues.

However, the average heating load for whole-home systems was **43%** of the contractor's design load during the extreme cold snap (noting that the average incorporates intervals of zero load).

Application	Conditioned Area, sq. ft	Sites	Average NEEP Total System Capacity (5°F), Btu/hr	Contractor Design Heating Load, Btu/hr	Cadmus Manual J Heating Load, Btu/hr	Cadmus / Contractor Heating Load, %	0-15F Average Measured Heating Load, Btu/hr	Cold Snap[2] Average Measured Heating Load, Btu/hr	Cold Snap / Contractor Design Load, %
Primary w/ Backup	1,500 to 2,000	1	30,100	59,886	54,230	91%	11,207	7,640	14%
Primary w/ Backup	2,000 to 2,500	2	54,834	58,392	52,641	93%	21,623	11,721	22%
Primary w/ Backup	3,000 to 3,500	2	60,535	72,008	89,451	126%	33,416	32,232	35%
Primary w/ Backup		**5**	**52,167**	**64,137**	**67,683**	**106%**	**24,257**	**19,109**	**26%**
Whole-Home	1,000 to 1,500	2	43,000	38,344	38,575	99%	14,796	14,455	41%
Whole-Home	1,500 to 2,000	4	47,900	40,460	49,012	123%	25,106	23,417	51%
Whole-Home	2,000 to 2,500	3	45,533	42,714	51,275	118%	17,027	19,907	40%
Whole-Home	2,500 to 3,000	2	67,920	57,1623	80,785	141%	24,042	22,967	28%
Whole-Home	3,000 to 3,500	2	43,650	41,624	63,659	155%	36,628	36,266	62%
Whole-Home		**13**	**49,026**	**43,403**	**55,070**	**126%**	**21,882**	**21,917**	**43%**
Overall		**18**	**49,899**	**49,163**	**58,574**	**120%**	**22,624**	**21,039**	**38%**

[1] For the 18 project sites where contractor Manual Js were provided

[2] Cold snap defined as 12 AM to 7 AM on January 31st (MA sites) and February 12th (NY sites). The average cold snap temperature for MA sites was 4.3°F and the average cold snap temperature for NY sites was 8.3°F.

Comparison of NEEP Heating Capacity to Measured Heating Load per Outdoor Unit

On average, metered data indicates that most systems operate **well below** their NEEP rated maximum capacity (at 5°F) during extreme cold periods, but systems in whole-home applications operated at 38% higher load than systems in primary with backup applications.

In whole-home applications, **systems <30,000 Btu/hr appear to operate closer to design capacity**, suggesting they may be more appropriately sized for the zone they serve.

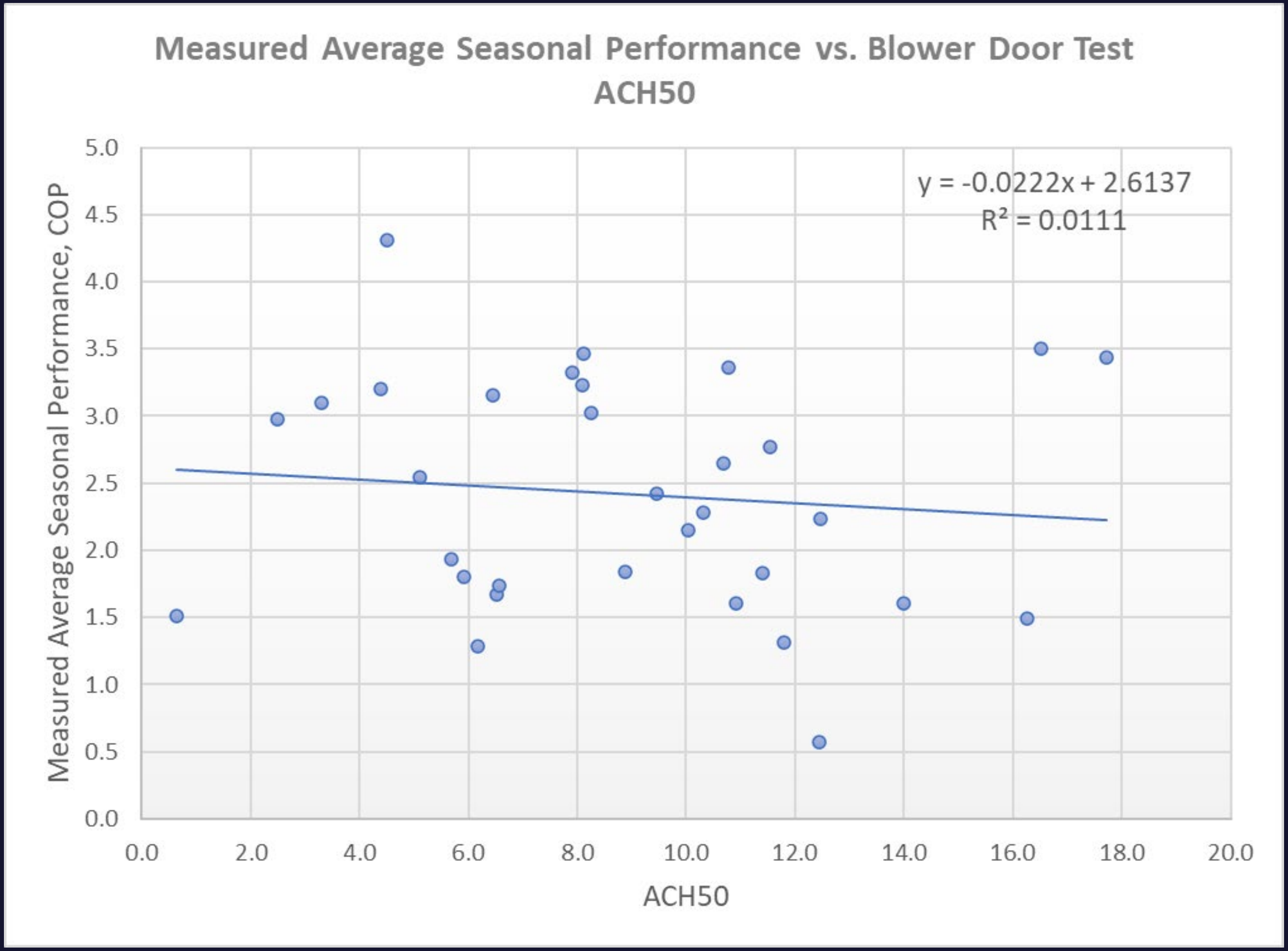
System Type	NEEP ccASHP Capacity Range (5°F), Btu/hr		Number of Outdoor Units	Population Average NEEP Capacity, Btu/hr	0-15°F Average Heating Load, Btu/hr	Cold Snap[1] Average Measured Heating Load, Btu/hr	Cold Snap Average Measured Heating Load / NEEP Capacity
	Min	Max					
Primary w/ Backup	10,000	20,000	6	15,610	5,748	1,929	12%
	20,000	30,000	17	24,696	13,262	10,575	43%
	30,000	40,000	9	35,092	11,766	6,279	18%
	40,000	50,000	4	44,568	13,683	12,575	28%
	Overall		**35**	**27,929**	**11,812**	**8,466**	**30%**
Whole-Home	0	10,000	2	8,700	2,011	0	0%[2]
	10,000	20,000	11	14,118	10,709	11,427	81%
	20,000	30,000	13	25,554	15,886	15,634	61%
	30,000	40,000	3	38,652	16,436	10,388	28%
	30,000	50,000	6	46,333	23,258	21,515	46%
	50,000	60,000	2	55,420	22,148	20,700	37%
	Overall		**38**	**27,363**	**14,834**	**13,955**	**51%**
Overall			**73**	**27,634**	**13,300**	**11,168**	**40%**

[1] Cold snap defined as 12 AM to 7 AM on January 31st (MA sites) and February 12th (NY sites). The average cold snap temperature for MA sites was 4.3°F and the average cold snap temperature for NY sites was 8.3°F.
[2] Systems were not used during the cold snap period.

ASHP System Performance vs ACH50

Measured ccASHP system seasonal heating performance is not closely tied to the measured leakiness of a home.

Home leakiness directly impacts space conditioning load, but many other factors influence performance. However, weatherization measures to reduce leakiness will help improve comfort and potentially provide fuel cost savings.



CADMUS

Building Weatherization Timing

Comparison of ASHP System Heating Load, Demand, and Performance

While there was no correlation between leakiness and seasonal heating performance, in this sample we observed **higher average seasonal heating performance in homes that completed insulation upgrades** than those without any insulation upgrades, though many of these homes still had relatively high air leakage rates after completing weatherization work. However, we cannot draw conclusions from this small sample.

Weatherization Upgrade Timing	Number of Homes	Cold Snap Heating Load per Conditioned Area, Btu/hr/sq. ft.	Average Operating Demand per Conditioned Area, kW/1,000 sq. ft.	Average Utility Peak Demand per Conditioned Area, kW/1,000 sq. ft.[1]	Average Seasonal Heating Performance, COP
No change to existing insulation	12	9.44	1.10	0.76	2.09
Before ASHP system installation	20	9.75	1.02	1.01	2.43
During ASHP system installation	6	7.40	0.82	0.89	2.42
After ASHP system installation	5	7.11	1.13	0.61	2.57
Overall	**43**	**8.90**	**0.98**	**0.88**	**2.34**

Cost Effectiveness Comparison

Average installation costs were **22% higher in whole-home sites** than primary with backup relative to square footage. Energy cost savings were higher for whole-home sites, though this was driven in part by differences in energy costs between states and more New York whole-home sites.

We estimated an **energy cost penalty for natural gas customers** in this sample, which is unsurprising due to the high cost of electricity and relatively low cost of natural gas in the Northeast. This result supports targeting delivered fuel and electric resistance heating customers for ccASHP systems first where economics are a priority.

Application	Fuel Type	N	Sq. Ft.	Avg. Installation Cost[1]	Avg. Installed Cost per Sq. Ft.	Annual Cost Savings[1]	Annual Cost Savings per Sq. Ft.
Primary w/ Backup	**All**	**20**	**2,167**	**$17,695**	**$8.50**	**$280**	**$0.20**
	Non-Gas	15	2,156	$17,031	$7.90	$461	$0.32
	Gas	5	2,200	$19,686	$8.95	-$262	-$0.15
Whole-Home[1]	**All**	**20**	**1,891**	**$18,755**	**$10.31**	**$264**	**$0.17**
	Non-Gas	10[1]	1,815	$20,207	$11.13	$682	$0.42
	Gas	10	1,968	$17,142	$9.18	-$153	-$0.09
Total		**40**	**2,029**	**$18,211**	**$9.38**	**$272**	**$0.18**

[1] Missing installation cost data for one whole-home site and energy savings were not able to be estimated for three whole-home sites.

Utility Bill Impacts

Most respondents' combined utility bills (electric, gas, propane, oil, etc.) were lower since installing an ASHP.

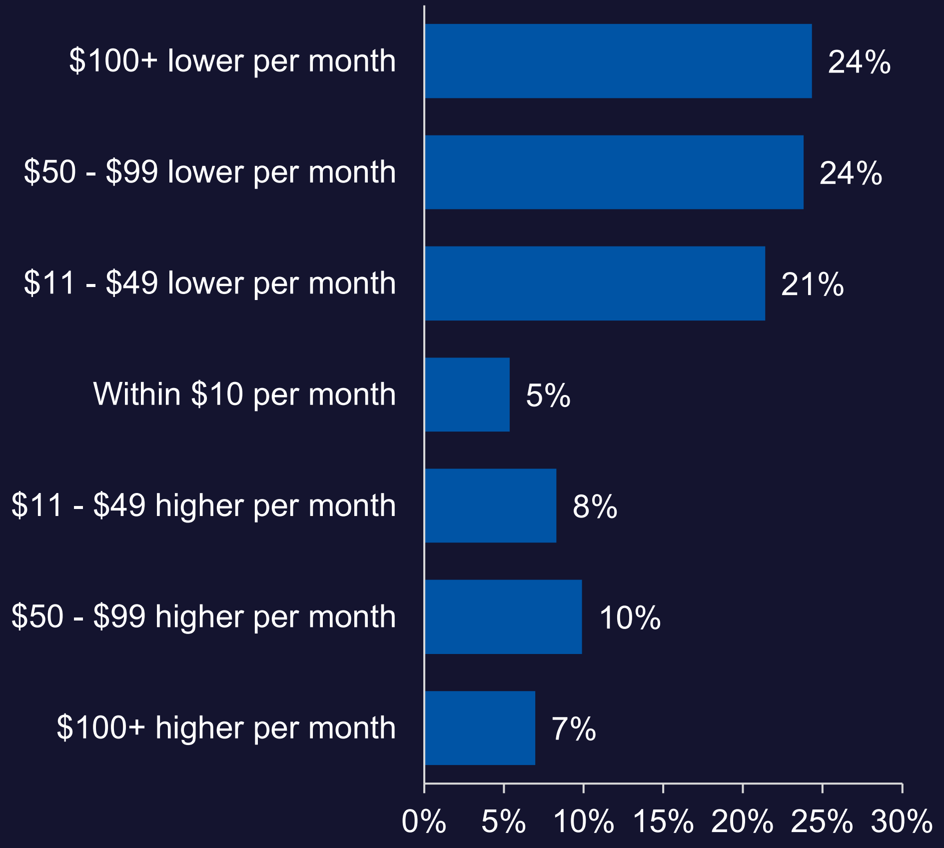
90% of respondents reported a change in their overall energy bills since installing an ASHP.

76% said the change was the same as what they expected.

Respondents who installed weatherization measures were significantly more likely to see a decrease of $100 or more per month (**26%**) compared to respondents who did not install weatherization (**19%**).

Respondents who had electric heating prior to installing their ASHP were more likely to see a decrease of at least $50 (**67%**) compared to gas (**32%**) and delivered fuel (**51%**) respondents.

Change in Overall Utility Bills since ASHP Installation



CADMUS

Objective 3: How does performance differ between whole-home and primary with backup applications?

CADMUS

Heating Season Metered Data Results

While on average, there was **no significant difference** in seasonal heating performance between whole-home and primary w/ backup applications, ductless systems tended to perform better in whole-home applications while ducted systems performed better in primary w/ backup applications.

Application	System Type	Homes	Avg. Utilization	Avg. ccASHP System Heating Season Demand, kW/1,000 sq. ft.	Avg. ccASHP System Utility Winter Peak[1] Demand, kW/1,000 sq. ft.	Measured Average Seasonal Heating Performance, sCOP	AHRI Rated sCOP (from HSPF)	Measured sCOP/ Rated sCOP
Primary w/ Backup	Ductless	14	50%	0.60	0.77	2.23	3.23	69%
	Ducted	5	38%	0.38	0.64	2.46	3.06	63%
	Mixed	1	48%	0.42	0.29	2.55	3.02	84%
	Total	**20**	**48%**	**0.54**	**0.71**	**2.30**	**3.18**	**68%**
Whole-Home	Ductless	13	75%	0.89	1.12	2.80	3.28	84%
	Ducted	6	43%	0.54	0.70	2.03	3.16	57%
	Mixed	4	69%	0.99	1.15	1.87	3.33	56%
	Total	**23**	**68%**	**0.82**	**1.03**	**2.38**	**3.26**	**71%**
Total		**43**	**58%**	**0.69**	**0.88**	**2.34**	**3.22**	**70%**

[1] Utility Winter Peak defined as 5:00 PM to 7:00 PM daily, December, January, and February.

Heating Season Metered Data Results

Study Results

- ccASHP systems used in whole-home applications were **40-50% more demand intensive** per conditioned area than in primary with backup applications.
- Overall average ccASHP system seasonal heating **performance of 2.34 sCOP was in line with results from other studies**, with slightly higher metered performance for whole-home systems.
- Ducted system utilization includes heat pump and backup ER usage, but the performance calculation reflects the heat pump power only (excludes ER). The actual performance of the five ducted systems with ER is expected to be lower.
- We used the AHRI-rated heating seasonal performance factor (HSPF) as a rough comparison metric for metered seasonal heating performance.
- For New York sites, we calculated the expected seasonal heating performance using the methodology in the New York State TRM V8.1 On average, those sites would have been expected to have an sCOP of 2.84, so the metered **seasonal heating performance was ~17% lower than expected under the TRM**.

Tentative Conclusions

- In-field ccASHP seasonal heating performance is only slightly lower than expected when AHRI ratings are normalized for the Northeast climate
- Ductless whole-home systems may perform better than ductless primary with backup systems despite operating at higher/colder hours due to various factors:
  - Continuous operation vs. more cycling during hours well below peak heating needs
  - More representative system sizing for actual space heating needs
- Ducted systems may perform less efficiently in whole-home configurations, possibly due to operating at lower outdoor air temperatures or being sized for higher heating loads, resulting in greater fan energy use.

[1] New York State DPS. Technical Reference Manual (TRM). https://www3.dps.ny.gov/W/PSCWeb.nsf/All/72C23DECFF52920A85257F1100671BDD

Objective 4: What are the electric grid impacts of ccASHP market scale up?

CADMUS

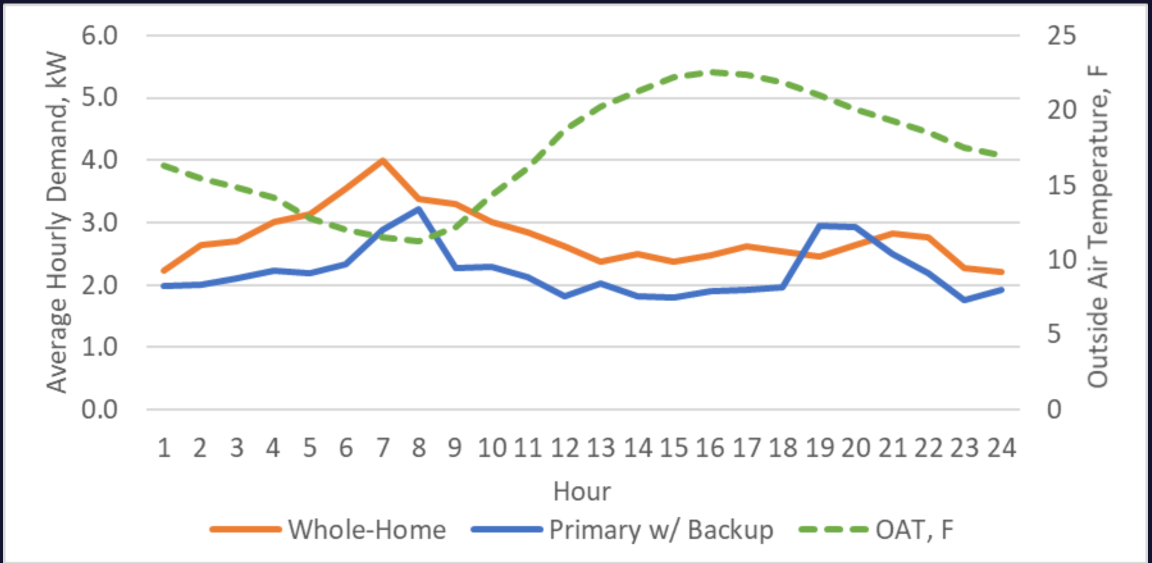
Heating Season Demand Impacts

While the average demand during the utility Winter Peak period was only 0.88 kW/1,000 square feet, the average hourly maximum demand was as high as 3.48 kW/1,000 square feet for mixed sites (both ducted and ductless systems) and instantaneous site-level demand for one mixed site was 9.12 kW/1,000 square feet.

System Type	Number of Homes	Average Conditioned Area, sq. ft.	Total System Electric Energy Use, kWh/ 1,000 sq. ft	Average ASHP Operating Demand, kW/1,000 sq. ft.	Average Maximum Hourly Demand, kW/1,000 sq. ft.	Average Utility Winter Peak Demand,[1] kW/1,000 sq. ft.	Site-Level Maximum 2-Minute Interval Demand, kW/1,000 sq. ft.
Ductless	27	1,878	2,728	0.91	2.11	0.90	5.47
Ducted	11	2,281	1,453	1.10	3.04	0.64	8.47
Mixed	5	1,907	3,468	1.05	3.48	1.04	9.12
Overall	**43**	**1,984**	**2,436**	**0.98**	**2.52**	**0.88**	**-**

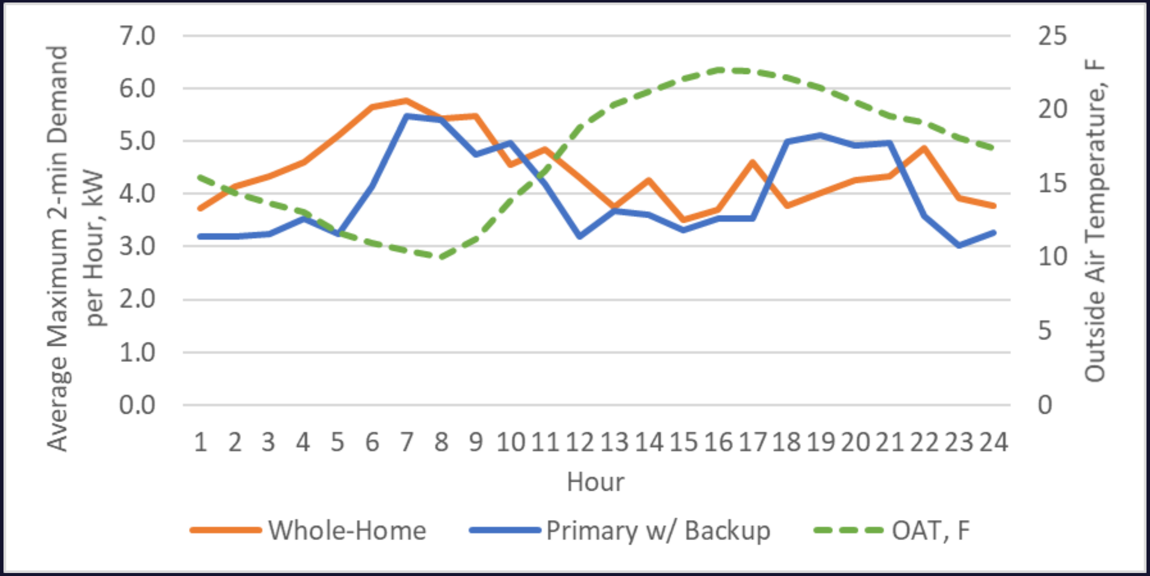
[1] Utility Winter Peak demand period defined as 5:00 PM to 7:00 PM daily during December, January, and February.

Whole-Home and Primary with Backup System Load Shape Comparison: New York Cold Snap Period[1]



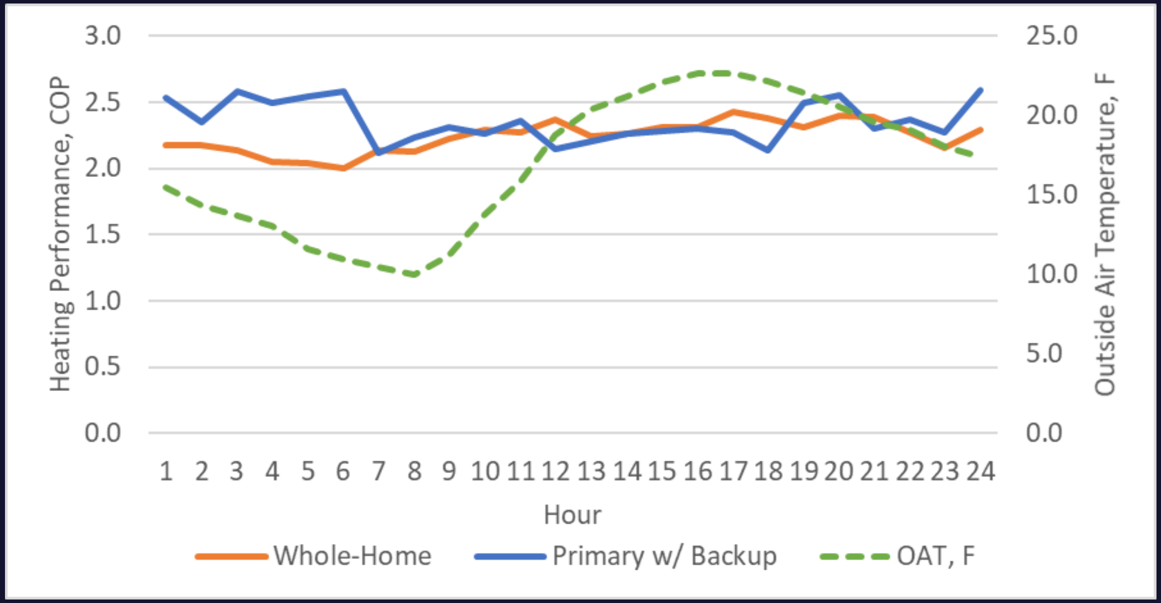
Electric grid impacts from wide-scale residential heating electrification may occur in the early morning hours when residents are waking up, implying the use of overnight space temperature setbacks.

[1] The New York three-day cold snap was defined as February 11th through February 13th (midnight to midnight). The average outdoor air dry bulb temperature across the 19 sites was 17.1°F during the three-day period.



CADMUS

Whole-Home and Primary with Backup System Load Shape Comparison: New York Cold Snap Period[1]



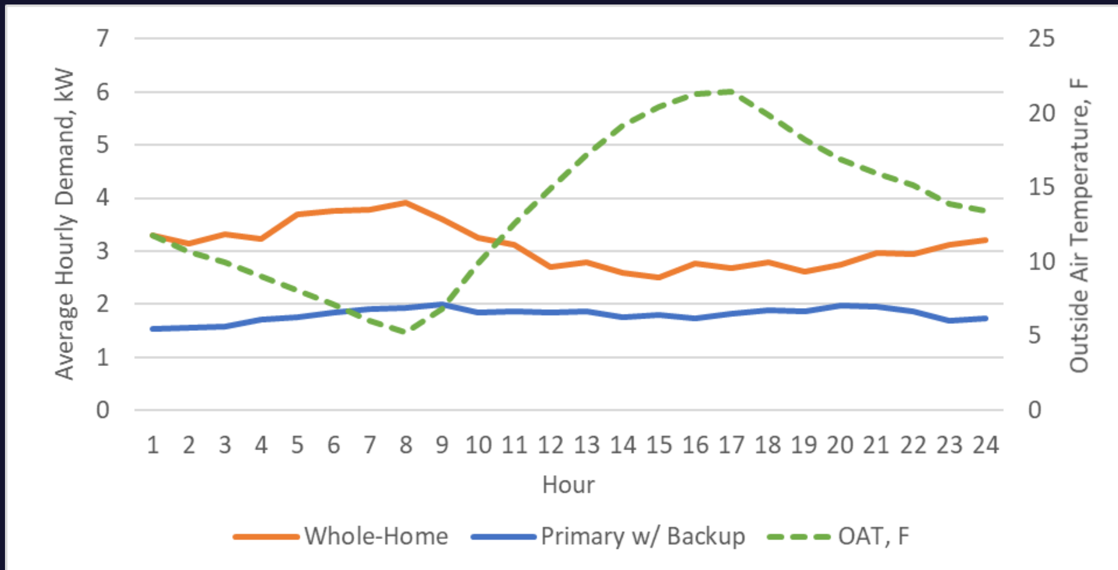
Heating performance[2] is relatively steady throughout the day.

Systems with electric resistance elements will have the greatest peak demand impact, reaching over 15 kW.

Summary Parameter	Application	
	Whole-Home	Primary w/ Backup
Number of Homes	12	7
Average Metered Demand, kW	2.77	2.21
Average Maximum Demand per Hour (2-min interval), kW	4.45	4.00
Maximum Site-Level Demand (2-min interval), kW	17.25	14.11
Average Measured ASHP Heating Load, Btu/hr	20,598	19,859
Average Heating Performance, COP	2.24	2.36
Average Outside Air Temperature, °F	17.2	16.9
Average Windspeed, mph	4.9	5.4

[1] New York cold snap defined as February 11th through 13th (midnight to midnight).
[2] Note that electric resistance demand is not included in the calculation of ducted system performance shown in this table. Actual performance for the three ducted systems in New York with ER is expected to be lower.

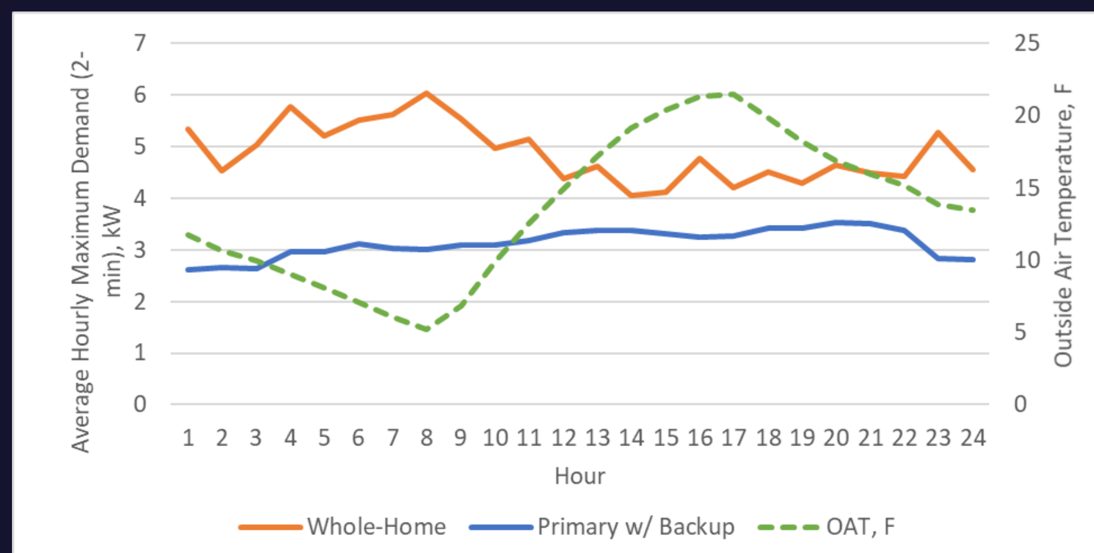
Whole-Home and Primary w/ Backup System Load Shape Comparison: Massachusetts Cold Snap Period[1]



On average, systems in whole-home applications will have a greater peak demand impact.

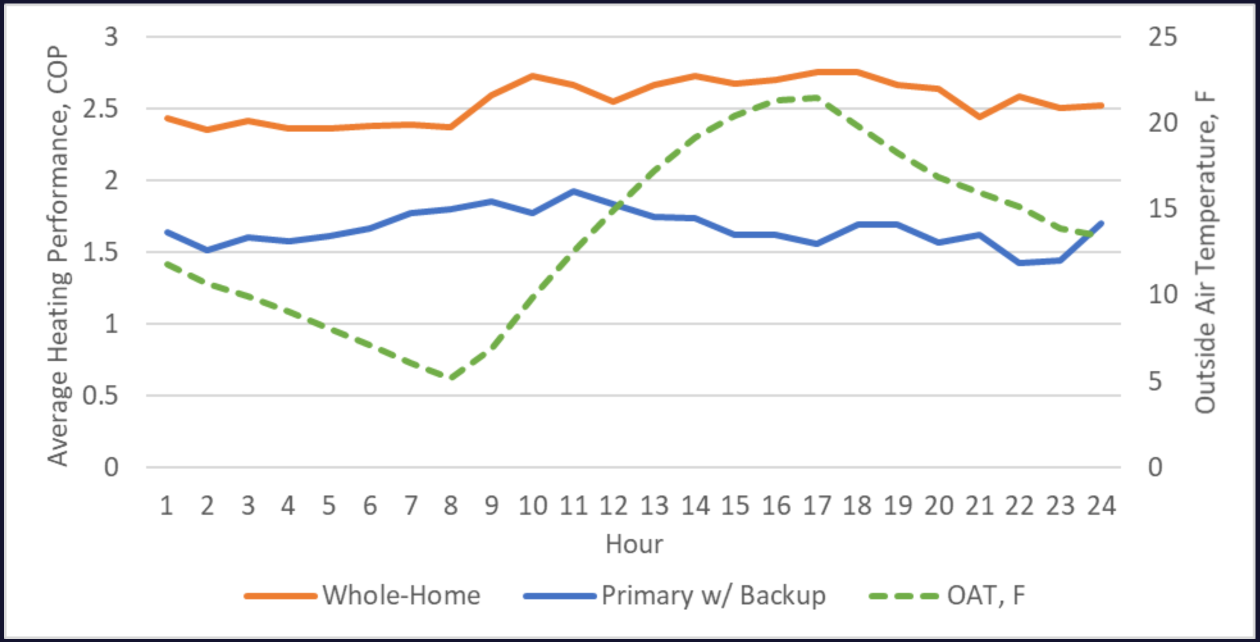
MA sites showed reduced early morning demand peak than NY sites, potentially due to Mass Save's set it-and-forget-it messaging.

[1] The Massachusetts three-day cold snap was defined as January 29th through 31st (midnight to midnight). The average outdoor air dry bulb temperature across the 24 sites was 12.9°F during the three-day period.



CADMUS

Whole-Home and Primary w/ Backup System Load Shape Comparison: Massachusetts Cold Snap Period[1]



Heating performance within applications is relatively steady throughout the day.

Summary Parameter	Application	
	Whole-Home	Primary w/ Backup
Number of Homes	9	13
Average Metered Demand, kW	3.11	1.81
Average Maximum Demand per Hour (2-min interval), kW	4.88	3.13
Maximum Site-Level Demand (2-min interval), kW	20.58	12.97
Average Measured ASHP Heating Load, Btu/hr	20,265	10,701
Average Heating Performance, COP	2.55	1.67
Average Outside Air Temperature, °F	13.6	12.5
Average Windspeed, mph	8.2	9.2

[1] Massachusetts cold snap defined as January 29th through 31st (midnight to midnight).
[2] Note that electric resistance demand is not included in the calculation of ducted system performance shown in this table. Actual performance for the two ducted systems in Massachusetts with ER is expected to be lower.

Cooling Season Demand Impacts

The metered average utility Summer Peak demand impact from ccASHPs in cooling mode of 0.21 kW/1,000 square feet was **76% less** than the average utility Winter Peak demand impact of ccASHPs in heating mode (0.88 kW/1,000 square feet).

However, the site-level, instantaneous demand impact for ductless systems was almost **20% higher** in cooling mode than heating mode.

System Type	Number of Homes	Average Conditioned Area, sq. ft.	Total System Electric Energy Use, kWh/ 1,000 sq. ft[2]	Average ASHP Operating Demand, kW/1,000 sq. ft.	Average Maximum Hourly Demand, kW/1,000 sq. ft.	Average Utility Summer Peak Demand,[1] kW/1,000 sq. ft.	Site-Level Maximum 2-Minute Interval Demand, kW/1,000 sq. ft.
Ductless	27	1,878	293	0.44	1.16	0.21	6.52
Ducted	11	2,281	217	0.56	1.27	0.23	2.43
Mixed	5	1,907	181	0.46	1.52	0.17	3.54
Overall	**43**	**1,984**	**258**	**0.49**	**1.23**	**0.21**	**-**

[1] Utility Summer Peak demand period defined as 1:00 PM to 5:00 PM daily during June, July, and August.
[2] For reference, the Massachusetts 2020 Technical Reference Manual estimates the average residential home cooling energy consumption for a central air conditioning system with 16.5 SEER to be 823 kWh/year.

Objective 5: What continued challenges with customer and contractor experience need to be addressed to scale the market?

CADMUS

Stakeholder Interview Feedback

Residential Electrification

Challenges	Benefits
Economic Concerns customers may have net higher energy bills due to lower fuel costs	**Improved Customer Comfort** appropriately sized systems: temperature control, reduced noise, improved internal air emissions
Technology Awareness and Reliability lack of trust in system reliability and general lack of awareness of technology for both customers and contractors	**Customer Relationship Building** strengthen electric utility relationship with customers
Costly Grid Upgrades electric utilities may need to invest in infrastructure upgrades to meet new winter peak demand	**Reduce Electricity Costs** defray cost of utility distribution by selling more energy for same distribution
Existing Building Stock aging northeast building stock presents challenges to whole-home ASHP systems	**Reduce Distributed Energy Generation Impacts** use energy generated at local nodes, i.e., solar energy coming back on the grid
Conflicting Priorities gas utilities may lose customers resulting in stranded assets	**Reduce Demand for Additional Gas Pipelines** particular concern in downstate New York

Stakeholder Interview Recommendations

- Encourage weatherization measures
- Provide more opportunities for New Construction whole home systems
- Increase incentives and consider upstream incentives
- Develop electric heating rates to encourage off-peak energy use
- Train contractors to properly size systems
- Educate customers on benefits of ccASHPs for heating
- Push-back on policies on integrated controls and backup systems
  - Recommending integrated controls encourages customer to retain backup fuel systems
  - Integrated controls are costly and difficult to install, even more difficult to operate correctly
  - But retaining existing system may be simplest way to get customers to invest in systems

Customer Concerns

Whole-home customers noted fewer concerns than other customer types prior to installation, but performance and cost were still top of mind.

	Whole-Home	Primary w/ Backup	Supplemental
System cost	60%	61%	64%
ASHP performance at low outside temps	44%	62%	43%
Understanding how ASHP works	45%	40%	38%
System maintenance	28%	38%	47%
ASHP ability to evenly cool or heat the required area	31%	34%	35%
Potential energy savings	24%	36%	24%
ASHP reliability	27%	31%	23%

Question C13: Did you have any questions/concerns about the air source heat pump prior to the installation? Please select all that apply. [MULTI-SELECT]

Contractor Interview Key Findings

- Customer **demand for ASHPs has increased** in recent years, driven by improved technology, widespread adoption, and rebates.
  - Most discussed benefits include the **higher efficiency and lower environmental impact** of ASHPs

- Contractors are overwhelmingly recommending cold-climate models; **ductless mini-splits still dominate over ducted systems.**
  - **Primary with backup systems are most popular** in both MA and NY
  - Main barriers for ducted systems are higher cost and logistical limitations based on home features
- Customers report **few performance issues** with cold-climate models, thanks in part to the education and best practices contractors provide.

- **MA contractors appreciate rebate programs** for driving installations of ASHPs, with satisfaction being highest with the Mass Save Program.
- **NY contractors expressed more room for improvement with rebate programs**, citing opportunity to improve program design and delivery.
- Contractors had positive feedback for trainings, but reported **challenges with recruiting trained, qualified staff.**

Contractor Interviews: *ASHPs Adoption Barriers*

Barrier	General Barriers	Specific to Central System	Specific to Ductless System	Specific to ASHP as Primary Heating System	Specific to Cold-Climate Models
Cost	✓	✓		✓	✓
Aesthetics	✓		✓		
Misconceptions about the technology	✓	✓		✓	
Customer desires (e.g., want cooling only)	✓				
Building logistics (e.g., lack of ducts, electrical power, and/or physical space)	✓	✓		✓	✓

Many NY contractors (6 out of 8 interviewed) reported that customers did not believe that ASHP technology would effectively heat/cool their home, compared to 3 out of 11 contractors in MA.

Conclusion

Key Takeaways

- Customers are **generally very satisfied** with ccASHP heating and cooling performance.
- Whole-home systems tend to be utilized more often than primary with backup systems.
- Whole-home systems tended to be more expensive to install than primary with backup systems.
- The overall average seasonal heating performance of **2.34 sCOP** is in line with similar studies.
- On average, seasonal heating performance was similar between primary with backup and whole-home applications, but varied significantly by home and system type, influenced by many factors.
- Winter Peak demand impacts of wide-scale ccASHP adoption will likely occur during **early morning hours**, not during traditional utility peak periods.
- Whole-home applications with electric resistance elements will have the greatest electric grid impact during extreme cold periods.
- Heating season demand impacts will be greater than cooling demand impacts.
- Contractors reported installation costs, aesthetics, customer misconceptions, and building logistics as the top cited barriers to wide-scale ccASHP deployment.
- A customer’s existing fuel type is an important factor to cost effectiveness. Natural gas customers will likely see overall utility bills increase by switching to electric ccASHP systems for heating due to the high cost of electricity relative to natural gas in the Northeast.

Conclusion

- Policymakers and utilities involved in the project seek to understand whether study results indicate a recommendation to focus on primary w/ backup vs. whole-home applications in ASHP programs and policies.
- However, the study sample size (43 homes) is insufficient to draw statistically significant conclusions, and observations relevant to our research objectives should be considered as directional.
- With regards to our research objectives comparing primary with backup and whole-home systems:
  - (1) Comfort differences reported by customers were minimal
  - (2) Observed differences in seasonal heating efficiency were minimal
  - (3) Electrical demand was higher for whole-home systems during cold periods
- Our study data does not suggest there are significant trends that would warrant policy/program decisions encouraging or discouraging whole-home systems based on concerns around customer comfort or system performance.
- However, the observed difference in electrical grid impacts (particularly in the context of mass market adoption) may be a more important factor for policymakers and utilities to consider for informing policy and programmatic decisions.
- As discussed, cold snap periods were warmer and shorter than design conditions and did not reflect periods of prolonged extreme cold that could have greater impacts on customer comfort and grid demand. Further study with a larger sample during such a weather event may provide more definitive conclusions on comfort, performance, and grid impact issues that could influence policymakers and program administrators.

Program and Policy Recommendations

- **Incentive levels.** Based on the projects metered, most sites will not achieve a payback during the system lifetime based on the incentive received. Incentive levels have since increased substantially for many NY and MA sites, which may enable greater savings.
- **Energy savings.** Electric resistance and propane customers were most likely to see significant energy savings, as well as oil customers in NY. High electricity costs limit energy savings in MA. Utility rate structures (particularly in MA) with lower volumetric costs to reflect higher grid utilization may improve economics, though such structures may be inappropriate in the long term with increasing electrification and winter peak concerns.

Recommendations for Future ccASHP Data Collection Efforts

While this study allowed us to perform in-depth analysis on a variety of factors that may impact ccASHP performance in the Northeast, we identified the following opportunities for future data collection studies:

- Collect data for a larger sample to achieve statistically significant results for a selected region
- Collect data for a longer duration (possibly multiple years) to capture annual variances
- Focus on whole-home installations; it is challenging to estimate heating load served by backup heating sources
- Collect data for a tighter interval (30s -1 min) to investigate defrost demand and energy use
- Investigate multi-zone system (>3 indoor heads) and branch-box system potential performance challenges
- Collect indoor space temperature setpoints to investigate times when ccASHP systems are not able to maintain setpoints