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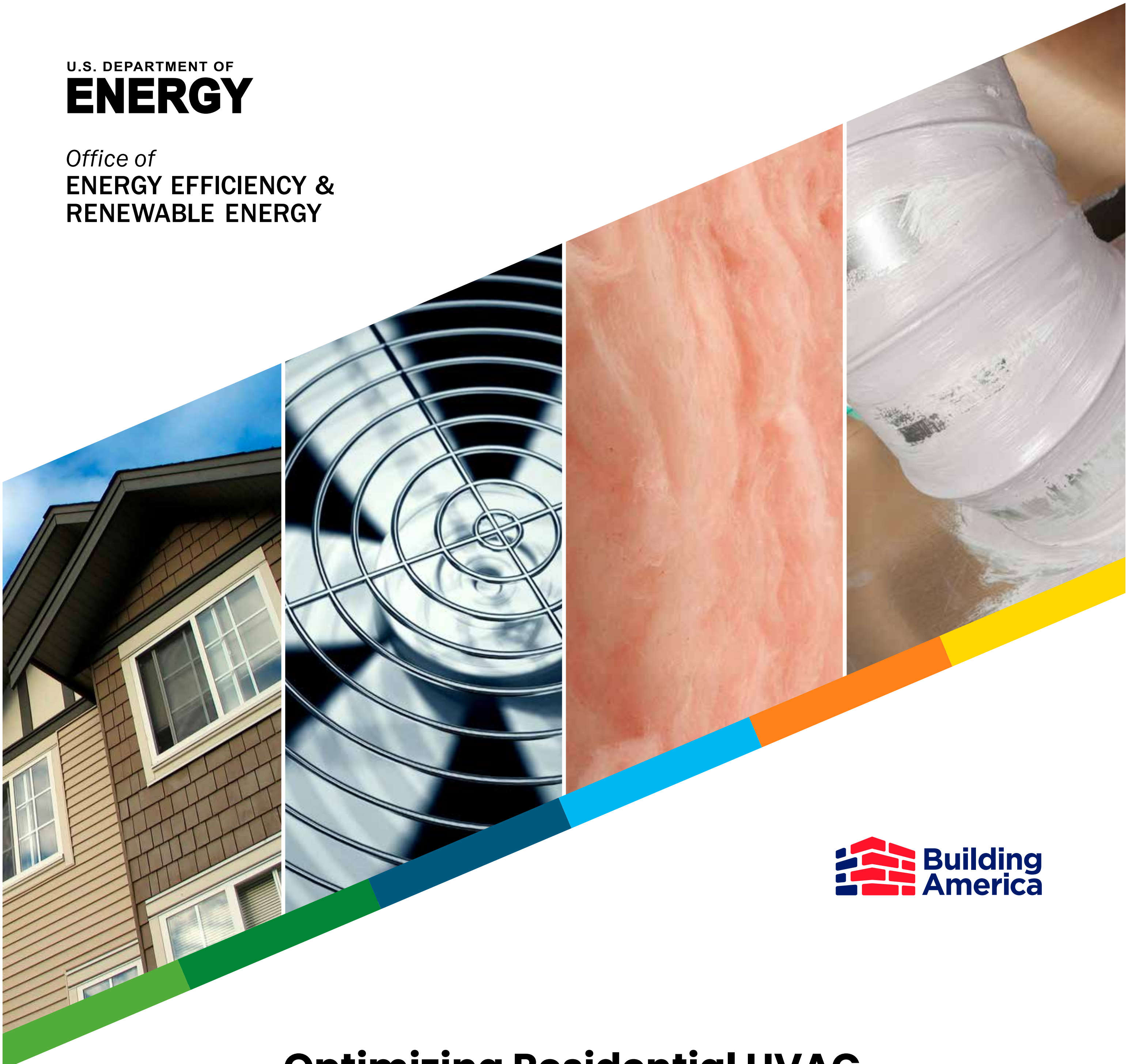

Building America

Optimizing Residential HVAC Systems: Evaluating How the Usage of Smart Diagnostic Tools for Quality Installation and Commissioning Impacts System Performance and HVAC Contractor Businesses

July 2024

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Optimizing Residential HVAC Systems: Evaluating How the Usage of Smart Diagnostic Tools for Quality Installation and Commissioning Impacts System Performance and HVAC Contractor Businesses

Prepared for:
U.S. Department of Energy Building America Program
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Foreword

The U.S. Department of Energy (DOE) Building America Program has spurred innovations in building efficiency, durability, and affordability for more than 25 years. Elevating a clean energy economy and skilled workforce, this world-class research program partners with industry to leverage cutting-edge science and deployment opportunities to reduce home energy use and help mitigate climate change.

In cooperation with the Building America Program, the Southface Institute is one of many **Building America teams** working to drive innovations that address the challenges identified in the Program's **Research-to-Market Plan**.

In this report, *Optimizing Residential HVAC Systems: Evaluating How the Usage of Smart Diagnostic Tools for Quality Installation and Commissioning Impacts System Performance and HVAC Contractor Businesses*, the team at Southface and its partners investigated and documented the HVAC market's current state using accessible data sources. This included examining system operating conditions in homes across various regions, typical practices of HVAC contractors regarding service and installation, and the key factors influencing business decisions in this industry. Data from measureQuick's user networks and publicly available data sets such as DOE's Buildings Performance Database were collected and analyzed.

As the technical monitor of the Building America research, the National Renewable Energy Laboratory encourages feedback and dialogue on the research findings in this report as well as others. Send any comments and questions to building.america@ee.doe.gov.

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List of Acronyms

ACCA	Air Conditioning Contractors of America
AFDD	automated fault detection and diagnostics
ASHP	air-source heat pump
AHU	air handling unit
BPP	business practice partner
CFM	cubic feet per minute
DOE	U.S. Department of Energy
EER	energy efficiency ratio
HVAC	heating, ventilating, and air conditioning
KPI	key performance indicator
mQ	measureQuick
NEI	non-energy (business) impacts
SCFM	standard cubic feet per minute
SEER	seasonal energy efficiency ratio
SHR	sensible heat ratio
TESP	total external static pressure
w.c.	water column

EXECUTIVE SUMMARY

The adoption of digital quality installation and fault detection tools has the potential to transform the $14 billon residential heating, ventilating, and air conditioning (HVAC) service and installation industry. Increased market penetration can be accelerated by providing an increased understanding of the energy and economic value proposition of the usage of these tools. In tandem with energy and HVAC system performance impact research and analysis, the Southface Team investigated the economic business implications for HVAC service and installation contractors adopting the use of measureQuick (mQ), a smart diagnostic app that aids in quality installation and fault detection and works agnostically with Bluetooth-enabled HVAC technician tools.

Data were collected from two sources for both the energy/HVAC performance analysis and non-energy/business analysis of this project. These two sources were: "at-large contractors" and "business practice partners" (BPPs). At-large contractors were individual technicians within the mQ userbase that used mQ workflows in their everyday new system commissioning and existing system tune-ups. These contractors were also asked to contribute to discussions on lessons learned and best practices about their use of the mQ tool. BPPs were a smaller set of eight contractor companies representing small, medium, and large HVAC businesses who pay to use the mQ tool's premier features and whose technicians all are required to use the app in the field. BPPs were also required to have business tracking software, such as Service Titan or House Call Pro, to track and report key performance indicators (KPIs). The identities of the BPPs have been anonymized in the results.

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To answer the questions of how new system installation and existing system tune-ups can be improved using the app, the Southface Team analyzed back-end data collected by the mQ app during business-as-usual HVAC contractor new system installation/commissioning and existing system tune-up/retrocommissioning for 12 months from 6/1/2021 to 5/31/2022. The efforts aimed to collect and analyze HVAC performance snapshot data under real-world conditions, without disrupting the normal processes or course of business for the participating contractors.

The HVAC performance snapshot data collected were found to contain errors resulting from incorrect technician usage of either the Bluetooth probes or the app. To clean the data of these snapshots containing user errors, the Southface Team devised a total of 12 user-error detection filters that each snapshot had to pass through to be used in the full analysis.

Technicians appeared to have the greatest difficulty correctly measuring system power and air handling unit (AHU) power, in particular. Power measurement error rates averaged 10.5% for new systems and 18.0% for existing systems. AHU power measurements averaged 33.6% for new systems and 31.4% for existing systems. Two of the BPPs had AHU power and total power measurement errors exceeding 60%, indicating systemic tool usage issues that need to be corrected with further training. The second most common error in existing system tune-ups was the return or supply probe data error at 20.54%. This indicates that many technicians were either incorrectly using hygrometer probes or had probes that were damaged. Contractors on average had the lowest error rates in using line temp clamps for new installs and using static pressure probes for tune-ups. Overall, 83.9% of the new installation snapshots were free from identifiable user errors and 32.7% of the tune-up snapshots were free from identifiable user errors.

The results from this user error analysis led to several of the filters being incorporated into future versions of the app, alerting the user of potential probe placement errors and measurement errors before an HVAC performance snapshot is taken. Additionally, feedback from the analysis was provided by mQ to each of the BPPs to address and improve systemic user errors and technician training. The results also have informed general mQ training overall.

Installed equipment performance appears to be high for systems commissioned with mQ, with an overall average 90.5% of total normalized capacity, 94.2% normalized sensible capacity, 0.55 total external static pressure, and 395.6 CFM/nameplate ton; however only 76.9% of systems had correct charge from a sample of 2,265 systems. These metrics were disaggregated by contractor group and by climate zone, showing regional and company trends in installation quality and performance. One BPP had the lowest average total normalized capacity, lowest normalized sensible capacity, and lowest percentage of systems with correct charge. We did reach out to the contractor to assist in improving their results, which resulted in the development of guided workflows in mQ to assist with probe placement and process completion. Excluding this one BPP, the averages ranged from 88%–104% of total normalized capacity, 94%–101% normalized sensible capacity, and 85%–96% of systems with correct charge. These results can be compared to the Building America residential HVAC fault baseline studies when published in 2024/2025 to see if following the mQ installation workflow improves the installation quality of new air conditioning and air-source heat pump (ASHP) systems.

A statistically significant average system performance improvement was found for all three metrics analyzed for tune-up/retrocommissioning workflow (3.3% increase in total normalized capacity, 5.4% increase of normalized sensible capacity, and 6.2% increase of energy efficiency ratio). Cleaned sample sizes were 608, 629, and 136, respectively. Comparing contractor groups, there was a wide range in improvement using the tune-up/retrocommissioning workflow, with statistically significant performance improvement averages as high as 15.5% for the at-large group and as low as 4.3% for one of the BPPs. However, there was enough variation within three of the nine contractor groups to cause their results to be statistically insignificant and pull the overall average improvement down to 5.4%. Therefore, the ceiling for

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performance improvement is high but it is dependent on the individual technician. Further research is recommended to track and correlate performance improvements for correcting various fault types while using mQ so that savings can be estimated based on individual fault correction and so best practices can be determined and implemented across contractor companies.

A generalized estimate of the annual cooling electricity and utility bill savings from an average air conditioning or ASHP tune-up using the mQ service workflow was calculated. Using the 5.4% increase in normalized sensible capacity found in this study, the Southface Team estimated 73.3–408.7 kWh/yr ($17.81–$58.82/yr) savings for an average system, depending on climate zone. To answer the question of how app usage affects the HVAC contractor businesses, data were collected in one-on-one interviews with a limited number of HVAC contractors (BPPs) and online surveys and in-person questionnaires for at-large contractors. Data were gathered from fall 2022 through winter 2023.

The Southface Team found that the majority of BPPs indicate new and renewed maintenance agreements have increased significantly since adding mQ to their business offerings, but the difficulty gathering KPI data from BPPs and direct interviews indicated BPPs may not be tracking this data. A major productivity gain with the use of mQ is in reducing callbacks for both new installs and service calls. Eighty-three percent of at-large contractors reported fewer callbacks since adopting mQ, but BPPs, during one-on-one interviews, indicated they are not tracking these data.

Fifty-five percent of at-large contractors reported seeing an increase in revenue per ticket/visit. All BPPs, during one-on-one interviews, reported that mQ has helped them increase their sales volume, with revenue[1] increases in the range of 20% to 80% for service call revenues and a range of 30% to 40% for new installation sales. Most respondents indicated more time is spent on-site, especially for service visits (64%) because use of mQ helps technicians find more faults to repair. The majority of mQ users (86%) are using the tool to determine service repair needs.

About half of at-large contractor respondents (25 of 47) indicated they use the mQ-generated report. Among BPPs, all use the mQ data to build job scopes and discuss a system's status with customers, but only two actively use the mQ-generated reports.[2] Regardless of whether reports were used, across at-large contractors and BPPs, 79% of all respondents indicated it helps build customer confidence in recommendations. The majority of BPPs (five out of six) reported using the "just in time" education features at least once per week, and 80% of respondents indicated the "just in time" education feature impacts technicians' and installers' work on jobs.

Both BPPs and at-large contractors reported that learning to use smart diagnostic equipment and mQ is challenging. Eighty-six percent of users reported that it takes some time to learn and integrate the mQ workflows into their existing business processes. However, many specifically use mQ because it helps them to rapidly onboard new technicians. BPPs report these newly mQ/smart diagnostic-trained employees can quickly elevate their skills to the level of a technician with 2 to 3 years of experience. Combined with the ability for senior technicians or management to remotely view mQ data, this gives management the confidence to send these newer technicians out on calls sooner.

1 Industry benchmarks are for gross margins; the reported business impact from BPPs is for revenue.

2 The mQ report (version 2.0) explains key system operations in nontechnical terms with an A through D grading and enables the technician to benchmark and compare the systems' performance.

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1 Introduction

1.1 Project Scope

Problem Statement

The adoption of digital quality installation and fault detection tools, such as measureQuick (mQ), holds transformative potential within the $14 billion residential heating, ventilating, and air conditioning (HVAC) service and installation industry. However, widespread market penetration of these tools faces obstacles rooted in contractors' limited understanding of the energy and economic benefits they offer. To overcome this barrier, the Southface Team conducted research exploring the economic implications for HVAC contractors integrating smart diagnostic tools like mQ into their operations. By illuminating the energy and HVAC system performance impacts and aligning them with tangible economic advantages, this investigation seeks to catalyze broader adoption of digital tools among contractors, driving industry-wide transformation.[1]

Hypothesis

The use of mQ at scale will both ensure quality installation of HVAC systems and allow for the detection and correction of faults, resulting in both energy and non-energy (HVAC contractor business) benefits.

Research Questions

Energy/HVAC Performance Impacts

1. What are the energy impacts for existing systems that are retrocommissioned with mQ?

Non-energy (Business) Impacts

2. Does the use of mQ increase the productivity of service contractors, including increased maintenance renewal rates, reduced number of callbacks, and increased revenue per ticket or visit?
3. Does the use of mQ increase the customer's reception of retrocommissioning services? Does it increase transparency of assistance provided?

[1] In 2019, when the Southface Team originally conceived of the Building America research project, the research plan included investigation of the use of both Sensi Predict and mQ, combined and independent of each other. However, due to market disruptions resulting from the COVID-19 global pandemic, manufacture and delivery of Sensi Predict monitoring devices were significantly impacted. As a result of low market adoption of Sensi Predict, particularly by HVAC contractors participating in the research project, and sale of Emerson Electric's climate technologies unit to Blackstone, resulting in the discontinuation of the Sensi Predict line, the Southface Team narrowed research to focus solely on analysis of energy and non-energy impacts of mQ use and adoption.

1.2 Literature Review

Over 90% of new construction homes in the United States include central air conditioning and 87% of existing homes are now equipped with AC, of which 76% are central air systems.[2] The U.S. Energy Information Administration (EIA) estimates that 51% of all residential site energy consumption is for heating and cooling, including 32% of total electricity use.[3] Several studies have documented that most residential heating and cooling systems are operating inefficiently with many being improperly installed with common faults including oversizing, incorrect airflow, incorrect refrigerant charge, and poor duct design.[4]

Roughly 70% to 90% of homes throughout the country exhibit various energy-wasting HVAC issues, encompassing problems such as incorrect airflow, excessive or insufficient refrigerant charge, improper sizing concerning loads, and duct issues arising from flawed design and sizing. When duct leakage is factored in, the rates are 90% to 100% (EERE 2018). These faults contribute to discomfort, reliability issues, and safety concerns for occupants in residential spaces. Consequently, homeowners face increased energy expenses and system inefficiencies due to inadequate HVAC installation and commissioning. Moreover, many homeowners are not even aware that their systems are operating improperly. A 2015 California utilities' survey of 350 homeowners found that most homeowners assume the system is properly installed if it turns on/works, looks okay, or they believe the contractor is competent (Steiner 2015).

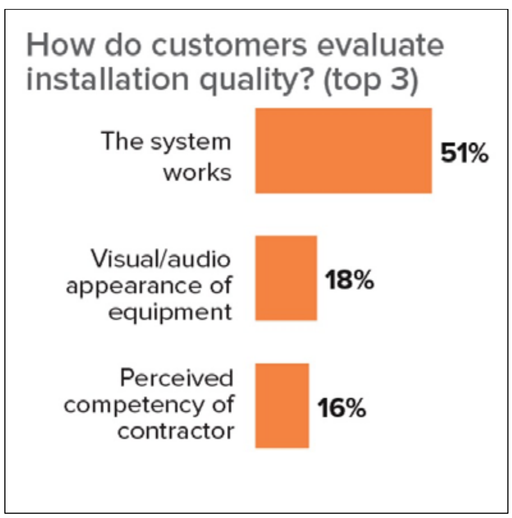

Figure 1. Customer understanding of residential HVAC system installation quality

[2] https://www.eia.gov/consumption/residential/data/2015/hc/php/hc7.3.php
[3] https://www.eia.gov/tools/faqs/faq.cfm?id=96&t=3
[4] DOE 2018. Residential HVAC Installation Practices: A Review of Research Findings. U.S. Department of Energy. https://www.energy.gov/sites/prod/files/2018/06/f53/bto-ResidentialHVACLitReview-06-2018.pdf

1.2.1 Residential HVAC Faults, Automated Fault Detection and Diagnostics, and Quality Installation Tools

There are limited data on the exact current fault prevalence in installed systems across America. Appropriately, there are two current studies[5,6] through Building America underway to determine baseline field fault prevalence and energy impact by fault type.

Two recent studies have also been performed by Pacific Northwest National Laboratory (PNNL) and the National Renewable Energy Laboratory (NREL), analyzing the automated fault detection and diagnostics (AFDD) residential market and modeling impact of installation faults, respectively (Butzbaugh et al. 2020; Winkler et al. 2020). Helpfully, they have already surveyed the existing literature and confirmed what was stated above regarding fault prevalence baseline studies. They state that “There is a dearth of statistically robust data for the prevalence and severity of airflow problems … [and, as] with indoor airflow rate, there are limited field-measured data documenting refrigerant charge fault ratios, making it difficult to arrive at a statistically meaningful summary of the severity and prevalence of this problem.”

However, they estimate using data compiled from 11 separate field studies of over 2,600 units, that roughly one-half of all units are correctly charged with refrigerant, one-quarter have low charge, and one-quarter have high charge. They also describe how existing studies have revealed a widespread and longstanding problem of incorrect airflow in a majority of systems and, of those systems, most err in having low (as opposed to high) airflow rates. In summary, “regional field studies conducted on behalf of utilities, as well as anecdotal reports from industry experts, point to a general consensus that installation faults such as improper indoor airflow rate and refrigerant charge are commonplace” (Winkler et al. 2020).

Recently, there has been major industry attention and momentum in addressing these installation faults, culminating in the publication of the new RESNET/ACCA/ANSI Standard 310-2020 “Standard for Grading the Installation of HVAC Systems.”[7] In addition to this standard, several companies have begun independently developing smart HVAC diagnostic tools and AFDD systems aimed at the residential market.

In examining the residential AFDD market, Butzbaugh et al. state “Unlike commercial buildings, HVAC equipment with embedded AFDD is uncommon in the residential sector … few HVAC manufacturers have embedded AFDD in their residential equipment, and when present, it exists in only high-end, variable-speed units specifically for the purpose of equipment reliability. Furthermore, the industry has yet to

[5] Hot-Humid and Hot-Dry Climate Zones: https://www.energy.gov/eere/buildings/investigation-prevalence-and-energy-impacts-residential-comfort-system-faults-hot
[6] Cold, Marine, and Mixed-Humid Climate Zones: https://www.energy.gov/eere/buildings/field-study-characterize-fault-prevalence-residential-comfort-systems
[7] https://www.resnet.us/wp-content/uploads/ANSIRESNETACCA_310-2020_v7.1.pdf

standardize the domain of residential AFDD or identify which types of faults should be consistently reported, how to report them, and which stakeholders are intended to receive what information."

Also, "AFDD-enabled technologies exist on a spectrum of data communications configurations, ranging from proprietary equipment-to-connected-thermostat systems to third-party sensor networks that attach to existing HVAC systems. The former is common throughout the market in higher end products, with major manufacturers offering diagnostic capabilities through Wi-Fi enabled networks that connect HVAC units of the same line to a "control center" connected thermostat. These systems can only provide diagnostic capabilities for equipment of the specified brand line, and the control center itself must be of the same brand or an approved subsidiary label ... Emerson's Sensi Predict represents the third-party side of the market, integrating with most HVAC units (except geothermal systems or those with proprietary communicating systems) as an external system with a sensor and diagnostic network."

In examining smart HVAC diagnostic tools, " ... which can monitor HVAC equipment over a finite timeframe using a combination of smart gauges, sensors, and a mobile app to diagnose performance issues to ensure quality installation and tune-ups" they state: "Most diagnostic applications are designed for use with the manufacturer's specific equipment (e.g., the Testo Smart Probes app only works with Testo equipment). The exceptions are ... two tools ... : measureQuick and RefTech … The app measureQuick stands out as it is not only a system in its own right, but the digital backbone of the Supco TechLink system, which is a Supco-branded tool developed by measureQuick" (Butzbaugh et al. 2020).

In 2022, Winkler et al. identified five barriers to the broader adoption of AFDD technology:

> "1. Evaluation barriers prevent AFDD technology users/stakeholders from assessing the technology's accuracy and capabilities.
>
> 2. Justification barriers are due to a lack of relevant field data for residential HVAC faults, and the documented energy saving potential of AFDD technology. These barriers prevent an accurate assessment of the potential benefit of AFDD technology.
>
> 3. Cost barriers can be due to hardware cost, labor cost to install and/or use the technology, and/or building occupant subscription costs associated with the technology.
>
> 4. Implementation barriers are primarily related to technological shortcomings or additional effort that is required to ensure successful deployment of AFDD.

5. Market barriers relate to the existing sales or service structure of residential HVAC equipment and general market awareness of the AFDD technologies" (Winkler et al. 2022).

This project was a field study validating one of the above highlighted technologies, measureQuick (mQ), and sought to address barriers 2 and 5. In the study, the Southface Team aimed to quantify the HVAC performance and business economic implications for contractors resulting from the adoption of these automated verification tools.

1.2.2 Residential HVAC Contractor Businesses

Understanding the Residential HVAC Market

There are over 145,000 HVAC contractor businesses in the United States, and that number is estimated to be growing on average 3% to 6% annually (IBIS World 2023). The majority of HVAC service and installation businesses are small businesses, often one-truck family-owned operations with less than 5 employees and with less than a million dollars in revenue (Better Buildings Neighborhood Program 2012). Companies of a medium (10 to 20 employees) or larger (more than 30 employees) size typically have higher revenue and are departmentalized with specific business units such as sales, maintenance, and service departments.

Consumers spend more than $10 billion each year on HVAC repair and maintenance services and, on average, 2 to 3 million systems are replaced annually in the United States (This Old House 2023). Today's market supply and demand pressures, however, are compressing profit margins, which are expected to fall 5.3% according to a January 2023 report from IBIS World. Most new installations are system replacements of old, nonfunctioning equipment. An estimated 30% to 50% of maintenance programs have customer drop-offs (Reed 2023). Competitive sales and speed to market characterize the HVAC contracting world. Referrals and cultivating long-term relationships with customers with maintenance service plans are a priority. For all HVAC business models, any HVAC operational faults usually lead to service call complaints, warranty claims, and customer dissatisfaction, all of which have bottom-line impacts.

Butzbaugh et al. (2020) summarize the state of the industry: "Based on the current business model, contractors earn greater profit from HVAC equipment replacement, which is considered the priority. Long-term servicing of equipment is not the focus of contractors. Manufacturers are reluctant to promote or train their certified contractors in AFDD operation, and as a result, a considerable number of HVAC contractors either do not know about AFDD or do not trust the technology. Coupled with certain manufacturers stepping away from embedded AFDD due to a lack of customer engagement, both demand and supply sides of the existing AFDD market are limited due to significant gaps in awareness and knowledge."

HVAC Industry Market Trends

HVAC market research experts note several strengthening trends in HVAC services and installation businesses. Today's residential occupant wants smart connected devices to facilitate home comfort, security, entertainment and more. According to SBE Odyssey, an HVAC business consulting services company, in 2022 the smart thermostat market alone was worth $1.2 billion and is projected to grow to $3.8 billion by 2029 (SBE Odyssey 2023). This trend has accelerated due to the global COVID-19 pandemic, and coupled with air pollution from wildfire smoke, is accelerating interest in indoor air quality devices. The U.S. indoor air quality market was worth $9.8 billion in 2022 and is projected to grow to $11.9 billion by 2027 (This Old House 2023).

Understanding HVAC Industry Key Performance Indicators

The Southface Team identified several key performance indicators (KPIs) through a literature review and consultation with HVAC contractors and industry.[8] SBE Odyssey indicates 43% of HVAC business owners expected a 5%–10% growth in their business in 2023. The average profit margin for an HVAC business is between 2.5% and 5%, with the top HVAC companies earning profit margins between 10% and 25% (SBE Odyssey 2023).

The standard KPIs HVAC companies should be tracking include sales revenue, gross margin, monthly profit and loss, service metrics (e.g., maintenance agreement renewal rates), customer retention, and advertising ROI (Service Titan 2023). However, it can be challenging for HVAC business to set, measure, and monitor their KPIs because many companies do not disaggregate tracking revenue by business units, which impedes an apples-to-apples comparison. The primary departments for residential HVAC businesses to disaggregate and set specific KPIs metrics for are residential replacement, residential service, residential maintenance, indoor air quality, residential new construction, plumbing, and electrical. For each of these, management should track separate cost items, including parts and materials, labor, equipment, subcontracts, permits, warranty reserve, extended warranty, buydown, rebates received, rentals, other, fringe benefits, and sales commissions. For this research project, the Southface Team focused on three departments—residential replacement, residential service, and residential maintenance—and four primary KPIs—sales revenue (e.g., conversion rates), gross margin, maintenance agreement renewal rates, and customer retention (e.g., satisfaction). Table 1 provides the range of industry benchmarks for these KPIs (Contracting Business 2017; Service Titan 2023; Smith 2020)

[8] The Southface Team interviewed industry experts Ruth King (Financially Fit Business) and Brian Feenie (Service Titan) in 2022. The Team also interviewed training and management consultants attending the 2023 HVACR Symposium.

Table 1. HVAC Industry Key Performance Indicators and Benchmarks

Business Department	HVAC Industry Key Performance Indicator Benchmarks			
	Gross Margin	Sales Conversion Rate	Customer Satisfaction (e.g., renewal rates)[9]	Service Efficiency
Residential Replacement	40% to 45%	40% to 60%	Not available	50%
Residential Service	60% to 65%	25%	Not available	
Residential Maintenance	55% to 60%	60% to 70%	60%	

1.3 Overview of Field Tested Systems

The measureQuick (mQ) platform is an app-driven tool that assists in standards adoption (such as Air Conditioning Contractors of America (ACCA) quality installation standards) as well as data aggregation required for compliance. It also is a vehicle to share data with standards developers for improved standards. It is used by field technicians to identify faults and potential faults at the time of service and installation, commission the system, and baseline the system performance. mQ aggregates data from Bluetooth HVAC contractor tools and allows for manual inputs of measurement data to measure or calculate over 100 points of system data and performance and assists in identifying over 100 system faults during installation or service. It is a brand-agnostic tool, working with many tool manufacturers and brands. mQ is ideal for field commissioning, retrocommissioning, and service of air conditioning, furnaces, and heat pump systems.

The mQ app produces a system report presenting the cooling performance, age degradation, initial seasonal energy efficiency ratio (SEER) and capacity, refrigerant charge, and static pressure of the duct system into a signal grade. The mQ Pro Report includes the test-in and test-out measurements, as well as detailed system measurements from the probes, performance calculations, system information, system profile, corrective actions, and pictures.

Manifold Cloud Services (developer of the mQ application) has been updating and refining the application and adding features since the proposal for this project. Additionally, they have continued working with Emerson on the rollout of the combined mQ/Sensi Predict solution. As of summer 2018, the mQ application had been

[9] There is scant published data on HVAC industry customer satisfaction benchmarks.

downloaded approximately 20,000 times, with an approximate active user base of 5,000. As of February 2021, mQ had approximately 170,000 downloads and 44,000 active users. As of October 2023, mQ has approximately 240,000 downloads and 102,000 active users.

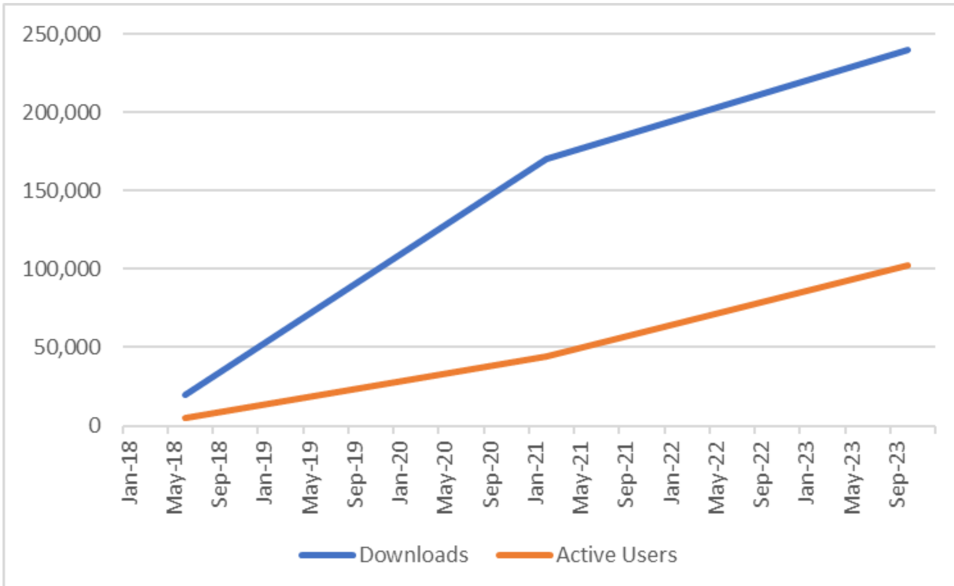

Figure 2. mQ total downloads and total active users from 2018 to 2023

2 Methodology

2.1 Data Gathering

2.1.1 Recruitment and Homeowner Interaction

There was no direct interaction between researchers and homeowners. The Southface Team analyzed data stripped of personally identifiable information collected by mQ during business-as-usual HVAC contractor new system installation/commissioning and existing system tune-up/retrocommissioning. The efforts aimed to collect and analyze data without disrupting the normal course of business for the participating contractors. This eliminated the need for financial compensation to the homeowners for participation in the study, as well as the need for extensive institutional review board involvement and social/behavioral training for contractors and allowed data collection during the year 2021, when COVID-19 was still a global health crisis and a priority was being placed on limiting person-to-person contact.

2.1.2 Data Collection Sources

Data were collected from two sources for both the energy/HVAC performance analysis and non-energy/business analysis of this project. These two sources were:

1. At-large contractors: A self-selected subset of the 40,000+ mQ userbase, at-large contractor participants are individual technicians across the United States that responded to a limited time invitation from mQ to have access to Building America-specific mQ workflows to use in their everyday new system commissioning and existing system tune-ups. These data were used to answer the energy impact/HVAC performance questions. The contractors who actively use the tool were also asked to participate/contribute to discussions on lessons learned and best practices about their use of the mQ tool.
2. Business Practice Partners: The Team identified a smaller set of eight business practice partners (hereafter referred to as BPPs), representative of small, medium, and large HVAC contractor companies who pay to use the mQ tool's premier features and whose technicians all are required to use the app in the field. BPPs were also required to have business tracking software, such as Service Titan or House Call Pro, to track and report KPIs.

HVAC performance snapshots stripped of personally identifiable information from both groups were shared with the Southface Team by mQ.

2.1.3 Energy/HVAC Performance Impact Data Collection Methodology

Participating contractors used Building America-specific mQ workflows that required data fields to be input with streamed HVAC probe data (avoiding user-entry error). Access to otherwise paywall-blocked mQ features was available to technicians using the designated Building America Workflows, thus encouraging workflow usage and contractor participation. In essence, the data collection was “crowd-sourced” for this project. Building America-specific mQ workflows are the same as the workflows used by the BPP participants; they differ only in workflow name for tracking and analysis purposes.

Figure 3 shows a demo example of the “Start a Project” screen with the Building America workflow options. Selecting one of the Building America workflows displayed a dialog pop-up stating “All data except for customer name, street address, and geotag will be shared with Building America for analysis as part of a DOE-funded research project.” The HVAC technician user had the option to select “Agree” or “Cancel.”

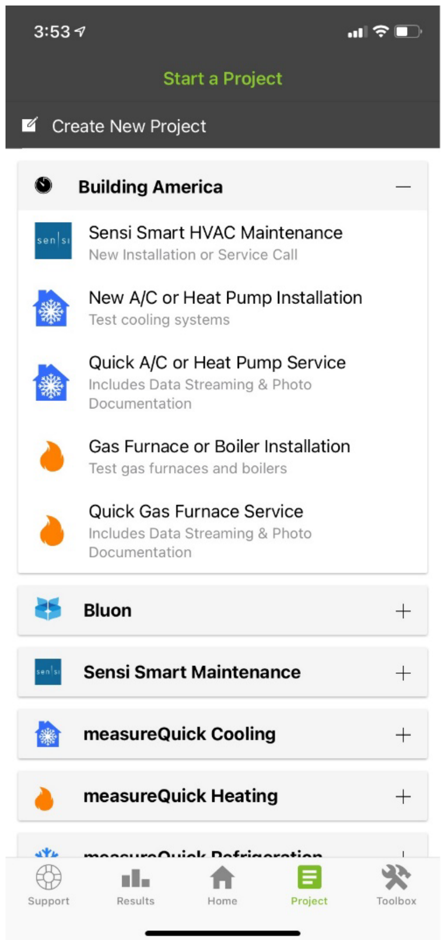

Figure 3. mQ “Start a Project” screen, showing Building America workflows as an option

The app guides a technician through a workflow (Figure 4) that requires the input of various data, including equipment model number and zip code. The actual performance data are streamed from Bluetooth-enabled HVAC technician tools (to avoid user-entry error) and captured as performance snapshots under “Test-in” and “Test-out” conditions categories.

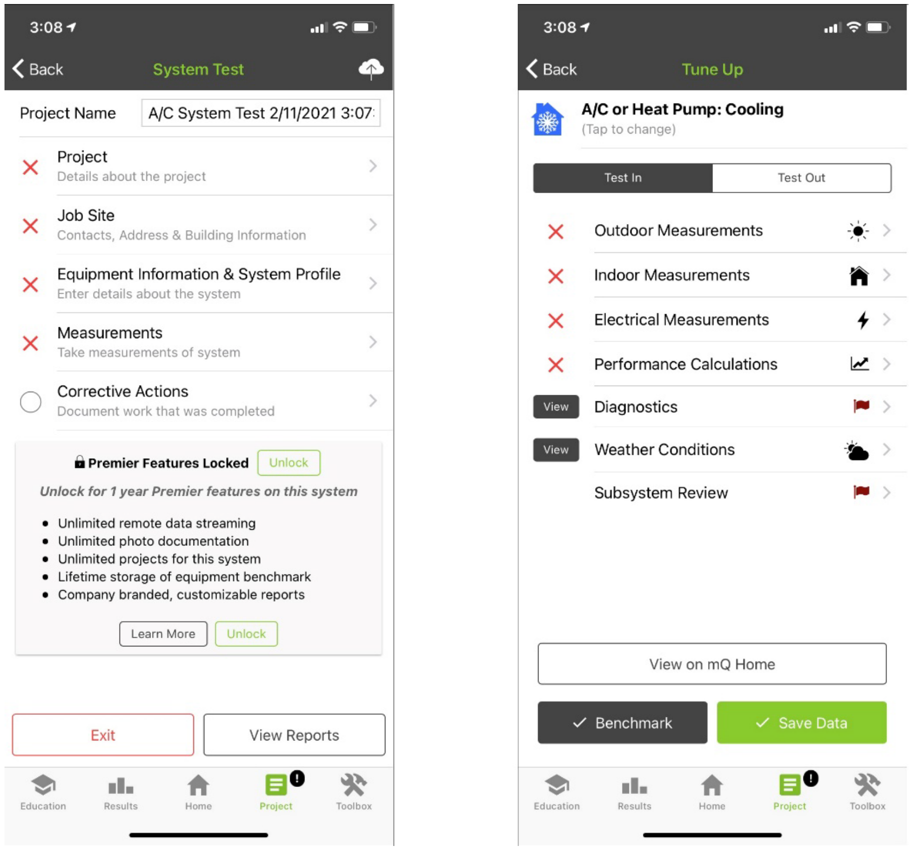

Figure 4. mQ Building America workflow (left) and test-in/test-out feature (right)

Bluetooth-enabled HVAC technician tools required for every performance snapshot are:

1. Return Air – Temp. Probe 1
2. Supply Air – Temp. Probe 2
3. Return Static Press. – Manometer 1
4. Supply Static Press. – Manometer 2
5. Outdoor Air – Temp. Probe 3
6. Suction temp clamp – Temp. Clamp 1
7. Liquid temp clamp – Temp. Clamp 2
8. Low pressure – Press. Port 1
9. High pressure – Press. Port 2.

For some of the metrics, additional measurements are required:

1. Power quality meter capturing AHU and condensing unit voltage, current, and power factor (for energy efficiency ratio (EER) and fan efficacy calculations)
2. Discharge Line temperature lamp (for additional heat pump diagnostics).

Probes 1–9 are required for all performance snapshots in this study. Snapshots that include probe 10 allowed calculation of fan efficacy (watts/CFM), EER, and an estimated SEER for a subset of the total snapshots collected.

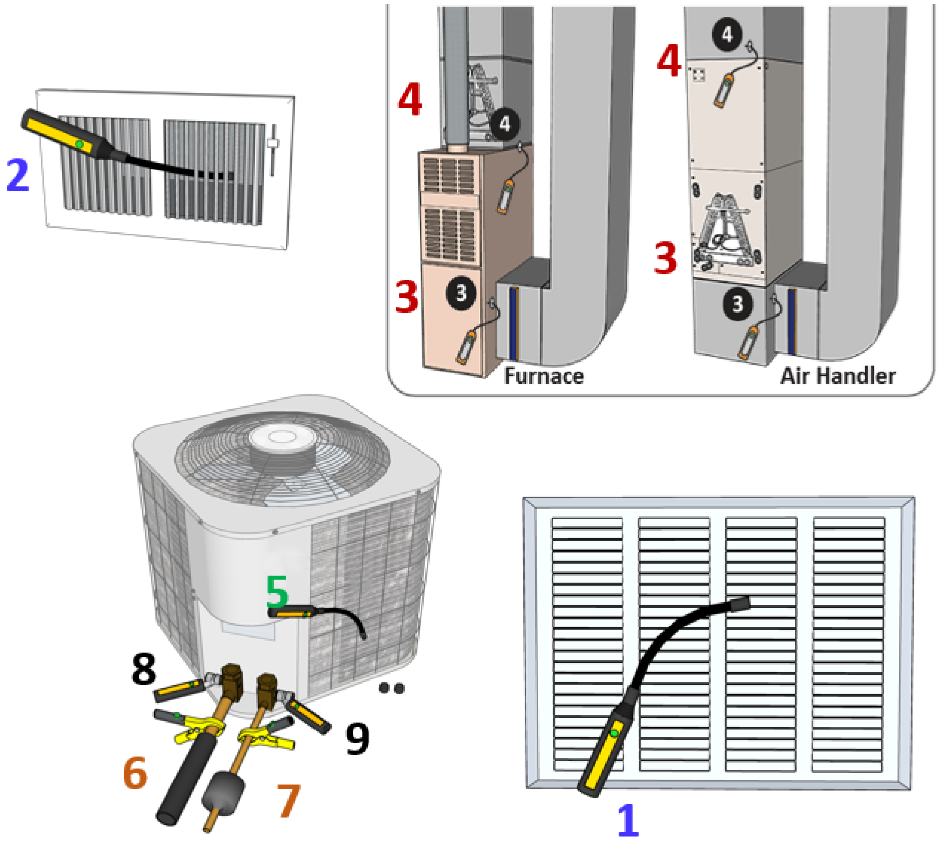

Figure 5. Probes required for all mQ performance snapshots

In addition to the performance data streamed from the Bluetooth-enabled HVAC technician tools, there are several data points for each system that require manual user input. Examples are:

1. AHU and condensing unit manufacturer, model number, and serial number
2. System type (split, package, mini-split, etc.)
3. Nominal tonnage
4. Refrigerant type
5. Approximate SEER
6. Metering Device (thermostatic expansion valve, piston, capillary tube, electronic expansion valve, automatic expansion valve)
7. Manufacturer’s target subcooling (default is 10°F)

8. Manufacturer's target superheat for thermostatic expansion valve (default is 10°F, target superheat is automatically calculated for a fixed-type metering device)
9. Target total external static pressure (TESP) (default is 0.5" w.c.)
10. Line set length, lift, and location
11. Liquid and suction line diameters
12. Location of ducts and duct R-value
13. Whether it is a zoned system.

Data collected for each performance snapshot from the mQ workflows are similar to that shown in Figure 6. These data fields were collected for both the new installation commissioning workflow and the existing system tune-up workflow for 12 months from 6/1/2021 to 5/31/2022.

Outdoor Measurements

Low Pressure (PSIG)	124.2
High Pressure (PSIG)	241.2
Suction Line Temp (F)	48.2
Liquid Line Temp (F)	69.8
Discharge Line Temp (F)	–
Outdoor Air Temp (F)	67.0
Superheat (F)	6.1
Subcooling (F)	11.5
Compression Ratio	1.8
Cond. Volts	243.0
Cond. Amps	1.1
Cond. Power Factor	0.99
Cond. Power (W)	266.0

Indoor Measurements

Return Dry/Wet Bulb (F)	68.4 / 51.3
Return RH (%)	30.3
Supply Dry/Wet Bulb (F)	47.9 / 41.8
Supply RH (%)	60.7
Est. Airflow (SCFM)	662
RESP (InH2O)	0.31
SESP (InH2O)	0.15
TESP (InH2O)	0.46
AHU Volts	243.0
AHU Amps	1.1
AHU Power Factor	0.99
AHU Power (W)	267.0

System Info & Weather

System Type	Split
Nominal Tonnage	1.5
Refrigerant	R410A
Rated Airflow	450
SEER	13-16
Metering Device	Piston
Atmos. Pressure (psia)	14.109
Elevation (ft)	1123
Benchmarked	Yes
System Stability	Stable

Performance Calculations

Nominal Capacity (Tons / Btu/h)	1.5 / 18,000
Normalized Capacity (Tons / Btu/h	1.4 / 16,733
Actual Capacity (Tons / Btu/h)	1.2 / 13,832 (83% Norm.)
Sensible Capacity (Tons / Btu/h)	1.2 / 13,832 (104% Norm.)
Latent Capacity (Tons / Btu/h)	0.0 / 0 (0% Norm.)
Sensible Heat Ratio	1.0
Temp Split Target (F)	18.2
Temp Split (F)	20.0
Dehumidification (lb/hr)	–
Fan Efficacy (W/SCFM)	0.4
Total Power (W)	533
EER/EER2	26.0/24.9
~SEER/SEER2	28.8/27.5

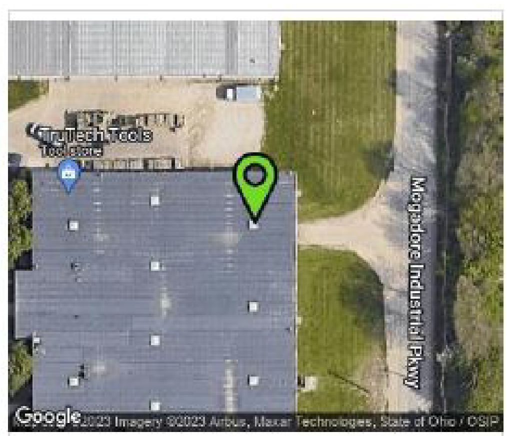

Figure 6. mQ Building America report content

A list of the major data outputs from mQ used for analysis in this study and the source of that data can be seen in Table 2.

Table 2. List of mQ Data Outputs Used For Analysis

Metric	Source
Nameplate Tonnage	User input from nameplate
% of Nameplate Tonnage	Field Measured/MQ Calculated
Total External Static Pressure (inches w.c.)	Field Measured
Normalized Tonnage Target (tons)	Field Measured/mQ Calculated
% of Normalized Total Capacity	Field Measured/mQ Calculated
% of Normalized Sensible Capacity	Field Measured/mQ Calculated
% of Normalized Latent Capacity	Field Measured/mQ Calculated
Sensible Heat Ratio	Field Measured/mQ Calculated
CFM	Field Measured or mQ Estimated
CFM/Nameplate Tonnage (CFM/ton)	Field Measured or mQ Estimated
Fan Efficacy (Watts/CFM)	Field Measured/mQ Calculated
EER	Field Measured/mQ Calculated at current conditions (not AHRI)
SEER	Field Measured/mQ Estimated
Subcooling (°F)	Field Measured
Superheat (°F)	Field Measured

All “Field Measured” data are streamed directly from connected Bluetooth probes to eliminate manual data entry errors. However, probe usage/placement and app usage errors were still possible and could be identified and removed from the data set (see section 2.2.1 Data Cleaning/User Error Filtering). Further detail on how mQ calculates the proprietary metrics can be seen in Section 2.2.2 HVAC System Performance Analysis.

2.1.4 Non-Energy (Business) Impacts Data Collection Methodology

For non-energy (business) impacts (NEI) data collection and research, the Southface Team targeted a pool of “at-large” mQ users who actively use the tool and were willing to participate/contribute to discussions on lessons learned and best practices about their use of the mQ tool. Additionally, the Team identified a smaller set of “business practice partners” (BPPs), representative of small, medium, and large HVAC contractor companies who pay to use the mQ tool’s premier features and whose technicians all are required to use the app in the field. BPPs were also required to have business tracking software, such as Service Titan or House Call Pro, to track and report on KPIs, focusing on three departments—residential replacement, residential service, and residential maintenance—and four primary KPIs—sales revenue (e.g., conversion rates), gross margin, maintenance agreement renewal rates, and customer retention (e.g., satisfaction).

Original NEI Research Approach

To indicate a change in business productivity due to a HVAC contractor’s use of mQ, the Southface Team planned to establish individual contractor organization baselines, as well as a comparison data points, such as those listed in Table 3. Table 3 presents which core NEI data points (e.g., maintenance renewal rates, business performance on new installs, and revenue per ticket) establish the baseline/control group comparison set.

Table 3. Core NEI Data for Baselines

Business Category	Data Point to Pull from Business Management Software	Baseline[10]	Market Standard[11]
Maintenance/ Service	Number of maintenance agreements	·	
Maintenance/ Service	Number of maintenance agreements, renewed	·	·
Maintenance/ Service	Number of service calls	·	·
All	Average travel time for all call types	·	
All	Average labor time charged for all call types	·	
New Installs	Number of new installs with mQ	·	·
New Installs	Number of callbacks on new installs with mQ	·	

After establishing the baseline, the Southface Team planned to collect data points presented in Table 4 from each BPP on a quarterly basis.

[10] The Research Team planned to collect, from each BPP, a historical lookup of the data point prior to using mQ workflow (e.g., data from April 2020 to October 2020).
[11] The Research Team planned to collect industry input by polling the at-large mQ users and, if possible, from ACCA.

Table 4. Planned Quarterly Data for BPPs

Business Category	Data Point to Pull From Business Management Software	Unit	Example Response
Maintenance/Service	Number of maintenance agreements per quarter	#	10
Maintenance/Service	Number of maintenance agreements renewed per quarter	#	2
Maintenance/Service	Number of service calls per quarter	#	30
Maintenance/Service	Average travel time for maintenance/service call per quarter	hour, min	1h, 12 min
Maintenance/Service	Average labor time charged for service/maintenance call per quarter	hour, min	45 min
New Installs	Number of new installs with MQ per quarter	#	20
New Installs	Number of callbacks on new installs with MQ per quarter	#	4
New Installs	Average travel time for new installs per quarter	hour, min	1h 12 min
New Installs	Average labor time charged for new installs per quarter	hour, min	45 min
New Installs	Average travel time for callback on new installs per quarter	hour, min	1h 12 min
New Installs	Average labor time charged for callback on new installs per quarter	hour, min	45 min

In support of KPI data collection the Team also prepared a series of interview questions to collect from BPP business owners. These questions are presented in Table 5.

Table 5. BPP Interview Questions

Topic	Question
Maintenance Agreements	On average, how many maintenance agreements did you close using mQ? Since adding the use of mQ to your services, have you increased the number of maintenance agreement customers?
Productivity	What is the average travel time for your service visit or new install jobs? When using the mQ workflow, what is the average labor time for your service visit or new install jobs? What impact does mQ have on the number of systems a tech can service? ○ On average, how many visits can a tech service in a day or week? [measure each quarter, compare peak seasons to lulls] ○ Is time per service visit going up or down? why? ○ Are callback rates for new installs or service visits with mQ going up or down? How does this compare with callback rates for non-mQ visits? How do the services/capabilities of mQ reports impact customer satisfaction? How do the mQ reports impact their decision to proceed with a contract (new install, repair, and/or maintenance agreement)?
Customer Interactions/ Reactions	How long does it take to train your contractors to use diagnostic measurement tools with mQ? How long does it take to train your contractors to use diagnostic measurement tools without mQ? How does the availability of "just in time" video training and expert guidance provided by mQ impact time for service, maintenance, and new install visits? How does use of mQ impact your hiring, onboarding and employee retention?

Over three-quarters—Quarter 4, 2021 through Quarter 2, 2022—the Southface Team sought KPI data and interview responses from BPPs, as described in Table 3. The Team sent a test data collection template to extract from BPPs' business management software. Despite repeated attempts, only one BPP contractor successfully submitted test KPI data; a second BPP attempted to make the data extraction from their system, however the data provided did not logically match the requested data fields. Because this KPI data collection sample is too small (only one), it cannot be anonymized, and it does not provide enough to characterize NEIs. As a result, the Southface Team outlined an alternative method to collect NEI data.

Revised NEI Research Approach

In spring of 2022, the Team prepared an alternative approach, focused on interviews of BPPs and online surveys for both BPPs and at-large contractors. Table 6 presents the amended set of interview questions.

Table 6. Revised BPP Interview Questions

Topic	Question
General	Why did you add mQ to your business service offerings? What is working well? What would you like to see improved?
Maintenance Agreements	On average, how many maintenance agreements did you renew using the mQ? On average, how many maintenance agreements did you close using the mQ? Since adding the use of mQ to your services, have you increased the number of maintenance agreement customers?
Productivity	Does the use of mQ increase the productivity of your service contractors? Collect the following KPIs, if tracked: ○ What is your average gross profit per service ($ per hour)? ○ What is your average labor cost per hour (due to use of mQ)? ○ What % are you above or below your revenue to goal? ○ What is your capacity to sell vs. actual (%)? ○ What are your lead turnover rates (%) for new installs and for maintenance agreements? Does use of mQ increase repair quote close rates? Does using mQ improve resource management and scheduling of service calls? How does baselining the system with mQ impact future service visits, repair calls or new installation quotes? What impact does mQ have on the number of systems a tech can service? On average, how many visits can a tech service in a day or week? [measure each quarter, compare peak seasons to lulls] Is time per service visit going up or down? why? Are callback rates for new installs or service visits with mQ going up or down? How does this compare with callback rates for non-mQ?
Customer Interactions/ Reactions	How does use of the mQ reports impact customer satisfaction? How does the mQ report impact their decision to proceed with a contract (new install, repair, and/or maintenance agreement)?
Training/ Workforce Development /Retention	How long does it take to train your contractors to use diagnostic measurement tools with mQ? How long does it take to train your contractors to use diagnostic measurement tools without mQ? How does the availability of “just in time” video training and expert guidance provided by mQ impact time for service, maintenance, and new install visits? How does use of mQ impact your hiring, onboarding and employee retention?

To reach at-large contractors, an online survey, presented in Table 7, was issued in May 2022 and again in January 2023.

Table 7. Online Survey Questions for At-Large Contractors

Question	Answer options
1) Using mQ report has helped me engage with customers in the following ways (click all that apply)	It helps me determine service repair needs It helps me document and verify the work performed It helps me prepare the customer for a future HVAC replacement installation It helps me explain the service need to my customer I don't use the mQ report with my customers
2) Learning to use the mQ app was	Fast and easy Took some time to get used to, but now it's smooth sailing I'm still figuring it out
3) I wish they would add the following to the app…	*Open text field*
4) On average, how many service calls can you complete a week?	< 10 10 to 15 > 15
5) Since adding use of mQ, my time per service visit is	Longer – I'm finding more things to fix About the same Faster – I diagnose more quickly, getting more jobs done
6) When using mQ for new installs, my time spent on the job is…	Longer – there are more diagnostics to conduct About the same Faster – I diagnose more quickly, getting more jobs done
7) How does the availability of "just in time" video training and expert guidance provided by mQ impact time for service, maintenance, and new install visits?	No impact Somewhat impacts Greatly impacts
8) Please provide any additional feedback on your company's use of mQ	*Open text field*

Additionally, the Southface Team conducted an in-person questionnaire, shown in Table 8, at the Fourth Annual HVAC/R Training Symposium held in January 2023.

Table 8. In-Person Questionnaire for At-Large Contractors

Question	Answer options
Do you use mQ for every job?	Yes/No
How are you using mQ? Are you using it to diagnose issues with systems? Are you using mQ with gauges? Please describe.	*Open text field*
Are you using mQ Premier Services to do your work?	Yes/No
Are you using it for new installs? Please describe.	Yes/No *Open text field*
Are you using it for service calls? Please describe.	Yes/No *Open text field*
Do you see a reduction in callbacks as a result of using mQ? Please describe.	Yes/No *Open text field*
Since using mQ, do you see an increase in revenue per ticket/visit? Please describe.	Yes/No *Open text field*
Is use of mQ integrated with your business management software/CRM? Please describe.	Yes/No *Open text field*
Please share the value for your business/work in using mQ.	*Open text field*

Data collected in one-on-one interviews with BPPs and via online surveys and in-person questionnaires for at-large contractors were gathered from fall 2022 through winter 2023. Across all data sets, responses were aggregated and anonymized. Where possible, data responses from aligned questions were merged to present a larger data set.

2.2 Energy/HVAC Performance Impact Data Analysis

The energy/HVAC performance impact data analysis was broken down into three general steps for both the tune-up data and the new installation commissioning data:

New Installation Commissioning Data Analysis

1. The data sets were passed through a set of filters to clean the collected data by removing snapshots that contain identifiable app or tool usage errors.
2. Cleaned data were used to determine the average performance for new systems commissioned with mQ and categorize by contractor group and by climate zone.

3. These data were compared to industry average baseline field data.

Tune-up/Retrocommissioning Data Analysis

1. The data sets were passed through a set of filters to clean the collected data by removing snapshots that contain identifiable app or tool usage errors.
2. Used cleaned data to determine the average performance difference pre/post tune-up and categorize by contractor group and by climate zone.
3. Determined the statistical significance of pre/post impact results.

2.2.1 Data Cleaning/User Error Filtering

After a brief inspection of the raw data set that was provided to the Southface Team by mQ, it became apparent that certain HVAC system performance snapshots were showing results that were either unreasonable or not physically possible. Further examination of specific snapshots revealed that user errors of either the Bluetooth probes or the app were to blame for the spurious results. To clean the data of these HVAC performance snapshots containing user errors, the Southface Team devised a total of 12 filters (plus one pre-filter that removed blank snapshots) that each snapshot had to pass through to be used in the full analysis. The filters and reasoning behind each are shown in Table 9. Power measurements were optional in these workflows and did not affect calculations outside of power metric outputs, so power measurement errors only resulted in the filtering of the EER, SEER, and fan efficacy. Also, because power measurements were optional, the denominator in the error rate calculations only included those snapshots where power was measured.

Table 9. User Error Filters and Outcome

Filter Number	Filter Name	Filter Reasoning	Filter Criteria	Snapshot Outcome
1	Tonnage Error	User accidentally left tonnage at default value of 1, leading to skewed calculations	Tonnage is left at default value of 1	Full Snapshot Removed
2	TESP Error	Manometers being used incorrectly leads to inaccurate TESP readings	TESP reading is below 0.2 or above 2.0 inches w.c.	TESP Tool Readings Removed
3	Line Temp Error	The suction line and liquid line clamps have been swapped, leading to inaccurate calculations	Suction line temperature is higher than liquid line temperature	Full Snapshot Removed
4	Power Measurement Error	Unrealistic power readings indicate that AHU and condensing unit readings are	AHU power is within 20% of the	EER and SEER efficiency

Filter Number	Filter Name	Filter Reasoning	Filter Criteria	Snapshot Outcome
		either swapped, duplicated, or another error was made	condensing unit power	readings Removed
5	Efficiency Error	Unrealistic EER is outside of ±50% of mQ predicted EER, indicating AHU/condensing unit power measurement error or return/supply T/RH probe error	EER is >150% or <50% of mQ predicted EER	Full Snapshot Removed
6	Fan Watt Draw Error	Unrealistic fan watt draw readings lead to inaccurate efficiency calculations	Watts/CFM reads below 0.2 or above 1.5	EER, SEER, and Fan Efficacy readings Removed
7	Non-Residential Check	While not truly an error, non-residential units are not part of this study	Tonnage is greater than 5	Full Snapshot Removed
8	Negative Temperature Split	Negative temperature split indicates an air-source heat pump (ASHP) is being tested in heating mode using a workflow intended for cooling	Temperature split is less than 2°F	Full Snapshot Removed
9	Outside Temp. Too Low	Low outside temperature does not allow for proper testing of an air conditioning system or ASHP in cooling mode	Outside Temperature is less than 55°F	Full Snapshot Removed
10	Return or Supply Probe Error	Either the return or supply air probe is missing a temperature or humidity reading, making accurate capacity calculations impossible	Snapshot is missing at least one temperature or humidity readings from either the supply or return	Full Snapshot Removed
11	Unrealistic % of Total Capacity	Unrealistically high % of total capacity indicates some app or tool error was made	% of total capacity is greater or equal to 200%	Full Snapshot Removed
12	Negative Latent Capacity	A negative latent capacity indicates system is not stable and water is evaporating from the evaporator coil	Latent capacity is below zero	Full Snapshot Removed

2.2.2 HVAC System Performance Analysis

After filtering out all data containing identifiable tool or app user errors, the Southface Team analyzed the cleaned data. The mQ HVAC performance data used in this study were divided into two types:

1. New system commissioning
2. Existing system tune-up/retrocommissioning.

For 1, the contractors followed the “New A/C or Heat Pump Installation” workflow, and for 2, the contractors followed the “Quick A/C or Heat Pump Service” workflow, as seen in Figure 3.

After cleaning the data, the Southface Team performed statistical analyses on each data set. For 1, averages for collected metrics (Table 2) were calculated by contractor group, climate zone, and overall. Standard deviations for each metric were calculated based on the overall data set. One additional metric was calculated that used the measured superheat and subcooling of each system to determine the percentage of systems with correct refrigerant charge. Correct refrigerant charge was defined as ±3°F of the subcooling target for thermostatic expansion valve, electronic expansion valve, and automatic expansion valve systems and ±5°F of the superheat target for fixed metering device systems. The calculated averages could then be compared to industry average baseline field data.

For 2, the same analysis was performed along with pre and post comparisons and a t-test. Because 2 contains performance snapshots both before and after the tune-up occurred, it was possible to calculate the average effect the tune-up/retrocommissioning service had on the existing system performance. A t-test, which compares the means of two groups (pre and post), was then used to determine if this change was statistically significant. For all tests performed in this study, the confidence level is 90%.

2.2.3 Internal measureQuick Calculations

Some of the metrics gathered in each mQ snapshot are calculated in real time while the user is making measurements (Table 2). Further detail on how each of these is calculated is provided below.

Normalized Capacity Target

The normalized capacity target calculation is a trade secret; however, it employs equations similar to those that Carrier and other manufacturers use for extended performance tables. It can correct for:

- Outdoor air temperature
- Indoor return air conditions
- Indoor airflow

- Line set length and lift
- Voltage.

Corrections are made only if the required Bluetooth tools are streaming the data required for each correction. The more Bluetooth tools are connected and measurements provided, the more the above corrections are able to be applied and the more refined the normalized capacity becomes. The normalization procedure begins with the user-inputted nameplate capacity and target airflow (in CFM/ton).[12] If target airflow is not specified, mQ defaults to 400 CFM/ton. The target temperature split is then calculated, and the resulting sensible and latent capacities are derived from total capacity available based on the current outdoor air temperature and the current load. Total capacity is a combination of sensible and latent capacities, however latent capacity is only realized when the evaporator coil temperature is lower than the return air dewpoint. Therefore, it is recommended to evaluate true performance and to make comparisons between systems using sensible capacity only, as latent is available capacity that may or may not be used. The above normalization procedure was tested at and compared with NIST calculations, showing very similar outputs. This was also verified by a third-party PE, however the detailed results were not published.[13]

CFM/Nameplate Tonnage

The procedure used to estimate CFM in mQ is a trade secret that has been refined over the years to account for many variables and conditions, but in essence an energy and mass balance is performed across the evaporator coil to solve for CFM/ton. The ASHRAE 2021 Fundamentals Psychrometric equations are used for almost every calculation in mQ.

For the CFM/ton estimation to work, hygrometer probe placement is critical. The supply probe must be inserted up into the supply register closest to the AHU, and the return air probe should be located at the face of the return grille (Figure 5). The supply probe must be inserted into the supply register so that a mixed air temperature is not measured at the face of the register due to air entrainment. The probe can also be radiantly cooled by the evaporator coil, so it is also important to not get too close to the evaporator coil. mQ can use up to four supply probes and four return probes that get averaged for the calculations, but in almost every instance with proper probe placement, only one probe for supply and return is needed.

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[12] The options for user-selected target airflow are <360 SCFM/ton, 360 to 440 SCFM/ton (400 SCFM/ton ±10%), and >440 SCFM/ton with in-app guidance based on climate region.

[13] A summary of the results can be seen here, but no formal report was published. We recommend a published study of the accuracy in the Discussion section under Future Work: https://www.linkedin.com/pulse/measurequick-tested-nist-jim-bergmann/?trackingId=HjID73sfRTiu8gzk4BuRRA%3D%3D.

CFM

Once CFM/nameplate tonnage is calculated, CFM is calculated simply by multiplying by the nameplate tonnage.

Capacity (Sensible/Latent/Total)

Delivered capacity is calculated by multiplying the estimated CFM (above) by the difference in enthalpies using the supply and return T/RH probe measurements.

Percent of Normalized Capacity

Once the normalized capacity target is calculated (above), the percent of normalized capacity is calculated by dividing the delivered total capacity of the system by the normalized capacity target.

Fan Efficacy (Watts/CFM)

This calculation uses the wattage of the air handler, measured by a power quality meter that incorporates power factor, and divides it by the CFM (calculated above).

EER

This calculation divides the delivered capacity in Btu/hr at the current conditions by the combined wattage of the AHU and condensing unit, measured by a power quality meter that includes power factor.

SEER

A generic compressor map is used to normalize the above EER at current operating conditions to those at AHRI conditions (this process has been patented) and then the below formula is used to solve for SEER (Hendron et al. 2010):

$$EER = -0.02 \times SEER^2 + 1.12 \times SEER$$

2.3 Non-Energy (Business) Impact Analysis

Data collected in one-on-one interviews with BPPs and via online surveys and in-person questionnaires for at-large contractors were gathered from fall 2022 through winter 2023. Across all data sets, responses were aggregated and anonymized. Where possible, data responses from aligned questions were merged to present a larger data set.

3 Results

3.1 Energy/HVAC Performance Impact Results

3.1.1 User Error Data Cleaning Results

Filtering the raw data provided by mQ reduced the total number of usable HVAC performance snapshots (observations) for research purposes. However, the results of the filtering provided key insights into the usage of the app by the various contractor groups. Descriptions of each of the filters and filter criteria can be seen in Section 2.2.1.

The at-large group had the lowest rate of user errors (Table 10 and Table 11). This group included self-selected individual mQ users who responded to a limited-time offer, so it makes intuitive sense that they would, on average, be more individually motivated to correctly learn and use the app. The other BPP groups included technicians on larger teams who were required to use the workflows as part of their company's policies. In their case, the value of the app is apparent to the managers but less apparent to the actual technicians using the tool. BPP #2 and BPP #6 had the highest error rates, with some fan watt draw and power errors exceeding 60%, indicating systemic tool usage issues that need to be corrected with further training. Technicians appeared to have the greatest difficulty correctly measuring system power (Filter 4), and AHU power, in particular (Filter 6).

The results from this user error analysis led to several of the filters being incorporated into the app, alerting the user of potential probe placement errors and measurement errors before an HVAC performance snapshot is taken. Additionally, feedback from the analysis was provided by mQ to each of the BPPs to address and improve systemic user errors and technician training. The results also have informed general mQ training overall.

3.1.1.1 New System Commissioning User Errors

Of the 2,741 total new system commissioning performance snapshots (observations), 40 observations were removed by the blank entry pre-filter, or 1.5% of the total observations. 2,265 remained after subsequent filtering for user errors. Thus, 83.9% of the non-blank new installation snapshots were free from identifiable user errors. The filters are all independent of one another and not additive, so the same observation likely triggers multiple filters in many instances (specifically filters 4, 5, and 6 due to their similarity). The "Overall" column is a weighted average of each groups' error rates, weighted by the total number of snapshots.

The most common error in new system commissioning was the fan watt draw error at 33.58%. The second most common was the power measurement error at 10.47%. BPP #2's and #6's error rates for filters 4, 5, and 6 indicate a systemic power measurement issue that requires additional technician training. To a lesser extent, BPPs #3, #4, and

#5 had this issue as well. Contractors, on average, had the lowest error rates in using line temp clamps with new installs. The at-large group had the lowest average error rate of the different contractor groups for new system commissioning.

Table 10. New System Commissioning User Error Rates

Filter #	Filter Name	At-Large (n = 143)	BPP #1 (n = 170)	BPP #2 (n = 217)	BPP #3 (n = 768)	BPP #4 (n = 130)	BPP #5 (n = 751)	BPP #6 (n = 97)	BPP #7 (n = 425)	Overall (n = 2,701)
		All values listed are percentages (%)								
1	Tonnage Error	0.70	0.00	16.13	0.00	5.38	0.00	2.06	0.94	**1.81**
2	TESP Error	4.35	21.30	0.00	0.00	15.91	2.32	4.17	2.40	**3.75**
3	Line Temp Error	0.70	1.18	4.65	0.00	4.84	0.40	1.03	0.00	**0.86**
4	Power Measurement Error	0.00	6.34	63.20	8.09	24.47	6.26	31.37	1.82	**10.47**
5	Efficiency Error	1.80	3.50	36.80	0.00	10.64	0.00	31.37	2.86	**4.40**
6	Fan Watt Draw Error	7.63	25.31	73.88	44.83	28.97	33.64	43.08	15.30	**33.58**
7	Non-Residential Check	0.00	0.00	0.00	0.26	0.77	0.00	0.00	0.00	**0.11**
8	Negative Temperature Split	0.70	1.76	2.76	5.60	6.92	0.40	5.15	0.71	**2.70**
9	Outside Temp. Too Low	4.26	2.47	3.72	6.58	0.83	1.48	2.17	2.13	**3.35**
10	Return or Supply Probe Error	0.70	0.59	0.92	4.17	3.85	0.27	4.12	0.00	**1.74**
11	Unrealistic % of Total Capacity	0.00	0.00	0.94	0.28	0.00	0.00	0.00	0.24	**0.19**
12	Negative Latent Capacity	0.70	2.35	0.46	4.95	3.85	4.79	6.19	3.06	**3.85**

3.1.1.2 Tune-up/Retrocommissioning User Errors

Of the 34,157 total tune-up observations, 7,930 or 23% were removed by the blank entry pre-filter, and 8,572 observations remained after error filtering. Thus, 32.7% of the non-blank tune-up snapshots were free from identifiable user errors. Within this cleaned data set, the Southface Team identified 608 valid pre and post tune-up snapshot pairs. Measuring system improvement requires two snapshots on the same system occurring at different times. Some systems were only measured once, and others were measured two or more times (resulting in large numbers of duplicates). For instance, where there were more than two snapshots for the same system, the first and last snapshots were used. The error filters are all independent of one another and not additive, so the same observation likely triggers multiple filters in many instances (specifically filters 4, 5, and 6 due to their similarity). The "Overall" column is a weighted average of each groups' error rates, weighted by the number of snapshots.

The most common error in tune-up/retrocommissioning was the fan watt draw error at 31.44%. The second most common error was the return or supply probe error at 20.54%. This indicates that many technicians, specifically for BPPs #1–7, were either misusing hygrometer probes or had probes that were damaged, causing the capacity calculations to be inaccurate. BPPs #1–7 also had high rates of power measurement error, indicating a need for corrective training. Contractors, on average, had the lowest error rates in the low outdoor air testing category and in measuring TESP for tune-ups. The at-large group had the lowest average error rate of the different contractor groups for tune-ups.

Table 11. Tune-up/Retrocommissioning User Error Rates

Filter #	Filter Name	At-Large (n = 1,746)	BPP #1 (n = 1,846)	BPP #2 (n = 1,938)	BPP #3 (n = 5,497)	BPP #4 (n = 1,882)	BPP #5 (n = 7,840)	BPP #6 (n = 2,307)	BPP #7 (n = 1,268)	BPP #8 (n = 1,903)	Overall (n = 26,227)
		All values listed are percentages (%)									
1	Tonnage Error	0.69	8.34	23.53	11.59	13.28	10.55	20.58	18.34	2.34	**11.44**
2	TESP Error	3.87	3.29	4.24	3.97	4.60	2.25	3.88	1.37	0.67	**2.71**
3	Line Temp Error	2.16	5.63	7.90	7.43	8.09	3.85	3.97	6.30	3.99	**5.31**
4	Power Measurement Error	2.07	40.10	35.19	30.61	18.54	14.29	62.62	6.78	2.51	**17.94**

Filter #	Filter Name	At-Large (n = 1,746)	BPP #1 (n = 1,846)	BPP #2 (n = 1,938)	BPP #3 (n = 5,497)	BPP #4 (n = 1,882)	BPP #5 (n = 7,840)	BPP #6 (n = 2,307)	BPP #7 (n = 1,268)	BPP #8 (n = 1,903)	Overall (n = 26,227)
		All values listed are percentages (%)									
5	Efficiency Error	5.27	17.01	40.43	23.83	19.36	8.52	39.10	34.92	6.88	**17.81**
6	Fan Watt Draw Error	10.57	53.20	43.79	39.53	20.47	35.33	63.97	31.40	15.40	**31.44**
7	Non-Residential Check	1.15	0.05	0.26	0.13	0.69	0.17	0.22	0.16	0.16	**0.26**
8	Negative Temp. Split	2.05	32.33	10.86	9.16	9.69	5.41	4.62	6.93	1.05	**6.44**
9	Outside Temp. Too Low	4.63	0.73	1.65	2.23	2.24	2.86	0.83	2.78	4.11	**2.66**
10	Return or Supply Probe Error	2.00	25.46	23.48	31.40	20.88	20.28	24.53	20.55	0.69	**20.54**
11	Unrealistic % of Total Capacity	0.23	0.33	0.00	0.64	0.59	0.09	0.65	1.48	0.22	**0.40**
12	Negative Latent Capacity	1.36	10.81	11.63	11.47	6.61	13.01	5.80	9.31	2.53	**8.56**

3.1.2 New System Commissioning Results

After user errors were cleaned from the data set, the overall averages for each metric collected (metrics explained in Table 2) during new system commissioning were calculated (Table 12). Table 12 lists n (number of snapshots/observations), mean (or average), and standard deviation (Std Dev) for each metric. Note that some variables such as EER and SEER have fewer observations than the rest of the table because only a subset of the projects made the power measurements necessary. Additionally, some of the user error filters only remove those power metrics containing the error and leave the rest of the snapshot. The average new system installed was 3.75 tons and achieved 94.2% of the sensible capacity target. The average airflow was 395.6 CFM/ton and the TESP was 0.55 inches w.c. Only a subset of the total sample had power measurements performed, and for these systems the average fan efficacy was 0.415 watts/CFM, the EER was 11.50, and the estimated SEER was 12.78. Additional metrics can be seen in the table.

Table 12. New System Commissioning Results

Metric	n	Mean	Std Dev.
Nameplate Tonnage	2,265	3.75	0.908
% of Nameplate Tonnage	2,265	83.2%	16.0%
Total External Static Pressure (inches w.c.)	1,681	0.55	0.249
Normalized Tonnage Target (tons)	2,265	3.44	0.848
% of Normalized Total Capacity	2,265	90.5%	16.4%
% of Normalized Sensible Capacity	2,265	94.2%	13.7%
% of Normalized Latent Capacity	2,223	88.5%	530.0%
Sensible Heat Ratio (SHR)	2,265	0.848	0.142
CFM	2,265	1,583.7	448.93
CFM/Nameplate Tonnage (CFM/ton)	2,055	395.6	65.25
Fan Efficacy (Watts/CFM)	1,273	0.415	0.224
EER	1,161	11.50	3.091
SEER (approximation)	1,161	12.78	3.434
Subcooling (°F)	2,265	7.61	4.248
Superheat (°F)	2265	8.53	8.174
% of Systems with Correct Refrigerant Charge	2265	76.9%	n/a

The above data set was disaggregated by both contractor group and by Building America climate zone[14] to observe any trends present. Also, histograms and box plots are presented for a visual representation of performance data distribution. For reference, the climate zone of each of the BPPs is given in Table 13. However, BPP #6 performs most of its service calls in the hot-dry climate, so there are very few marine climate performance snapshots.

[14] Building America Best Practices Series Volume 7.3: Guide to Determining Climate Regions by County. Pacific Northwest National Laboratory, August 2015. https://www.energy.gov/eere/buildings/articles/building-america-best-practices-series-volume-73-guide-determining-climate

Table 13. Building America and IECC Climate Zone for Each BPP

BPP	Building America Climate Zone	IECC Climate Zone
BPP #1	Hot-Humid	2A
BPP #2	Hot-Dry	3B
BPP #3	Hot-Dry	3B
BPP #4	Hot-Dry	3B
BPP #5	Hot-Dry	2B
BPP #6	Marine	3C
BPP #7	Hot-Dry	2B
BPP #8	Hot-Dry	3B

The number of snapshots (observations) from each contractor group can be seen in Figure 7, and the number of observations from each Building America climate zone can be seen in Figure 8. BPP #5 contributed the most to the study with 693 total observations, while BPP #6 had the least at 64. As seen in Figure 8, the data set is heavily weighted to the hot-dry climate, so overall average results must be interpreted with this in mind. BPP #8 did not use the new system commissioning workflow for installs, so they have no data presented in this section.

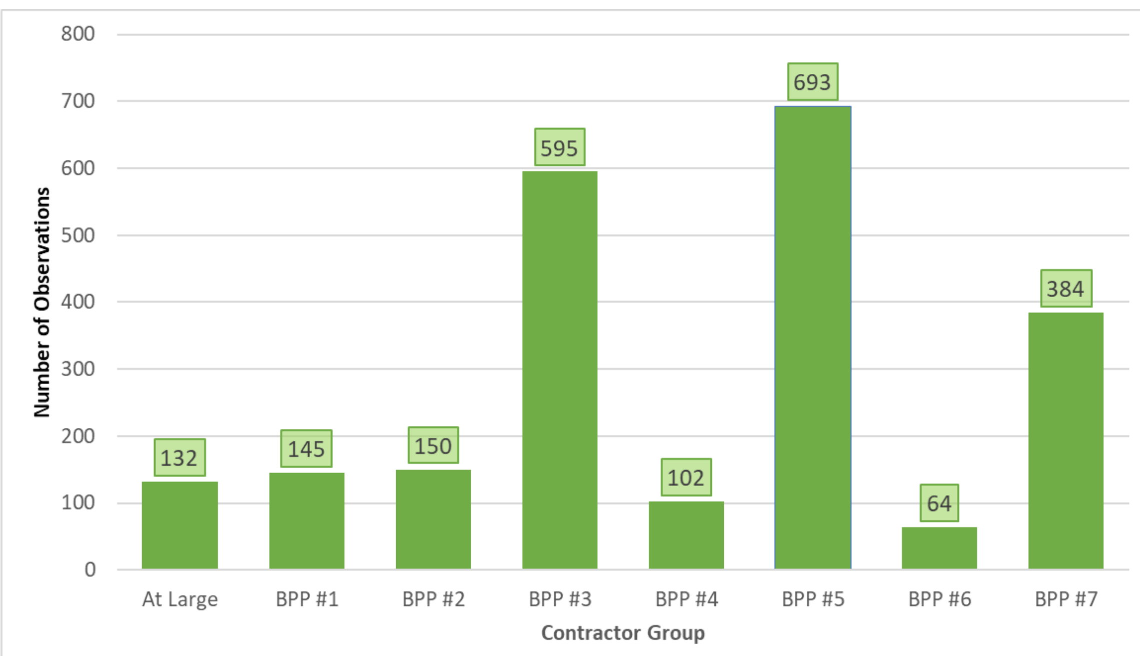

Figure 7. Number of new system observations by contractor group

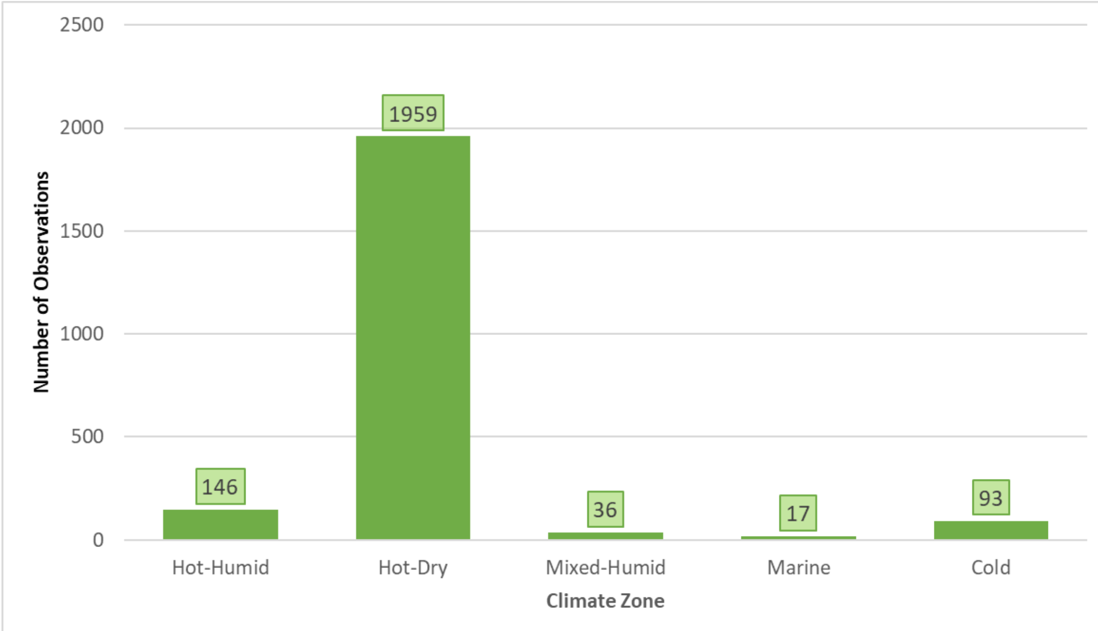

Figure 8. Number of new system observations by climate zone

Nameplate tonnage, which denotes the nominal capacity of the unit, is given in 0.5-ton discrete increments. The overall average for the study was 3.75 tons, which falls between the available 3.5- and 4-ton unit sizes. As seen in Figure 9, BPP #7 installed the largest units, with an average unit size of 3.96. The at-large group had the smallest average unit size of 2.86. Further observations by climate zone are shown in Figure 10. Mixed-humid and cold climates had the lowest average unit sizes, at 2.72 and 2.91, respectively. Hot-dry and marine climates had the largest average unit sizes. Figure 11 shows the overall nameplate tonnage distribution.

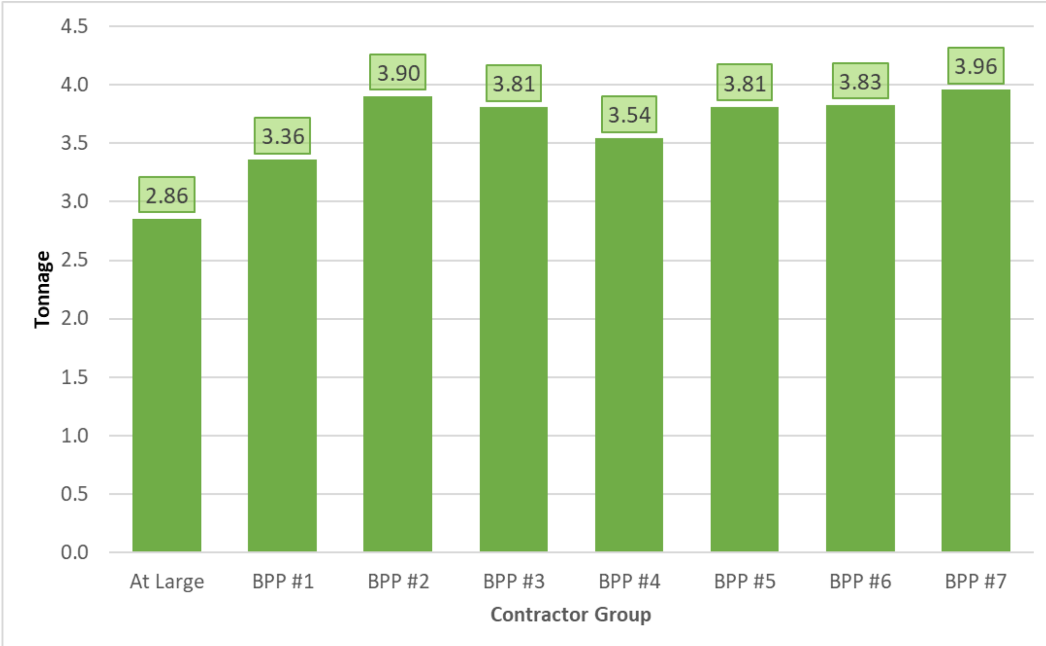

Figure 9. Nameplate tonnage by contractor group

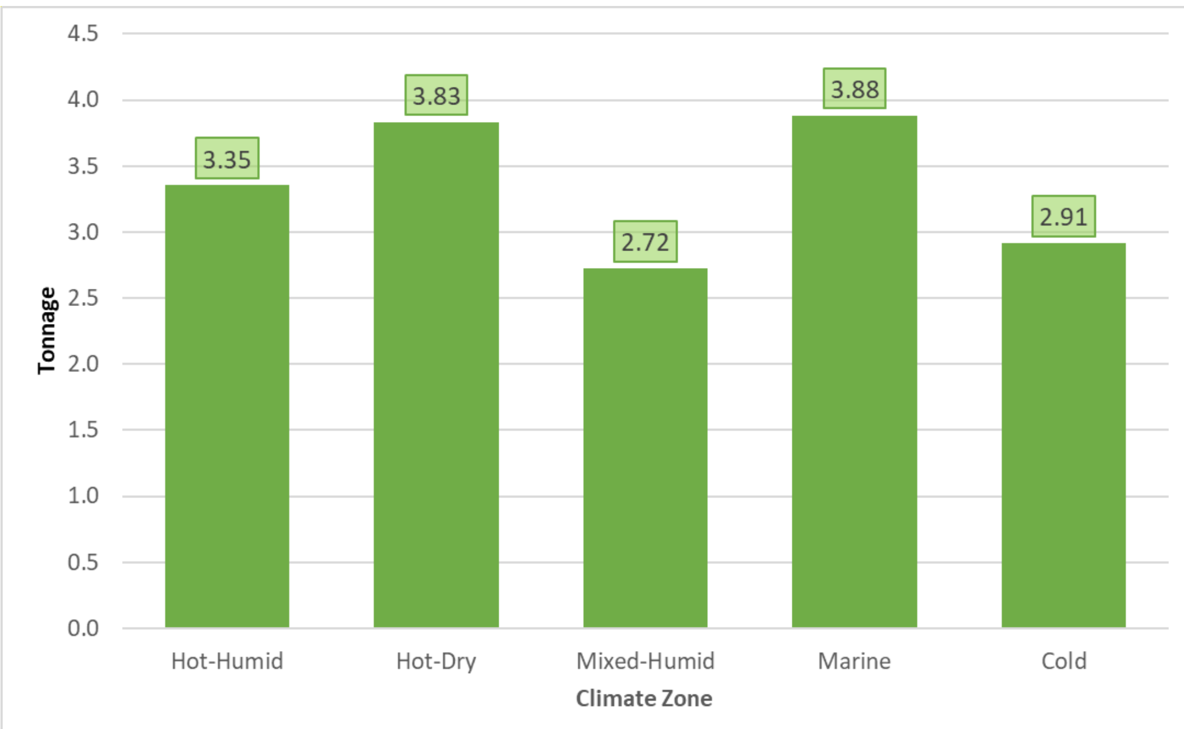

Figure 10. Nameplate tonnage by climate zone

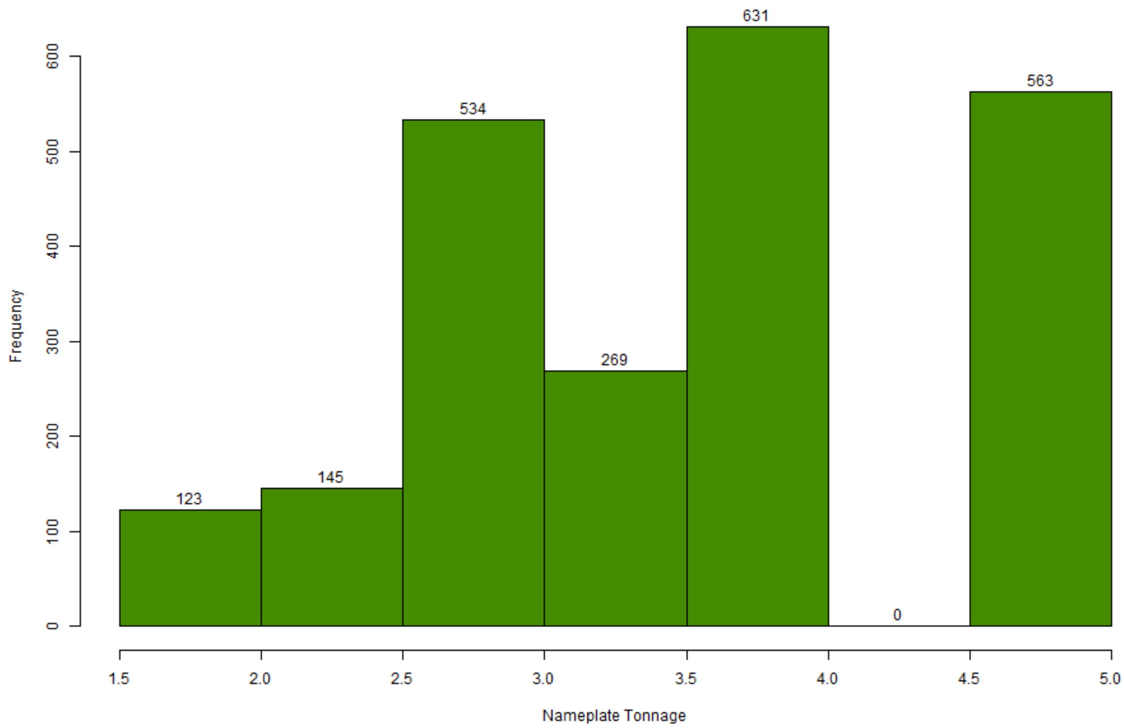

Figure 11. Nameplate tonnage distribution histogram

Figure 12 displays the breakdown by contractor group for TESP. It should be noted that BPP #2 did not record this metric, so the displayed average is zero. All groups are within ±0.08 of the 0.55 average, with the outlier being BPP #6 at 0.83 inches w.c.

Figure 13 shows the average by climate zone. Across climate zones, there is slight variation in the averages with the maximum occurring in the marine climate zone at 0.68 inches w.c. and the minimum occurring in hot-humid zone at 0.47 inches w.c. Figure 14 shows the overall TESP measurement distribution.

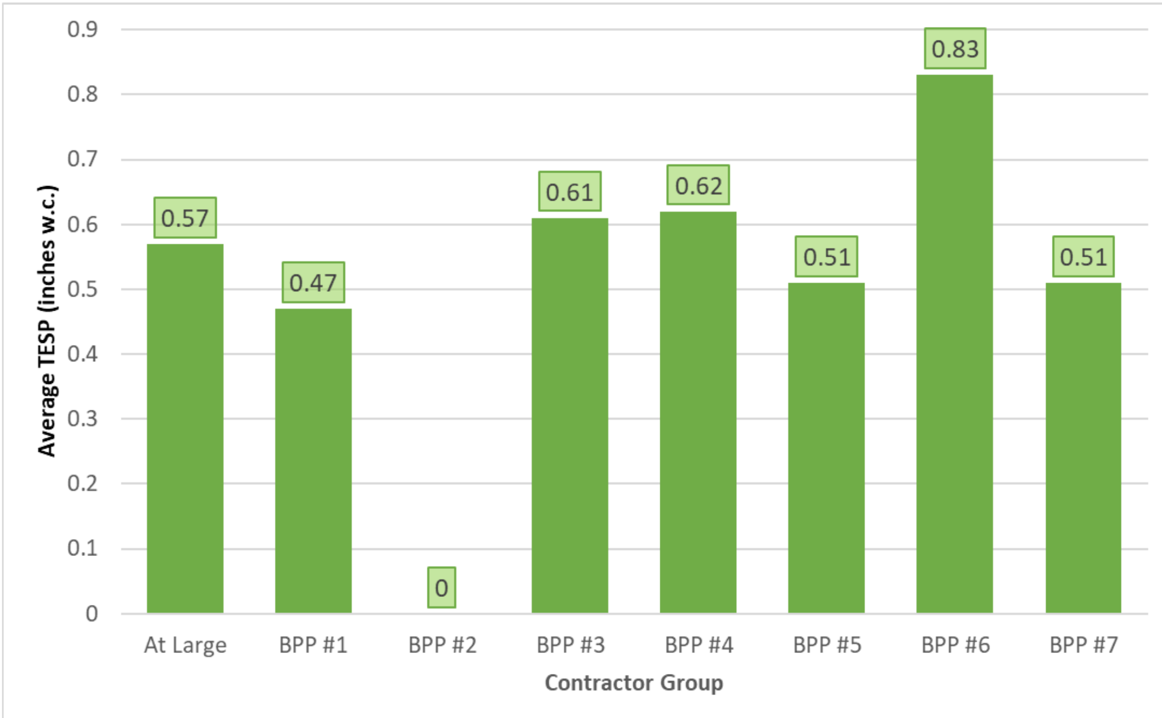

Figure 12. Average TESP measurement by contractor group

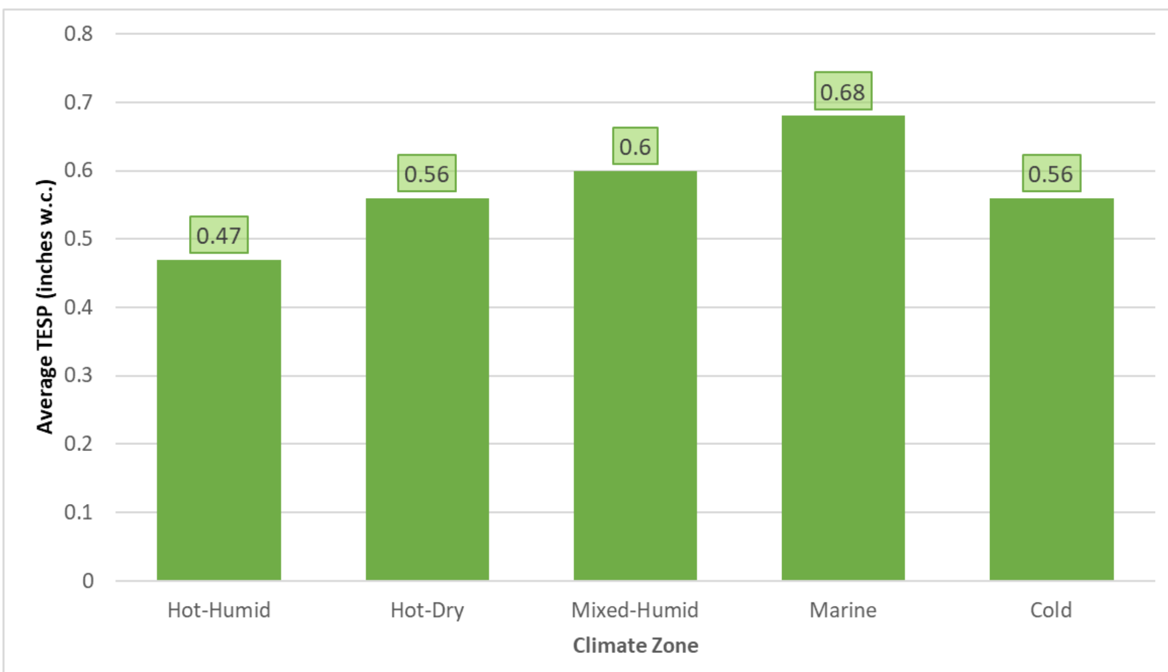

Figure 13. Average TESP measurement by climate zone

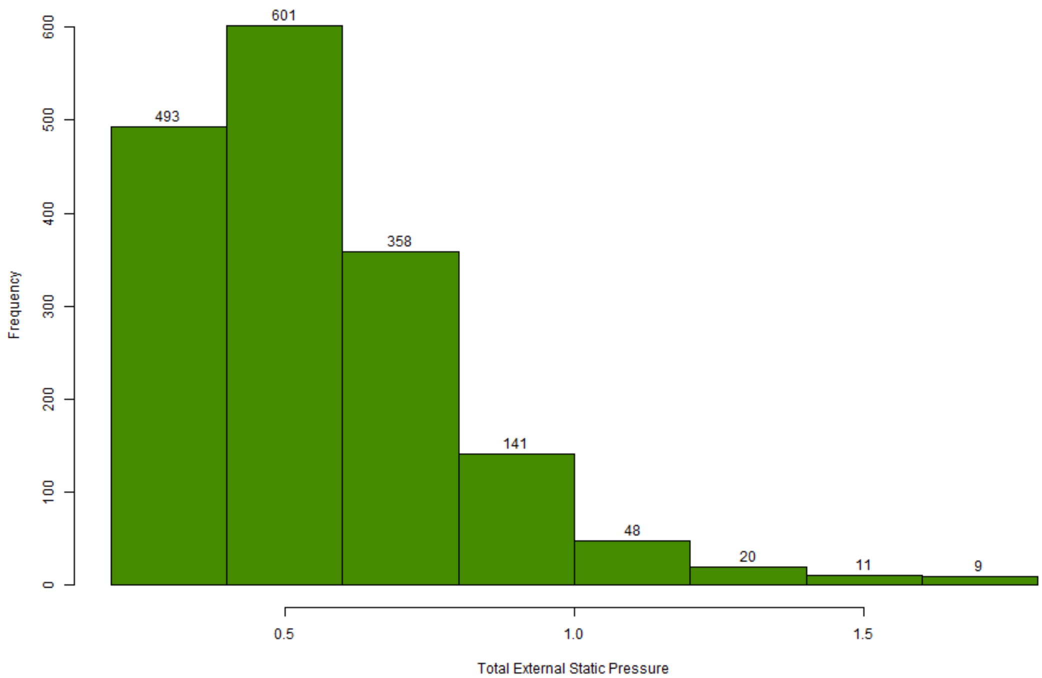

Figure 14. TESP measurement distribution histogram

The percent of total normalized capacity by contractor group is shown in Figure 15. BPP #2 had the highest average total capacity at 103.8%, and BPP #3 had the lowest average total capacity with an average of 84.2%. The overall average was 90.5%.

Figure 16 breaks down the same metric by climate zone. The Mixed-humid zone had the highest average at 103.2%, and hot-dry had the lowest at 89.2%. Figure 17 shows the percent of total normalized capacity distribution in a box plot. The average for the data set was 90.5%.

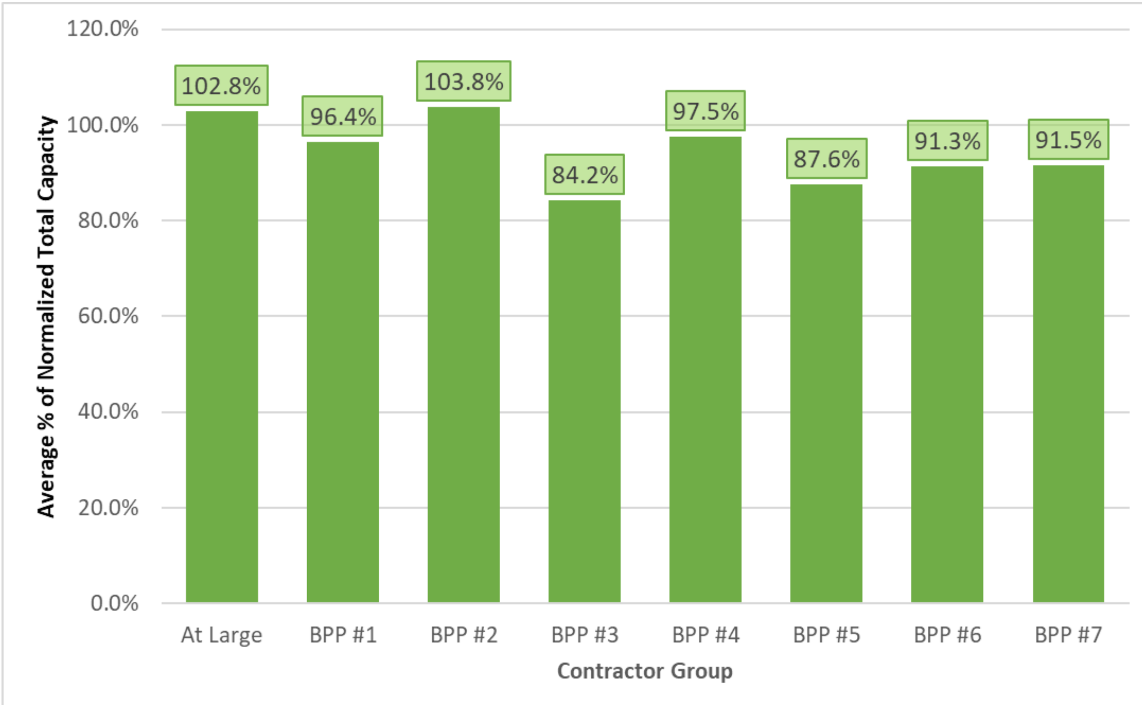

Figure 15. Average percent of total normalized capacity by contractor group

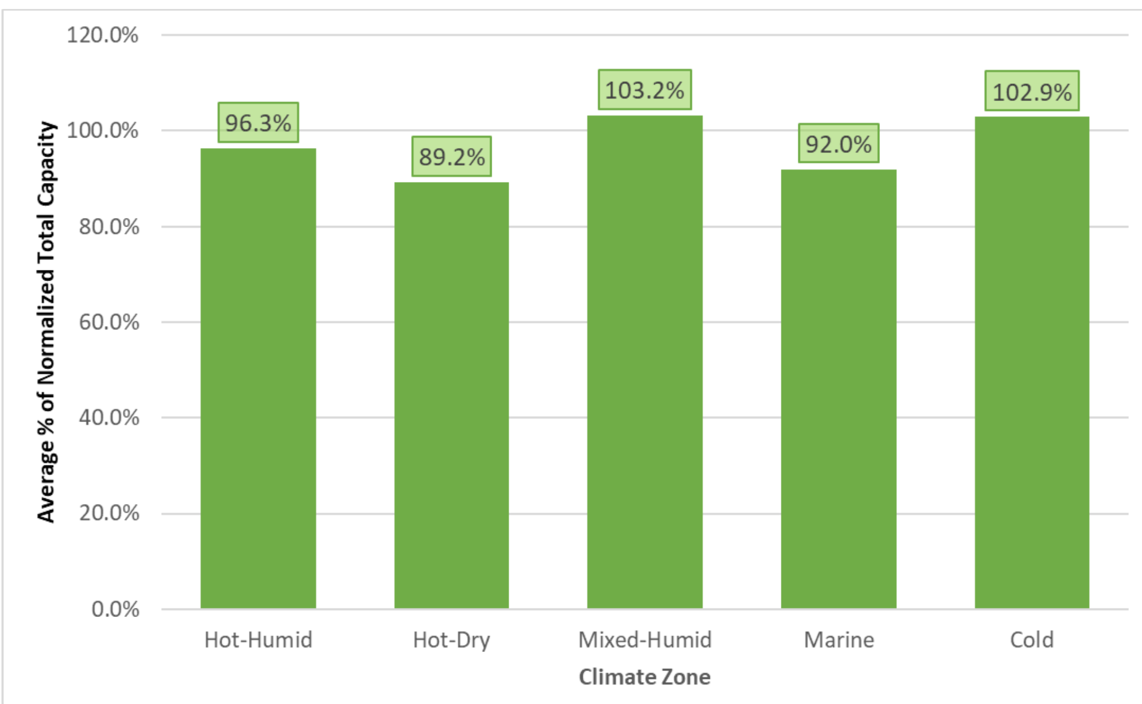

Figure 16. Average percent of total normalized capacity by climate zone

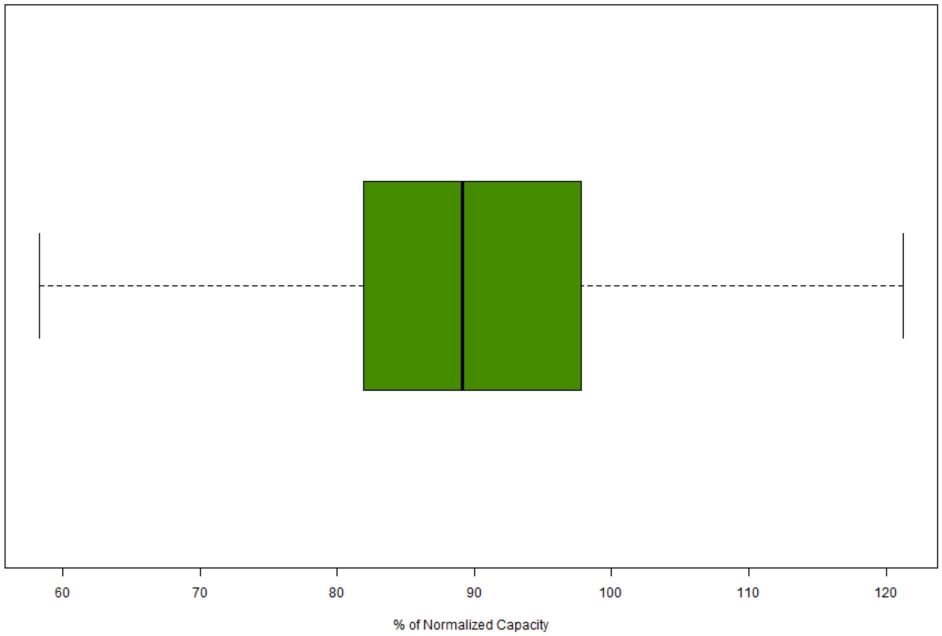

Figure 17. Percent of total normalized capacity box plot

As described in Section 2.2.3, total available capacity is a combination of both sensible and latent capacity, and latent capacity is only realized when the evaporator coil temperature is lower than the return air dewpoint. Therefore, total capacity can be misleading when comparing delivered capacities between systems, especially across climate zones such as hot-dry where latent capacity can often be zero. This volatility can be seen in the overall averages in Table 12, where the sensible capacity standard deviation (13.7%) is lower than the total capacity (16.4%) and an order of magnitude lower than the latent capacity standard deviation of 530%.

Figure 18 shows the percentage of normalized sensible capacity data broken down by contractor group, and Figure 20 shows the distribution in a box plot. There is a much tighter range for sensible capacity distribution when compared to the total capacity distribution in Figure 15 and Figure 17. This is the metric that mQ uses to determine if the delivered capacity is “acceptable.” It is considered acceptable if the percent of normalized sensible capacity is greater than 90%. The overall average for this data set is 94.2%. Figure 19 shows the average by climate zone, also showing a tighter distribution compared with the total capacity by climate zone (Figure 16).

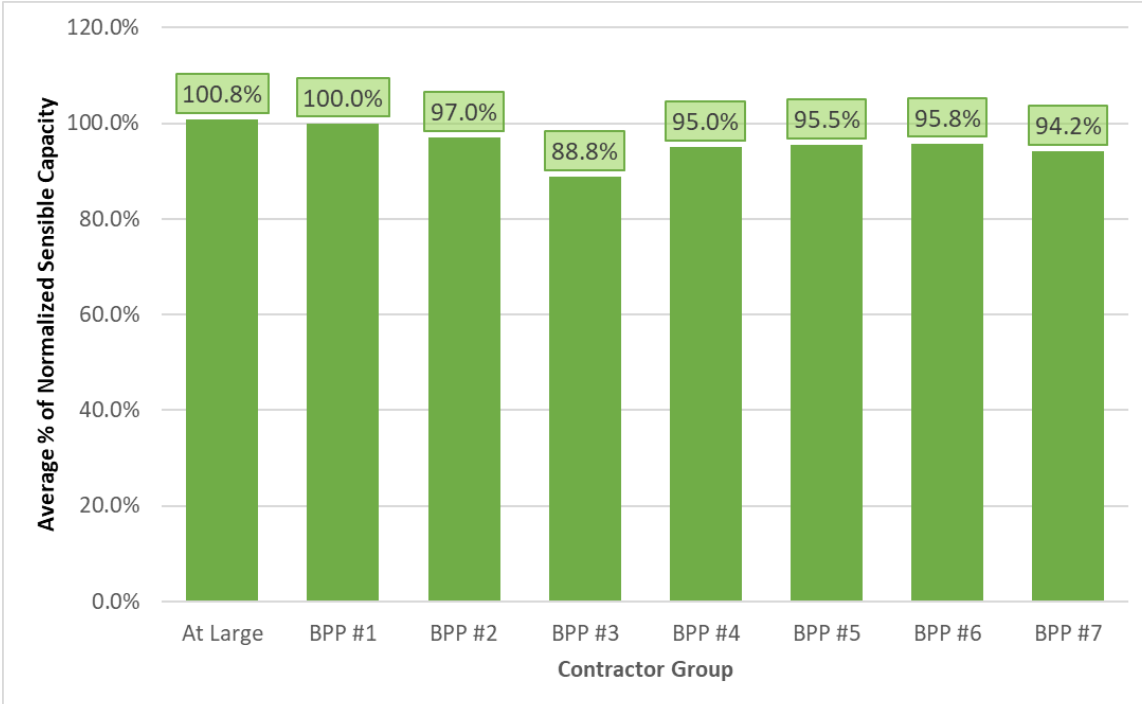

Figure 18. Average percent of normalized sensible capacity by contractor group

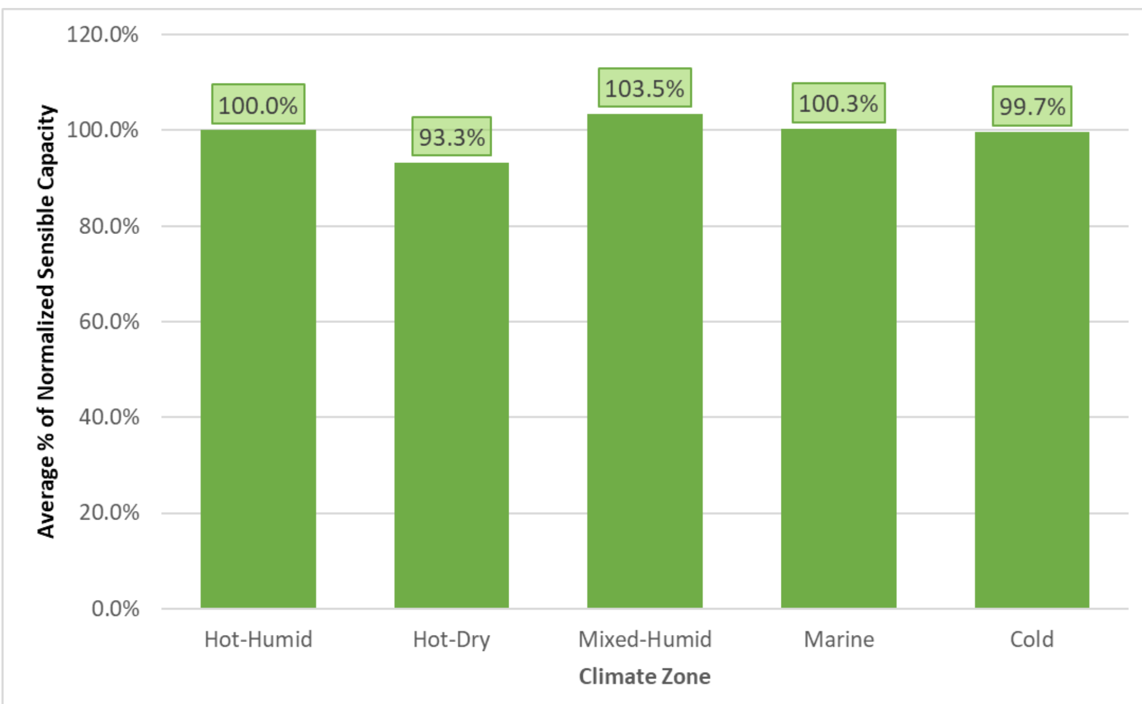

Figure 19. Average percent of normalized sensible capacity by climate zone

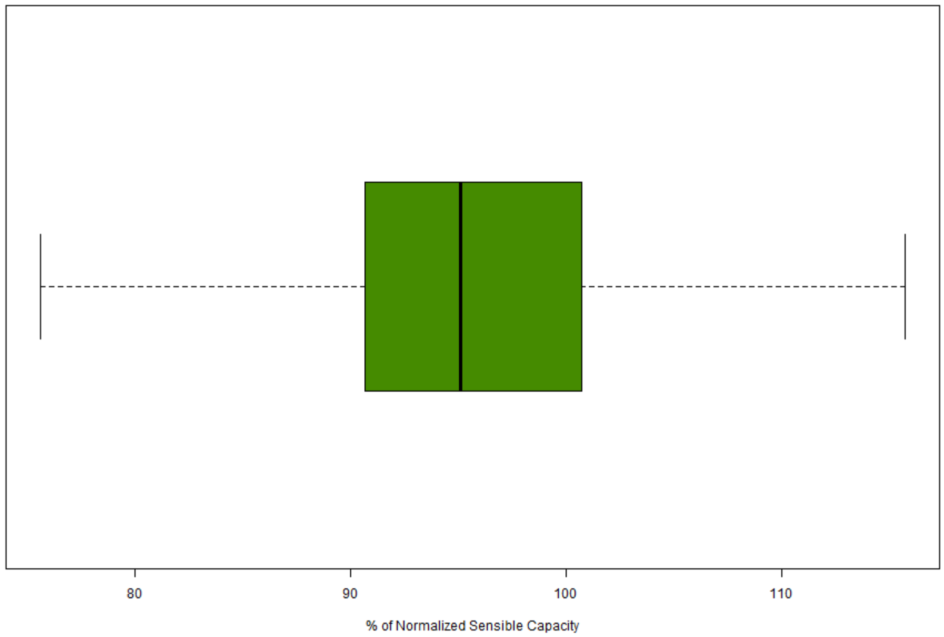

Figure 20. Percent of normalized sensible capacity box plot

The overall average sensible heat ratio (SHR) for the study was 0.848. Figure 21 shows the breakdown by contractor group, but Figure 22 shows an expected trend where it is disaggregated by climate zone. As expected, the highest average SHR is in the hot-dry climate. Figure 23 shows the SHR distribution for the entire data set.

Figure 21. Average SHR by contractor group

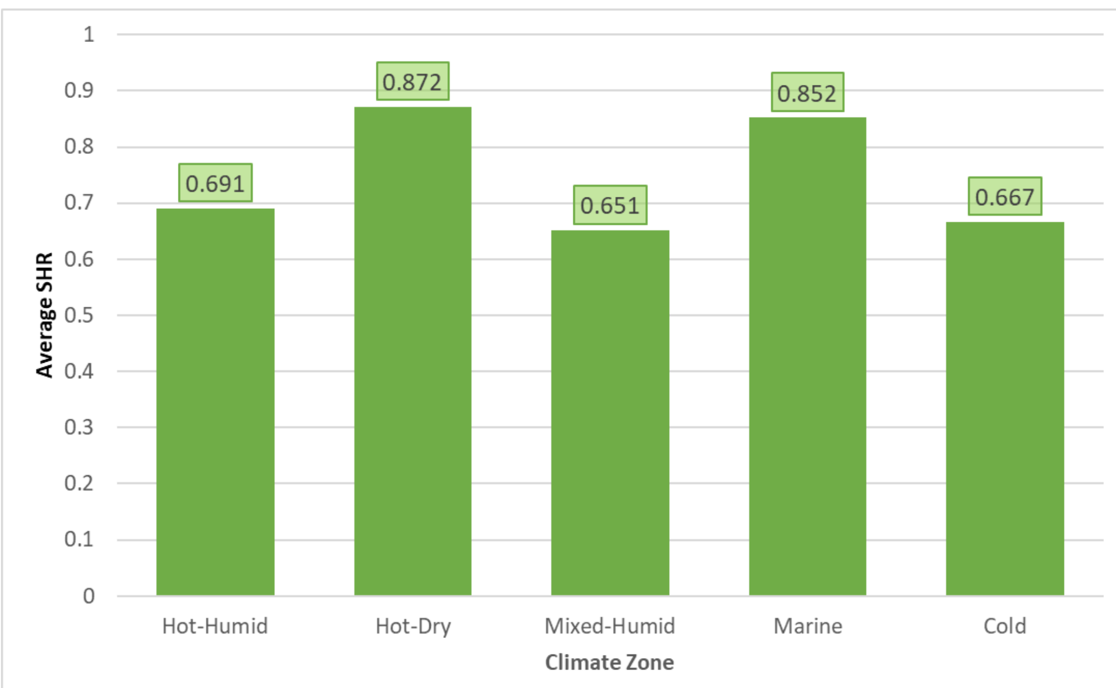

Figure 22. Average SHR by climate zone

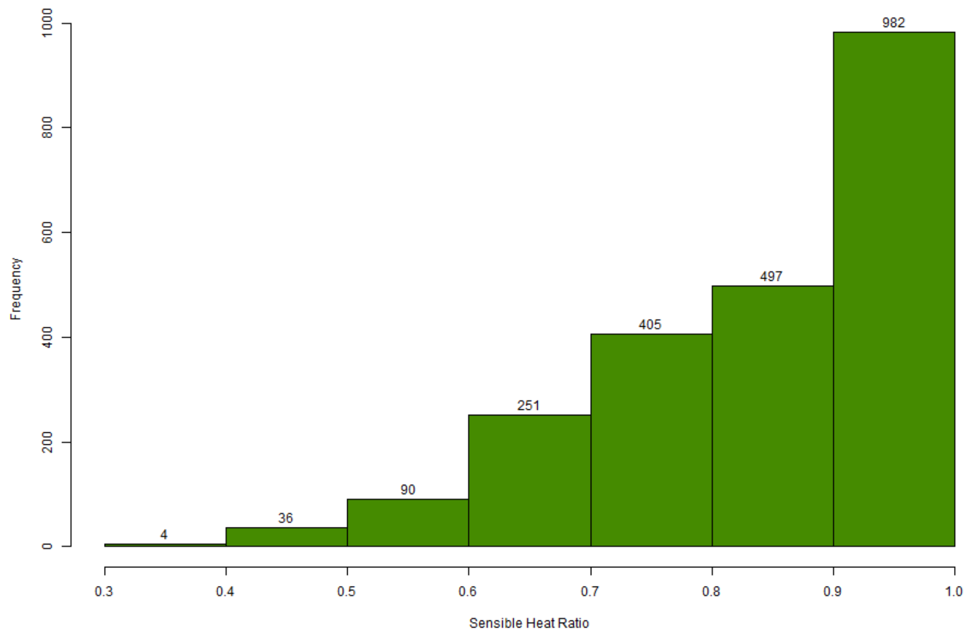

Figure 23. SHR distribution histogram

The overall average CFM/ton was 395.6. The recommended target airflows within the mQ app are 350 CFM/ton, 400 CFM/ton, and 450 CFM/ton based on climate region (Figure 24). 6.84% of commissioned systems were below 325 CFM/ton, and 22.8% were above 475 CFM/ton.

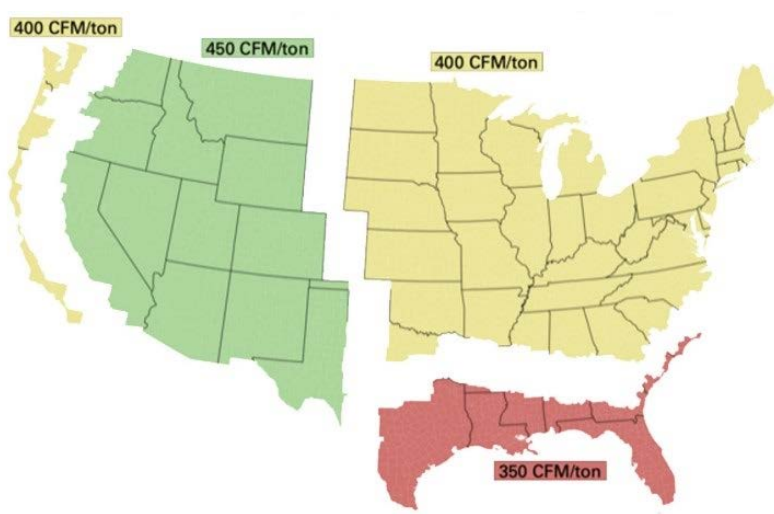

Figure 24. mQ in-app recommended target airflow by region

The averages by contractor group and by climate zone can be seen in Figure 25 and Figure 26, respectively. Hot-humid is the lowest and hot-dry is the highest, as expected. However, hot-humid would ideally be closer to 350 CFM/ton, and hot-dry closer to 450

CFM/ton. It is likely that many of the new systems commissioned in the hot-humid region are not dehumidifying as well as they could be.

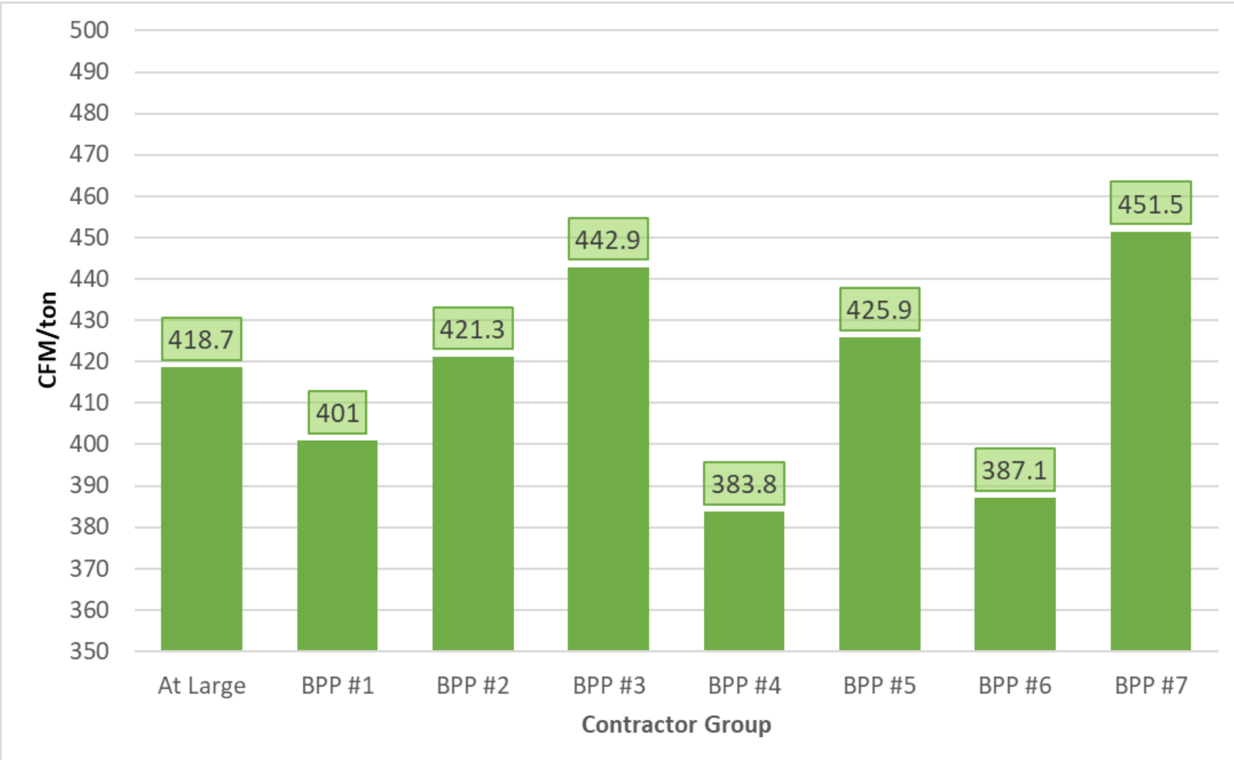

Figure 25. Average CFM/ton by contractor group

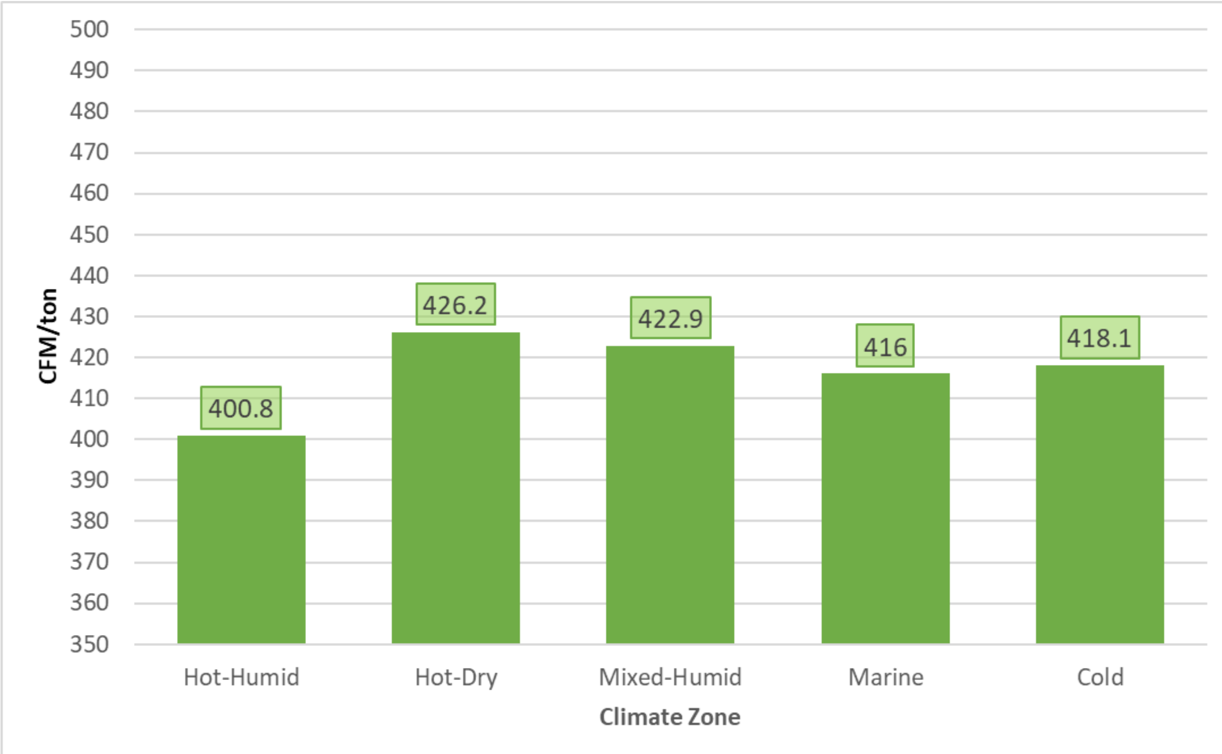

Figure 26. Average CFM/ton by climate zone

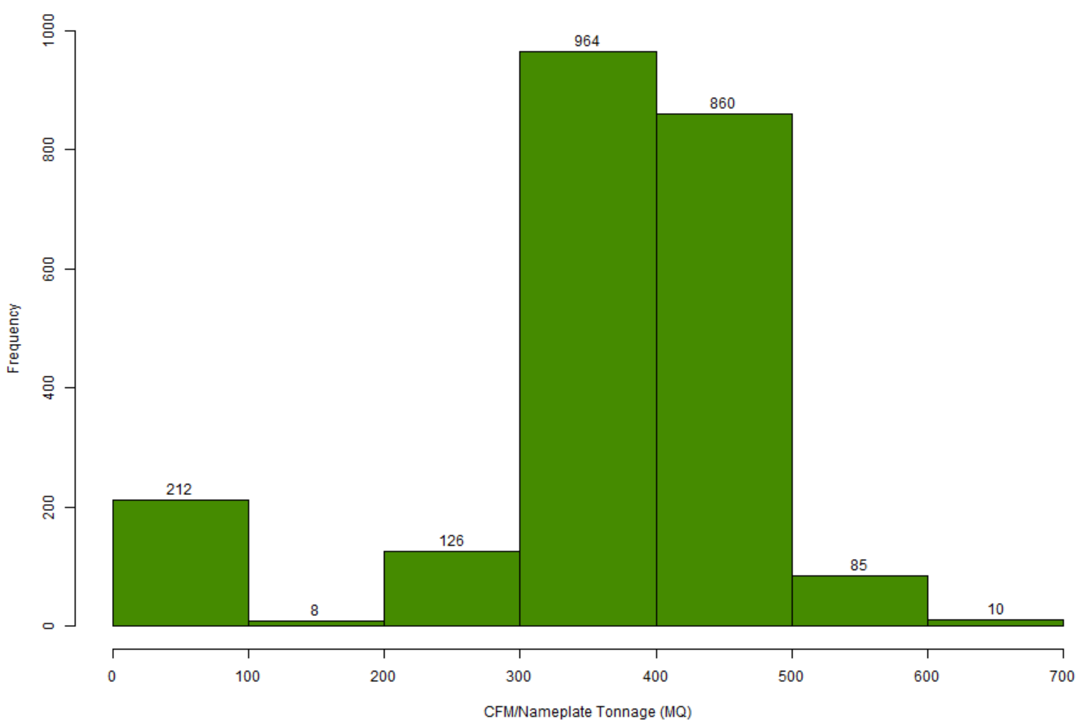

Figure 27. CFM/ton distribution histogram

The average fan efficacy recorded in the study is 0.415 watts/CFM. Figure 28 shows this metric by contractor group. BPP #2 reported the highest value at 0.783. All other groups fall within ±0.1 of the overall average. When broken down by climate group (Figure 29), the range narrows further. The highest and lowest values, cold and marine respectively, fall within ±0.08 of the average.

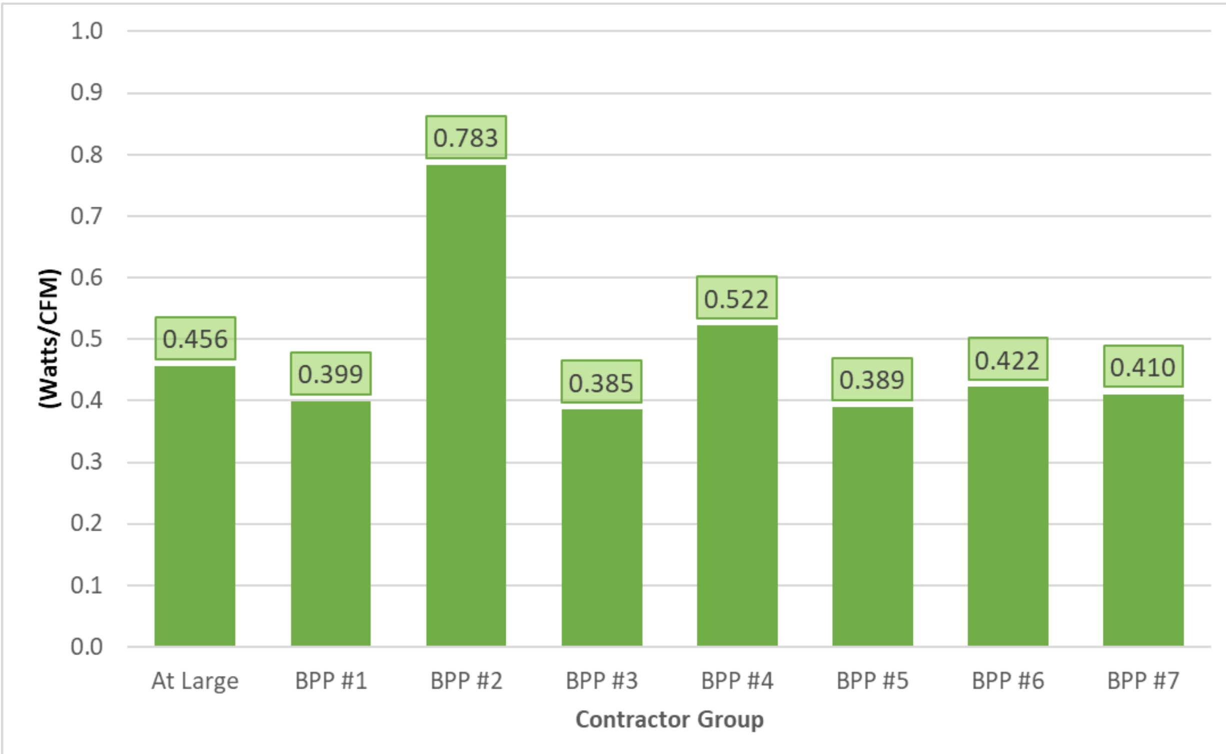

Figure 28. Fan efficacy by contractor group

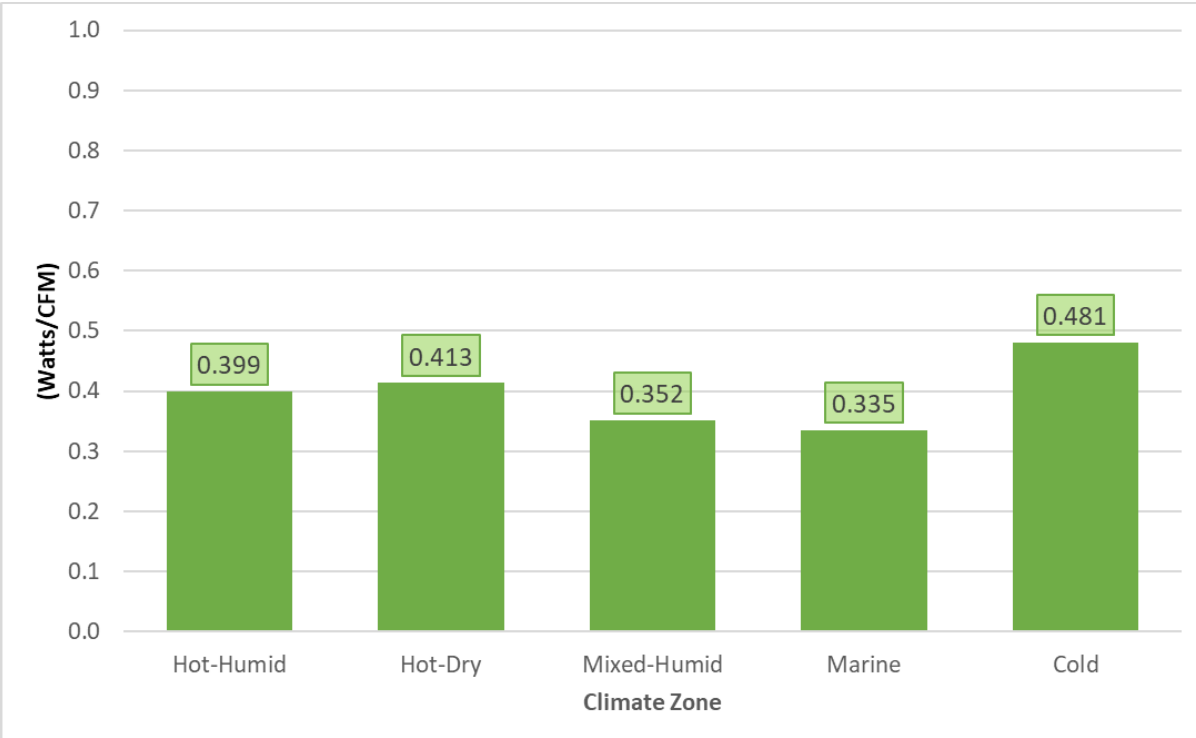

Figure 29. Fan efficacy by climate zone

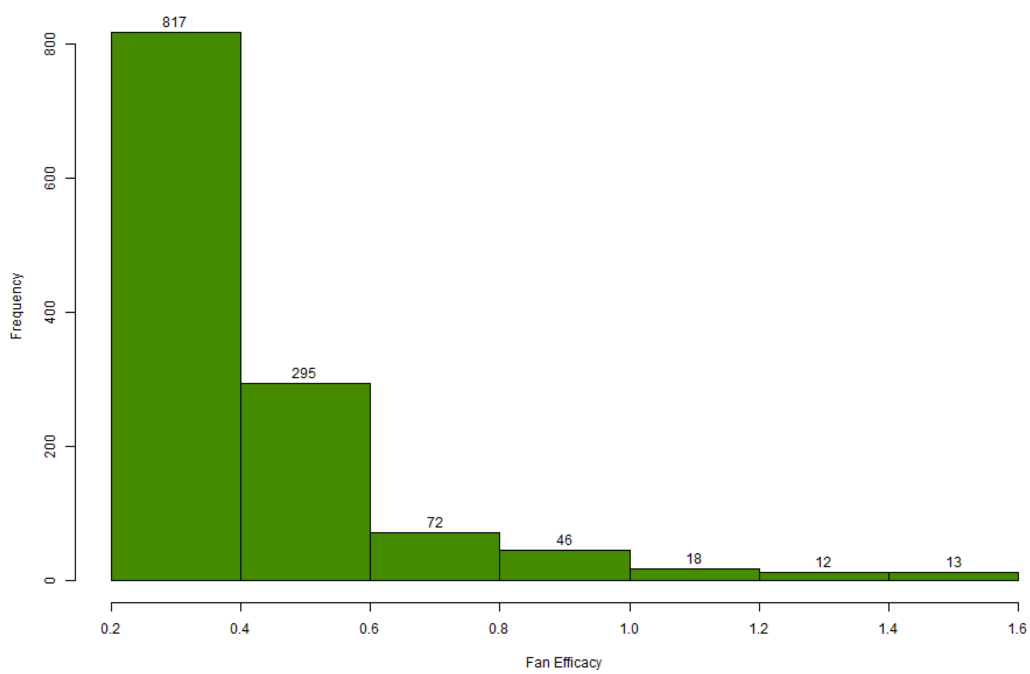

Figure 30. Fan efficacy distribution histogram

Out of all new installations in this study, 76.9% had the correct charge after commissioning. When disaggregated by contractor group (Figure 31), we can see that four out of the eight groups had correct charge on over 90% of installs. BPP #3 had the lowest rate with the correct charge at 76.64%. These results can be compared to the Building America residential HVAC fault baseline studies when published in 2024/2025.

Figure 32 shows the percentage by climate zone. The hot-humid climate had the highest percentage with correct charge at 95.7%, and hot-dry had the lowest percentage at 85.5%.

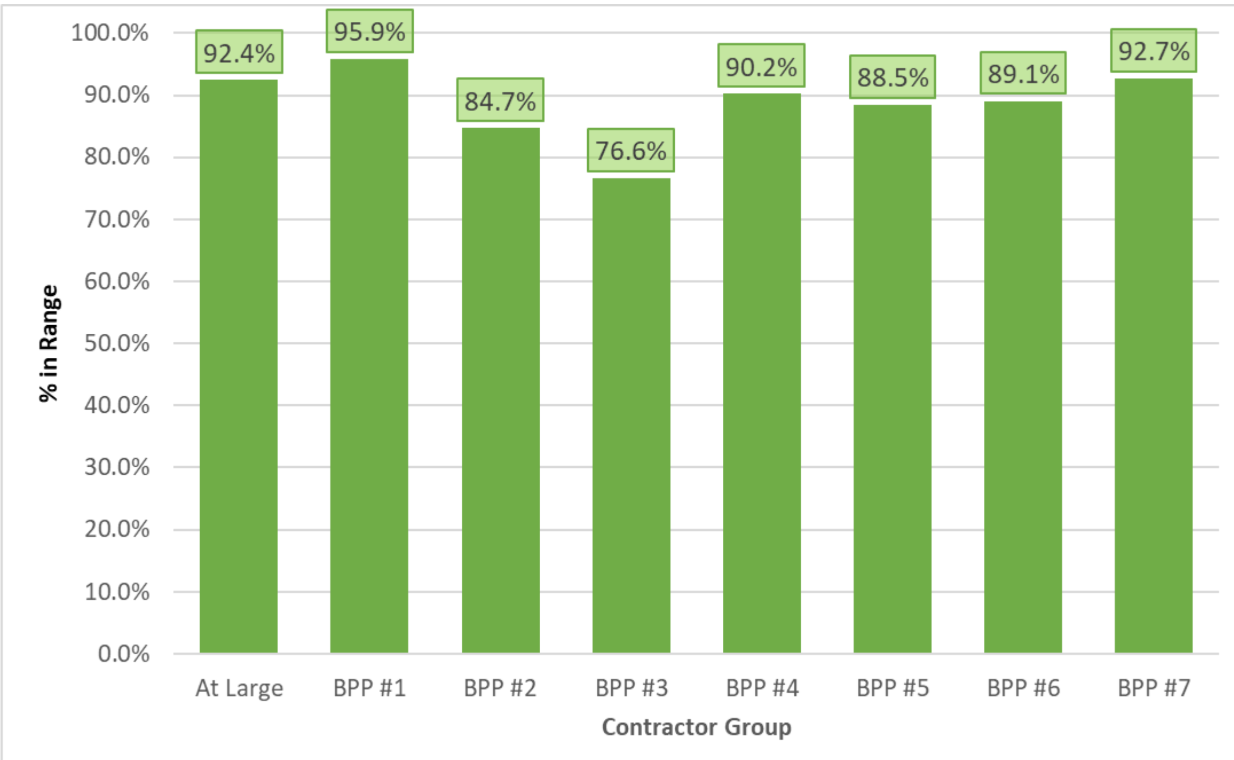

Figure 31. Percent of systems with correct charge by contractor group

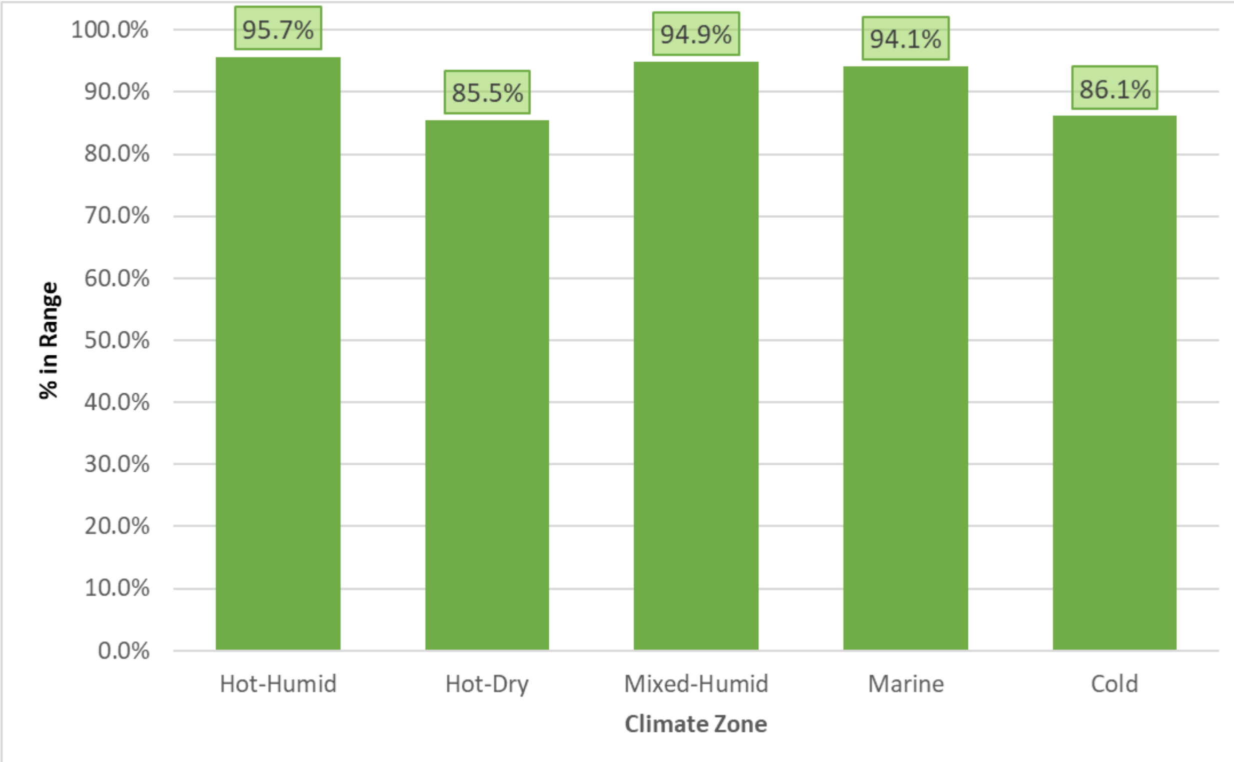

Figure 32. Percent of systems with correct charge by climate zone

3.1.3 Tune-up/Retrocommissioning Workflow Results

Tune-up data were collected when contractors serviced existing systems and recorded the snapshots both before and after tune-up. Three key metrics were analyzed to determine any changes in system performance: percentage of total normalized capacity, percentage of normalized sensible capacity, and EER. After cleaning, there were 608 total normalized capacity test-in/test-out performance snapshot pairs. The distribution of these snapshots among contractor groups is shown in Figure 33.

Table 14 displays the overall average test-in and test-out results for this metric, as well as the delta and p-value from a t-test. With 90% confidence, using mQ led to a 3.3% average increase in the total normalized capacity of all systems tested. The performance change by contractor group can be seen in Figure 34, and the distribution can be seen in Figure 35.

Table 14. Tune-Up Percent of Total Normalized Capacity Results

Change in Percent of Total Normalized Capacity						
	n	Test-in	Test-out	Delta	T-test p-value	Elapsed time (minutes)
Average	608	84.6%	87.9%	**3.3%**	2.7e-5	52.9

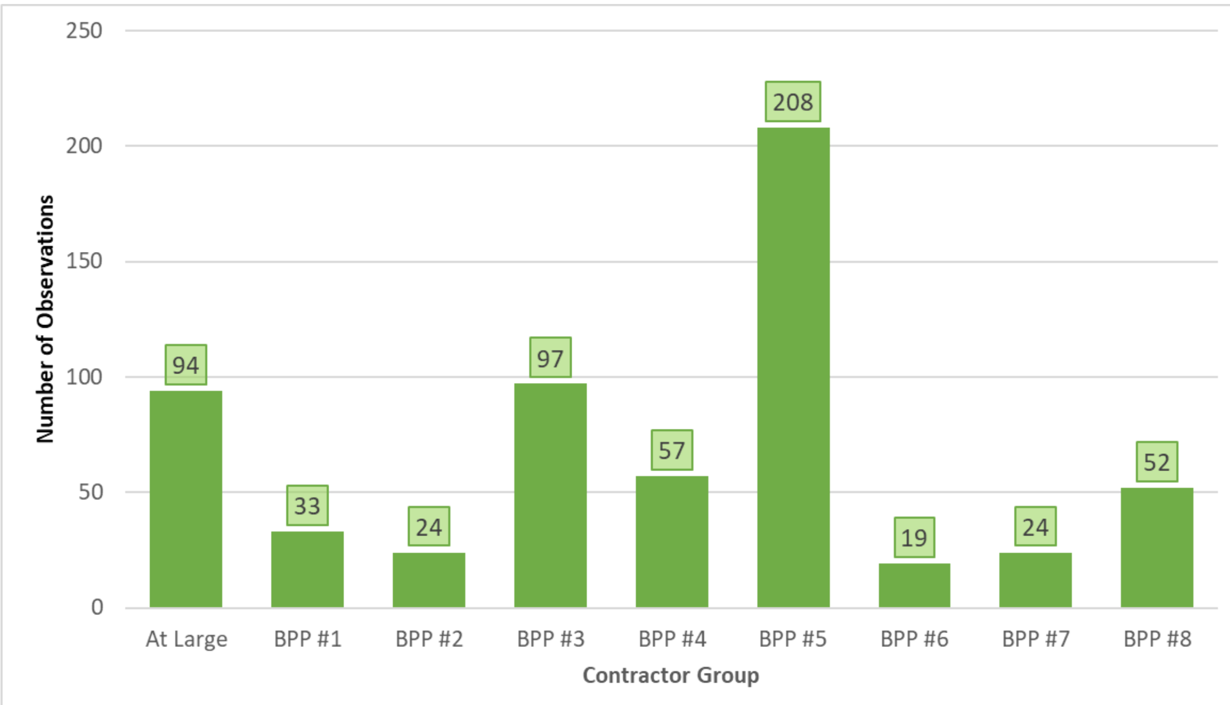

Figure 33. Number of observations with normalized total capacity readings by contractor group

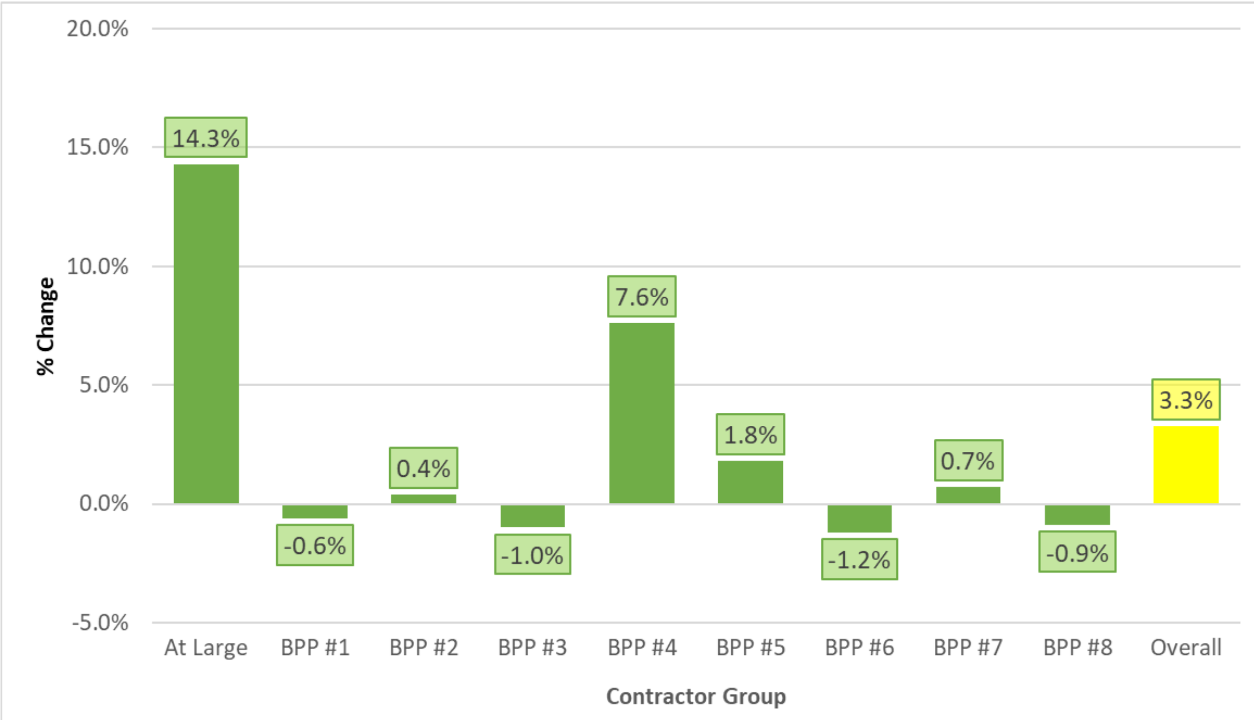

Figure 34. Change in percent of total normalized capacity by contractor groups

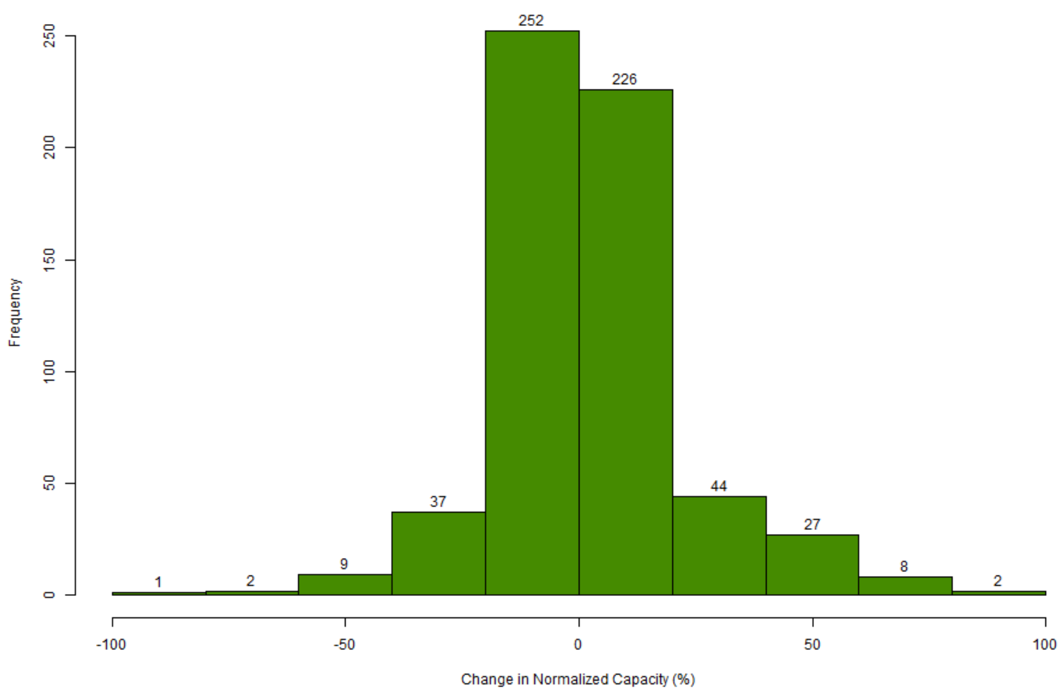

Figure 35. Change in percent of total normalized capacity distribution

As described in Sections 2.2.3 and 3.1.2, due to the influence of latent capacity, percent of total normalized capacity can be misleading when comparing delivered capacities between systems, especially across climate zones such as hot-dry where latent capacity can often be zero. Additionally, because the vast majority of thermostats call for cooling based on dry-bulb temperature alone, sensible capacity is what determines the actual runtime and annual energy usage of an air conditioning or ASHP system in cooling mode. Therefore, percentage of normalized *sensible* capacity is the more appropriate metric to use when comparing performance and energy usage before and after a tune-up.

There were a total of 629 test-in/test-out sensible capacity snapshots, and Figure 36 shows the breakdown of count by contractor group. Overall, contractors using mQ for tune-ups saw a statistically significantly 5.4% average increase in normalized sensible capacity. The test-in and test-out averages, as well as the average elapsed time for service, are shown in Table 14. With 90% confidence, using mQ for tune-ups/retrocommissioning led to a 5.4% average increase in the normalized sensible capacity.

The performance change by contractor group can be seen in Figure 37. Every contractor group except BPP #3 had a positive average change in delivered sensible capacity; however as seen in Table 16, the delta values for BPPs #3, #7, and #8 were not statistically significant. Table 16 breaks down this metric even further. The furthest right column displays the p-value that resulted from a t-test. Only the at-large group and BPPs #4 and #5 were highly statistically significant, while BPPs #1, #2, and #6 were moderately statistically significant. The overall result was highly statistically significant. The highly and moderately statistically significant groups ranged in sensible capacity improvement from 4.3% to 15.5%, where 15.5% had the highest significance. Figure 38 shows the overall distribution of results.

Table 15. Tune-Up Percent of Normalized Sensible Capacity Results

Change in Percent of Normalized Sensible Capacity						
	n	Test-in	Test-out	Delta	T-test p-value	Elapsed time (minutes)
Average	629	87.2%	92.6%	5.4%	1.3e-9	52.8

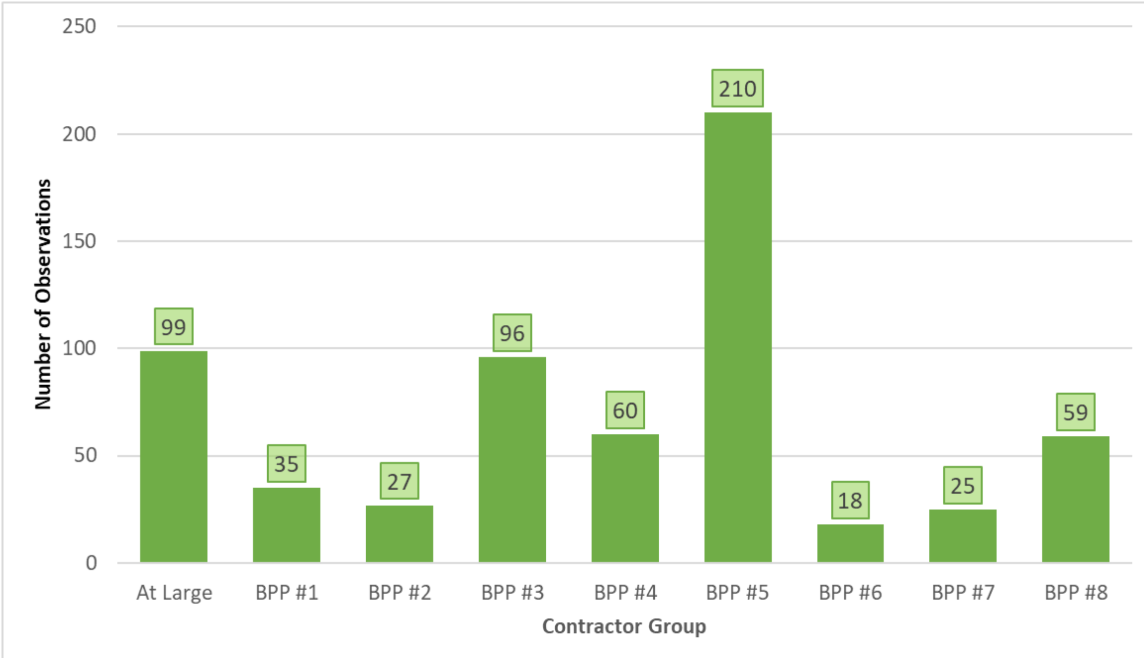

Figure 36. Number of observations with normalized sensible capacity readings by contractor group

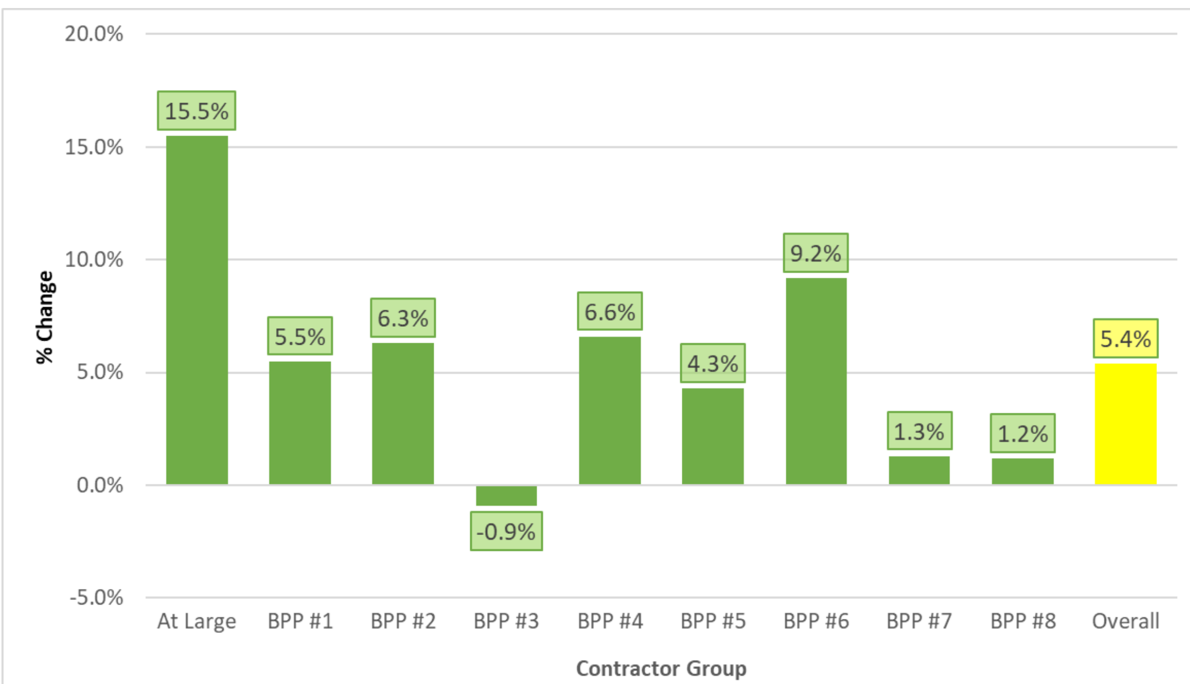

Figure 37. Change in percent of normalized sensible capacity by contractor groups

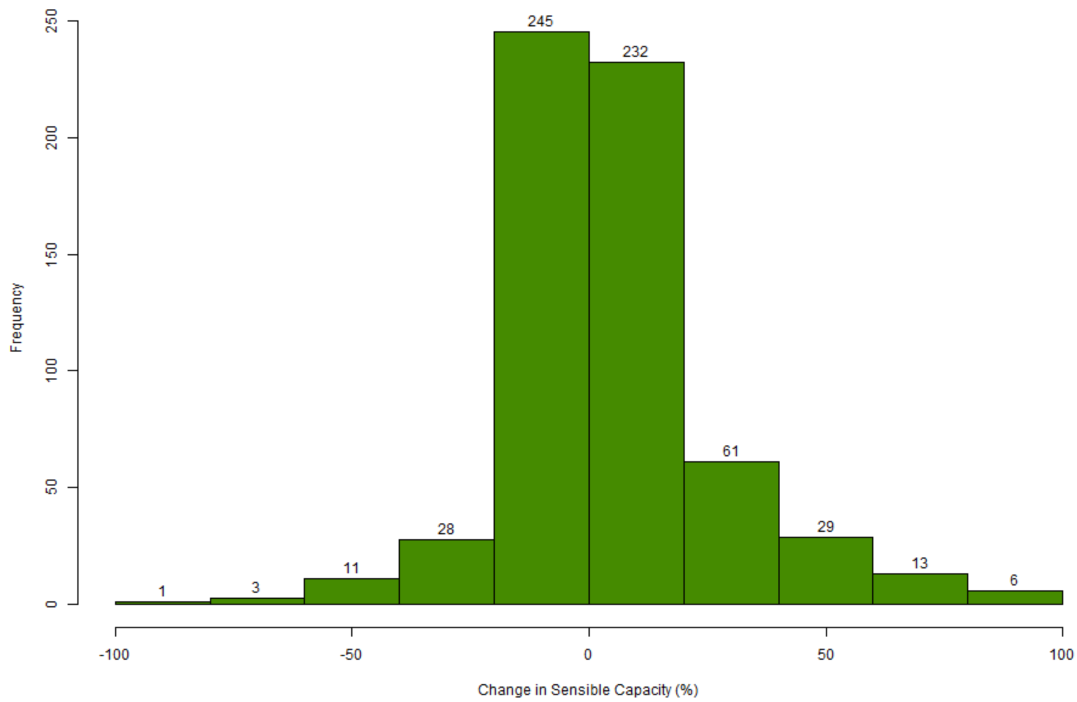

Figure 38. Change in percent of normalized sensible capacity distribution

Table 16. Tune-Up Percent of Normalized Sensible Capacity T-Test Results

Contractor Group	n	Test-In %	Test-Out %	Delta	Elapsed Time	p-value
At-large	99	80.5%	96.0%	15.5%	47.3	1.99E-08
BPP 1	35	92.2%	97.8%	5.5%	54.9	0.07622
BPP 2	27	87.8%	94.1%	6.3%	54.2	0.07543
BPP 3	96	85.3%	84.5%	-0.9%	39.2	0.6845
BPP 4	60	85.8%	92.4%	6.6%	67.5	0.01013
BPP 5	210	88.8%	93.1%	4.3%	57.9	0.003471
BPP 6	18	82.6%	91.8%	9.2%	48.7	0.07125
BPP 7	25	82.6%	91.3%	1.3%	59.3	0.3777
BPP 8	59	94.5%	95.7%	1.3%	47.5	0.2885
Overall:	**629**	**87.2%**	**92.6%**	**5.4%**	**52.8**	**1.38E-09**

Finally, the change in EER was investigated. There were 136 total test-in/test-out snapshots for this metric, and the breakdown by contractor group is shown in Figure 39. On average, there was a 6.2% increase (0.73 Btuh/kW) in EER across all contractors.

The results of the t-test are displayed in Table 17, which show that the increase is statistically significant. With 90% confidence, using mQ for tune-ups/retrocommissioning led to a 6.2% average increase in EER. Figure 40 shows individual contractor groups' average EER delta, and Figure 41 shows the overall distribution of results.

Table 17. Tune-Up EER Results

Change in EER						
	n	Test-In	Test-Out	Delta	T-test p-value	Elapsed Time (minutes)
Average	136	11.8	12.5	**0.73 (6.2%)**	0.0062	64.5

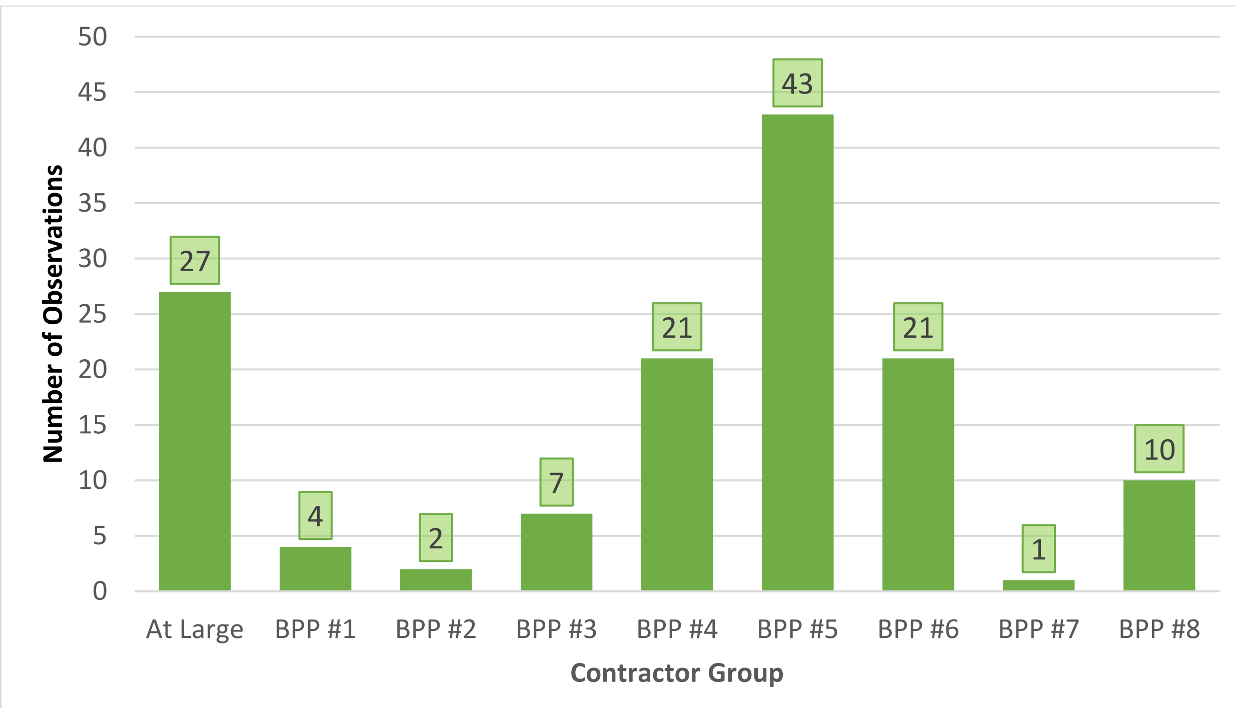

Figure 39. Number of observations with EER results by contractor group

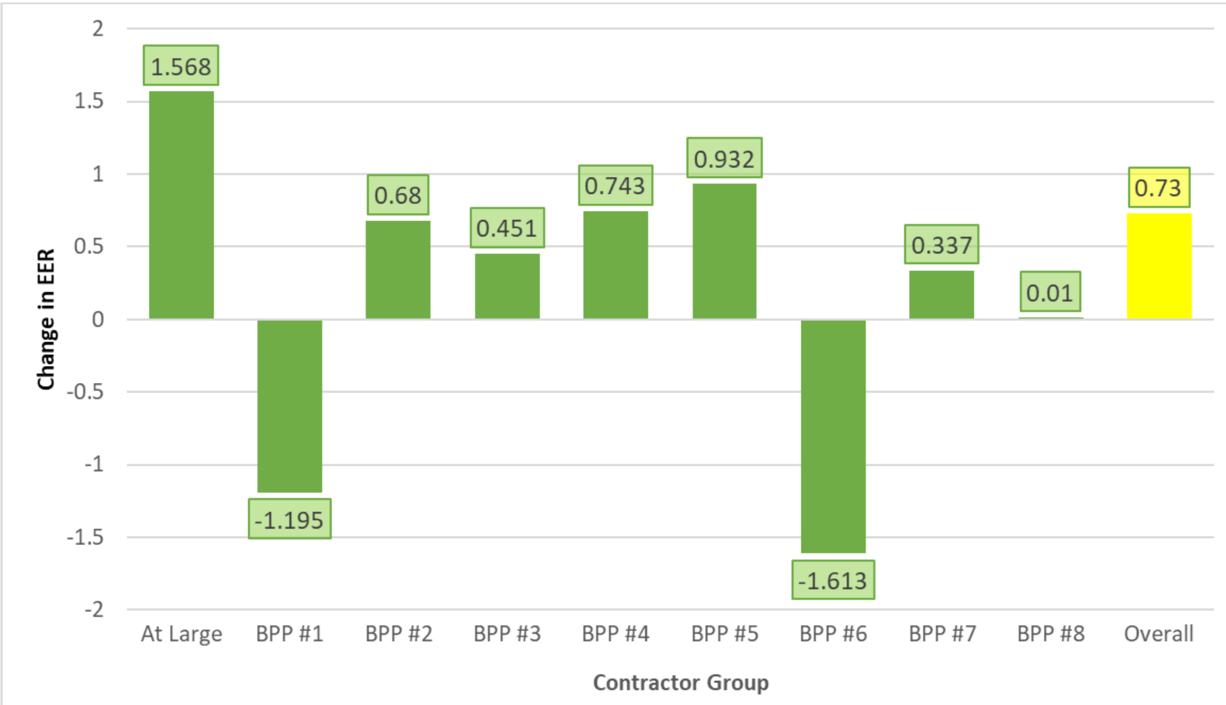

Figure 40. Change in EER by contractor groups

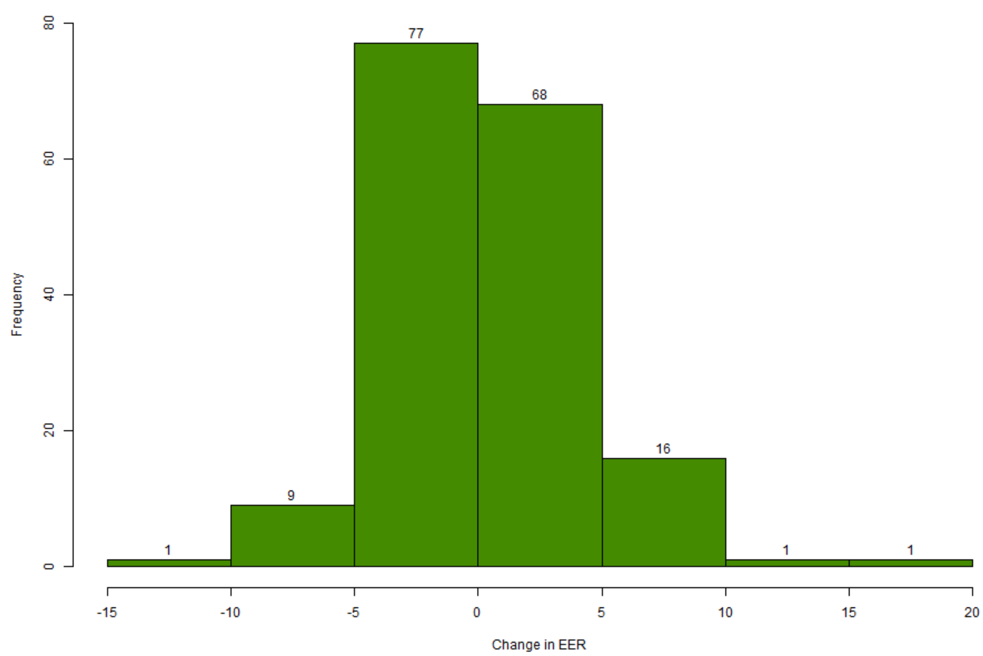

Figure 41. Change in EER distribution

3.2 Non-Energy (Business) Impact Results

3.2.1 Characterizing Respondents

In spring 2021, the Southface Team recruited voluntary participants for the Building America research project by issuing an online survey call to the mQ user base and conducting an open webinar; 195 mQ users covering 41 states responded with affirmative interest in participating in the research. Among over 200 HVAC technicians, business owners, and trainers attending the January 2023 HVACR Symposium, the Southface Team issued a paper questionnaire to self-identified mQ users. Pooling these data sets, the at-large contractor research pool, as shown in Figure 42 and Figure 43, mainly represented small businesses (143) and technicians (151).

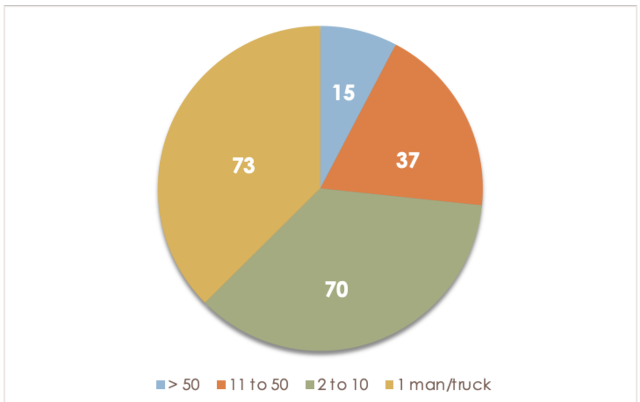

Figure 42. Number of employees of at-large contractors

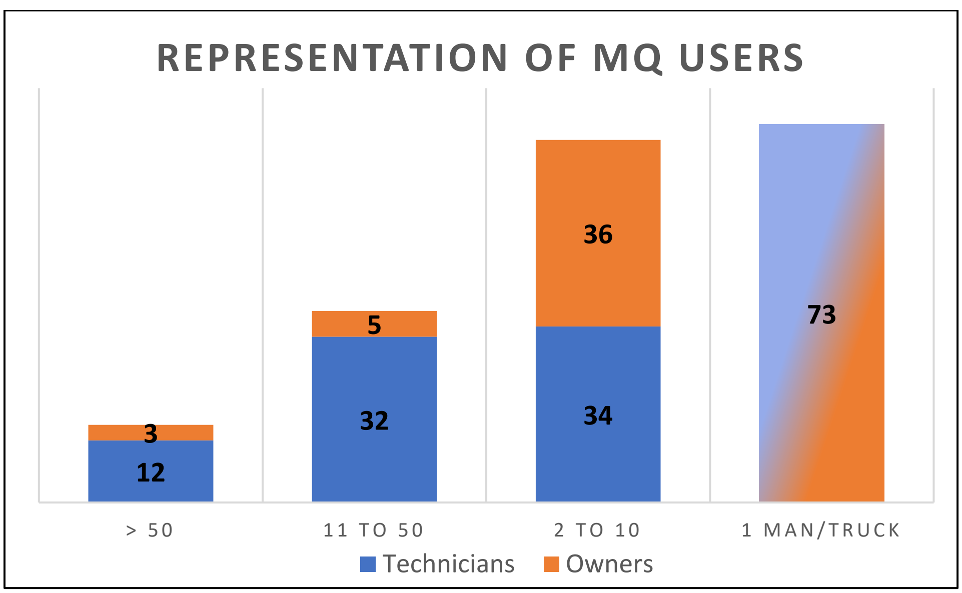

Figure 43. Business role of at-large contractors

The Southface Team interviewed six BPPs, representative of diverse HVAC industry sizes and serving customers in four of six targeted climate zones, as shown in Table 18.[15] The majority of BPPs use Service Titan as their business tracking software.

Table 18. Characteristics of BPP Respondents

BPP Company Size	# Participating Companies	Business Software		IECC Climate Zone Represented			
		Service Titan	House Call Pro	2	3	4	6
>50	2	2		·	·	·	·
11 to 50	2	2			·	·	
<10	2		2	·	·		

3.2.2 Summary of NEI Data Results

Over 300 online or in-person NEI surveys were issued to BPPs and at-large contractors. Collectively, the Southface Team captured 64 full responses from at-large contractors representing a mix of trainers, owners, and installer/service repair technicians. Additionally, six BPPs responded to both online NEI surveys and interview questions issued in winter 2022–2023. The Southface Team pooled responses across data collection methods[16] to determine the following primary findings across five lines of questioning for NEI impacts:

- General Usage: why use and what value?
- Maintenance agreements: sales and renewals
- Productivity: time, revenue, and callbacks
- Customer Interactions and Engagement
- Employee Training and Retention.

3.2.3 Measuring General Business Impact by Understanding the Value Proposition

The majority of mQ users (86%) said they use the tool to determine service repair needs, as shown in Figure 44. Additionally, respondents indicated that priority reasons for using the tool are to document/verify work performed and to support conversations with customers about the service repairs needed. During the period of data collection, mQ users could produce snapshots of their system test-in and test-out measurements.

[15] Originally there were eight BPPs; however, only six responded to the interview and engagement process for the investigation of business impacts.
[16] Because responses are pooled across data collection methods, the data set value (n) varies.

mQ users paying for Premier Services could produce a system report with detailed system measurements concisely presented in homeowner-friendly terms with a system score.

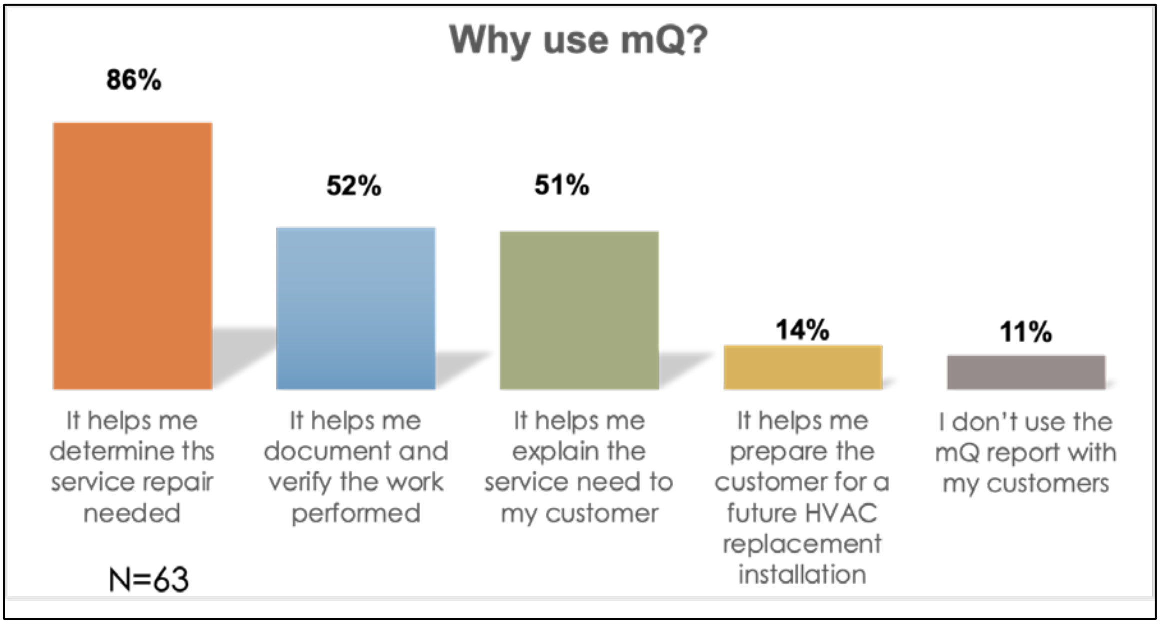

Figure 44. Why do businesses use mQ?

Both at-large and BPP respondents, as shown in Figure 45, indicated use of mQ for both new installations and service calls, with a slightly higher percentage of users focused on using mQ for service calls.

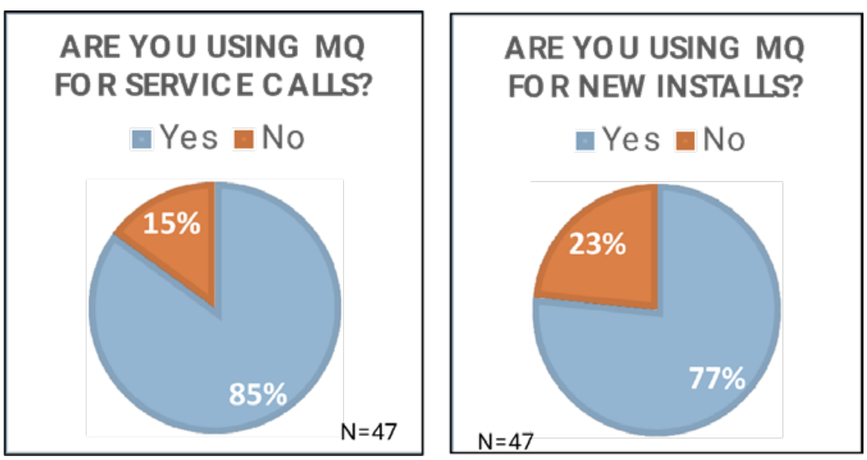

Figure 45. Use of mQ for service calls and new installations

Several mQ user quotes, highlighted in Table 19, summarize the value of mQ to support quality service to customers.

Table 19. Selected Respondent Quotes on Why Incorporate Use of mQ

General Questions: Why did you add mQ to your business service offerings? What is working well?	Respondent Type
"We do company quality installs, with pictures."	*At-Large*
"We use it to set up customer profile on their system and to maintain."	*At-Large*
"… it's about diagnosing, with an aid for explaining/documenting…"	At-Large
"…there is better time management and a real-time snapshot of what is happening."	*At-Large*
"We address more issues so we conduct less calls daily at a higher value for our customers and company."	*BPP*

3.2.4 Measuring Impacts to Maintenance Agreements Sales and Renewals

The Southface Team only measured impacts on sales and renewals of maintenance agreements among the BPPs.[17] Via the online survey questionnaire, the majority of BPPs (four out of eight) indicated new and renewed maintenance agreements have "increased a lot since adding the use of mQ to their business services," as shown in Figure 46.

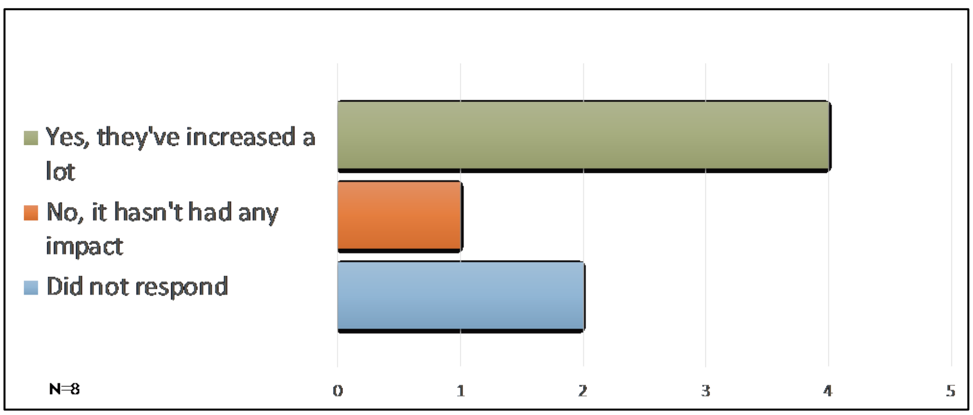

Figure 46. BPPs' indication of impact on maintenance agreements

During one-on-one interviews, BPP responses to inquiries about maintenance agreement sign-ons and/or renewals, more often than not, were intertwined with impacts to service call sales, with an indication they are generally going up. A few BPPs

[17] Anticipating that at-large contractors would be heavily represented by technicians, rather than business owners, the Southface Team did not inquire about maintenance agreements among the general mQ user population.

(two of eight) indicated they do not track these data. Table 20 presents selected BPP responses during one-on-one interviews.

Table 20. Selected BPP Quotes on Impact to Maintenance and Service Calls Sales

BPP Interview Responses Related to Maintenance Agreements and/or Service Calls
"Not much [help from mQ] on maintenance agreements, but it has helped some with sales."
"We see about a 15% conversion rate; maintenance sales are up 40 to 50%."
"Since adding mQ service sales have gone up."
"Having the data to show homeowners has increased sales by 20%."
"[mQ] saves on warranty work (manufacturers just want to sell their boxes), techs sell service. The mQ platform as an independent system verifier is a game changer for tech service/sales."

3.2.5 Measuring Productivity Impacts on Revenue, Labor Time, and Callbacks

Both at-large and BPP respondents indicated that use of mQ increased their company's revenue. As shown in Figure 47, 55% of at-large contractors saw an increase in revenue per ticket/visit.

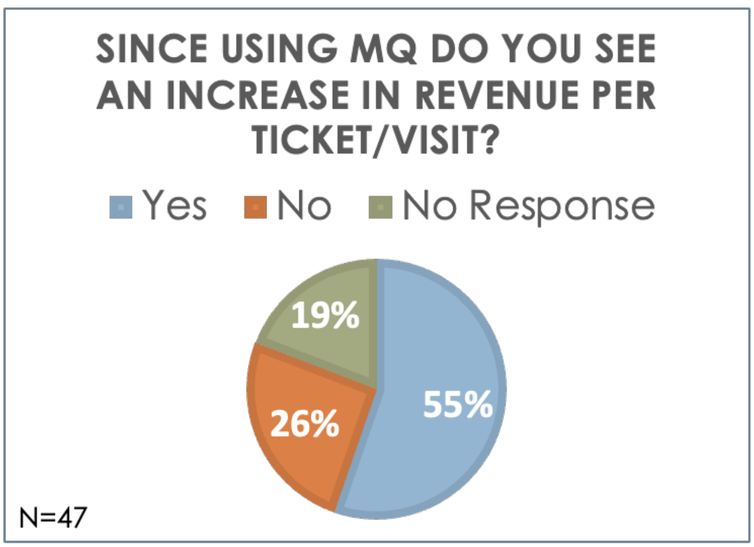

Figure 47. Impact of mQ use on revenue

The Southface Team attempted to gather KPI data from BPPs; however, most would not give specific data either because they were not tracking such data, did not know how to report it from their business management software, and/or were not willing to share the information. As summarized by one BPP, "There is no magic bullet here. No one thing that impacts the revenue to goal pursuit … for sure mQ helps [our] volume." All BPPs reported that mQ helped them increase their sales volume, with revenue increases ranging from 20% to 80% for service calls and 30% to 40% for new installation sales, but none produced the data to back up this claim.

Looking at time as a measure for productivity, the Southface Team tried to examine changes in time for technicians to complete service and installation jobs. As shown in Figure 48, most indicated that more time is spent, especially for service visits (64%) given that use of mQ helps technicians find more things to fix. Responses on time spent for new installs are fairly evenly represented, indicating no specific trend.

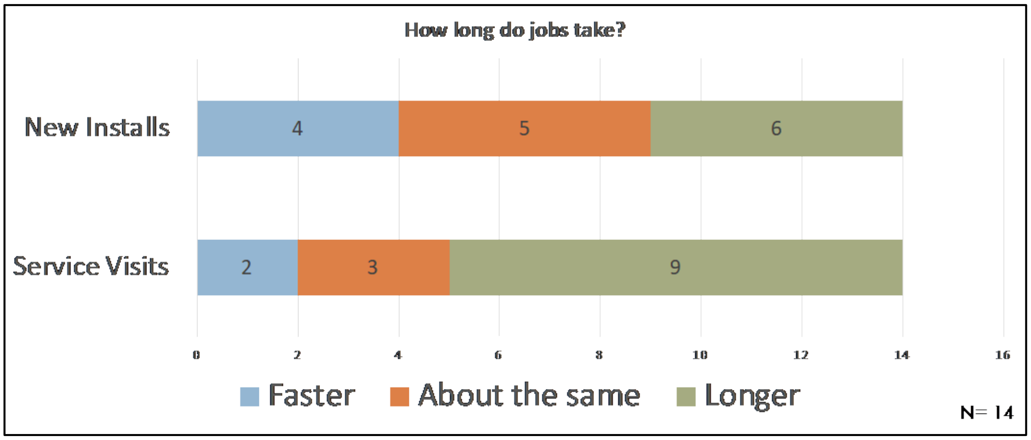

Figure 48. How long jobs take with mQ

In one-on-one interviews with BPPs, responses varied depending on the speed for closing the sale on service job quotes. Some indicated they were issuing more quotes because they found more issues, such as dirty coils, charge issues, airflow issues, static pressure issues, line restrictions, or return duct leakage, that can be presented to the homeowner as billable opportunities/repairs; however they were not necessarily closing faster. Others indicated that the mQ reports helped speed up delivery of documentation to customers and also the time to close a sale because they could show a third-party verified score. As one BPP summarized, “remote monitoring and mQ flattens [the] seasonality of calls.” With the standardized use of mQ in their business procedures, during the “slow season,” technicians can complete up to five calls per day (industry standard is four). Table 21 presents selected BPP responses during one-on-one interviews and open text responses from at-large contractors responding to surveys.

Table 21. Selected Respondent Quotes on mQ's Impact on Job Time

Impact on Time, When Using mQ	Contractor Group
"Techs are more efficient in diagnosing … but more time is spent."	BPP
"It adds time because it's creating a conversation for the tech with the homeowner."	BPP
"We use the product to build value. Building value takes time and cannot be rushed. In our company, 5 calls a day works out to a 10-hour day with an average of 30 minutes travel and 1.5 on-site. During Peak time we can run 6 to 7 a day but that's a 12–14 hour day."	BPP
"[We] address more issues so we conduct less calls daily at a higher value for our customers and our company."	BPP
"With sales, it has given us the ability to prove to customers that their units are not performing as well as they thought. Being able to show current SEER and performance metrics has definitely helped sway customers into purchasing new efficient equipment."	BPP
"[mQ] provides good technical data to help us get to a solution quicker."	At-Large

An additional productivity gain with the use of mQ is in reducing callbacks for both new installs and service calls. As shown in Figure 49, 83% of respondents reported fewer callbacks since adopting the use of mQ. During one-on-one interviews, several BPPs indicated that they are not explicitly tracking technicians' time on the job nor the rate of callback incidents, but they "know callbacks are reduced."

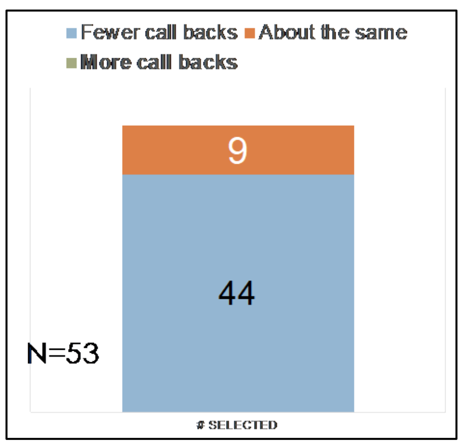

Figure 49. Impact of mQ Use on Callbacks

Table 22 presents selected open text responses from at-large contractors responding to the survey questions about callback incidences.

Table 22. Selected At-Large Contractor's Quotes on mQ's Impact on Callbacks

At-Large Contractor Comments on Use of mQ's Impact to Callbacks
"[When we use mQ,] it prevents tons of callbacks, while also creating upselling opportunities."
"[mQ use leads to] decreased callbacks and peace of mind."
"[If there's an] install callback, [it's] generally manufacturer component failures."
"Understanding of problems/systems has been greatly increased and callbacks have dropped. [We are] able to show clients and boss what I am finding and [that] gives more confidence on what I [am] saying."

3.2.6 Measuring Impact on Customer Interactions and Engagement

The Southface Team asked BPPs and at-large contractors about customer satisfaction and reactions to their use of mQ data results and mQ reports. Responses were largely anecdotal via surveys among at-large contractors and direct interviews with BPPs. About half of at-large contractors (25 of 47) indicated they use the mQ report. Among BPPs, all used the mQ data to build job scopes and discuss a system's status with customers, but only two actively used the mQ reports.[18] Regardless of whether reports were used, across at-large contractors and BPPs, 79% of respondents indicated they helped build customer confidence in recommendations, as shown in Figure 50.

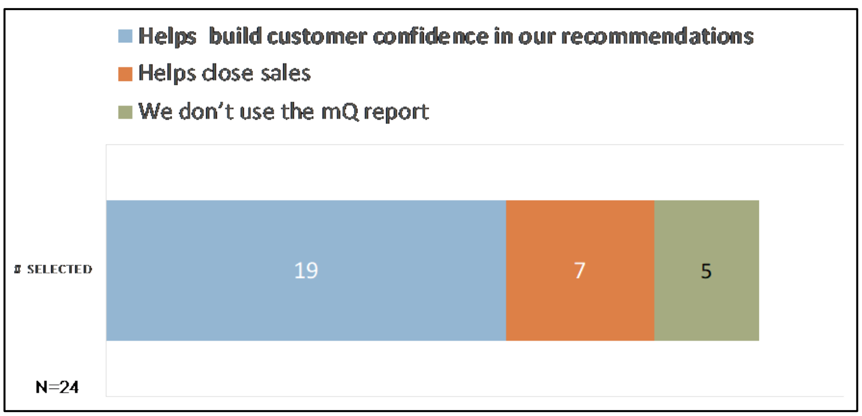

Figure 50. mQ helps build customer confidence in recommendations

Many contractors among both the BPP and at-large respondents proudly reported integration of mQ into business processes for all service and new installation jobs, designing "digital maintenance service" that emphasize the use of the smart diagnostic tools and the mQ app and "installation certification" offerings that include commissioning report documentation. Several respondents indicated how the mQ data lend parity among contractors' work by documenting a system's operation. For instance, one BPP

[18] In May 2022, mQ issued a new mQ report (version 2.0), which explains key system operations in nontechnical terms with an A through D grading, and enables a technician to benchmark and compare systems' performance.

shared how mQ data were used to demonstrate third-party verification of a system's failures, which the previous contractor had left unaddressed. Other contractor respondents indicated the mQ report and data provided a conversation starter and a method for service technicians to explain service repair needs. The simple A through D grading on the mQ report empowers the customer to determine decisions on next steps while bolstering the authority of the technicians' reported service repair needs. Table 23 presents selected BPP responses during one-on-one interviews and open text responses from at-large contractors responding to surveys.

Table 23. Selected Respondent Quotes on the Impact of mQ Data and Reports

Impact of Use of mQ Data and/or Reports on Customer Satisfaction	Contractor Group
"mQ report helps techs build buy-in with the customer. It offers a 3rd party/independent review of the customer's system. Its transparency of the system's in-field performance and gives the choice to the homeowner to decide what option they want to take (vs. the technician's opinion)."	BPP
"The mQ interface is one of the most powerful transparency tools for customer interactions in the industry. Creating confidence for our customers in the diagnosis and repair we provided."	BPP
"[mQ] has increased the trust by showing actual data on how their system is operating."	At-Large
"So far, most customers really like the ability to have verification. That they don't have to just take someone's word about how the system is performing or what the issue is. Being able to backup conversation with verifiable data is something this industry should have done long ago."	At-Large
"[mQ data] makes me and my team look good."	At-Large
"[mQ] keeps the techs honest."	At-Large

3.2.7 Measuring Impact on Employee Training and Retention

The Southface Team assessed how use of mQ impacted BPP and at-large contractors' employee hiring and/or retention rates. The Team also examined how the availability of "just in time" video training and expert guidance provided in the mQ app impacts service time per new install and service time per maintenance visit. The "just in time" education features in the mQ app, found via the "i" icons throughout the tool, offer tips and training on proper methods, diagnostic results, and other expert guidance for proper installation and/or service repairs.

As indicated in Section 2.2.1, many of the filters developed through the user error analysis were incorporated into the mQ app, enabling improved user performance by alerting about potential probe placement errors and measurement errors before a performance snapshot is taken. This "just in time" education helped to advance the training of mQ users. Additionally, mQ's 2.5 software release enhanced "just in time" education features with "guided workflows" that offer simpler step-by-step directions to train technicians.

The surveys of BPPs indicated a majority (five out of eight) reported using the "just in time" education features at least once per week. In surveys of at-large contractors, 80% of respondents indicated that the "just in time" education features impact technicians' and installers' work on jobs, as shown in Figure 51.

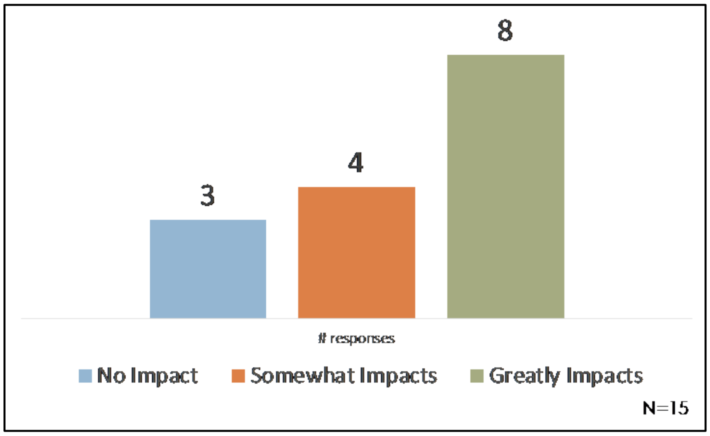

Figure 51. Impact of "just in time" education features in mQ

Both BPPs and at-large contractors reported that learning to use smart diagnostic equipment and mQ is challenging; 86% of users reported that it takes time to learn and integrate the mQ workflows into their business processes, as shown in Figure 52.

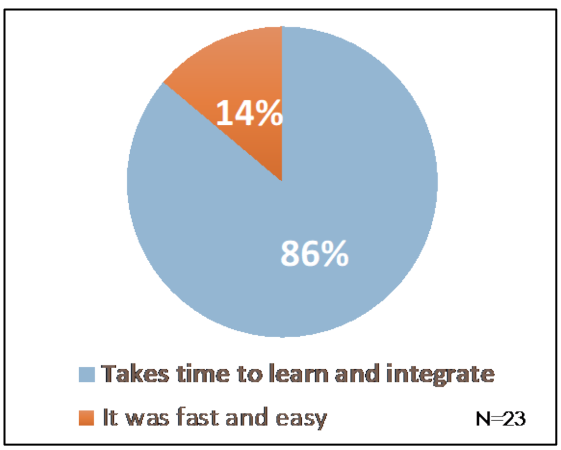

Figure 52. How easy is it to use/incorporate mQ?

During one-on-one interviews with BPPs, respondents indicated it takes two to three months, with both in-field and virtual support, to train employees. Hindering their progress is a reluctance to take training among HVAC technicians. Table 24 presents selected BPP responses during one-on-one interviews.

Table 24. Selected BPP Quotes on Experience Integrating mQ

Challenges in Training	Contractor Group
"Techs are reluctant to do training; it's a big issue. There's a culture or perception that they should be paid to take training (it's helping my employer, not me)."	BPP
"[mQ] adoption is somewhat slowed/difficult because techs need more training (and buy-in) to the tool's value. I want it to be 100% but we're about 50% there."	BPP
"it takes getting buy-in … the techs are like why do I need training."	BPP
"I am actively looking for newer techs to be more receptive to using the app and smart devices. The old techs really have a hard time getting on board with the program."	BPP

While the majority of BPPs and at-large contractors report the training "takes time," many specifically use mQ to rapidly onboard new technicians. BPPs report that employees newly trained in mQ/smart diagnostics can quickly elevate their skills to the level of a technician with two to three years of experience. Combined with the ability for senior technicians or management to remotely view mQ data, myQ gives management the confidence to send these newer technicians out on calls sooner. Table 25 presents selected BPP responses during one-on-one interviews and open text responses from at-large contractors responding to surveys.

Table 25. Selected Respondent Quotes on Use of mQ to Onboard New Technicians

Utilizing mQ for Onboarding New Technicians	Contractor Group
"mQ has allowed us to recruit and retain more "technical" employees. We have made the process all about "it's just what we do." Those who are not technical and cannot grasp mQ are quickly identified and many make the choice on their own not to work here. And that's ok, might not be a good fit anyway. Those who grasp the concept, embrace it, and want more of it. In fact, many of our technical service meetings are filled with mQ report results and what they mean."	BPP
"We use mQ to train and onboard new staff."	BPP
"We added mQ as a method to deal with a shortage of techs and need to rapidly onboard newbies."	BPP
"I use it in training and teaching; [I] love using mQ with Fieldpiece and students can see the same info."	At-Large

4 Discussion

4.1 Results Discussion

4.1.1 Energy/HVAC Performance Impact Results Discussion

The “at-large” group had the lowest rate of tool/app user errors (Table 10 and Table 11). This group was composed of self-selected individual mQ users who responded to a limited-time offer, so it makes intuitive sense that they would, on average, be more individually motivated to correctly learn and use the app. The other groups are technicians on larger teams who were required to use the workflows as part of their company’s policies. BPPs #2 and #6 had the highest error rates, with some fan watt draw and power errors exceeding 60%, indicating systemic tool usage issues that need to be corrected with further training.

Technicians appeared to have the greatest difficulty correctly measuring system power and AHU power, in particular. Specifically, technicians had problems measuring both the indoor blower amperage and voltage while a system was operating, and they often used the condensing unit wattage instead of the AHU wattage (doubling the condensing unit wattage as the total). Power measurement error rates averaged 10.5% for new systems and 18.0% for existing systems. AHU power measurements averaged 33.6% for new systems and 31.4% for existing systems. The Southface Team recommends building user error detection into the app to increase usability and reduce error rates. We also recommend emphasizing the most common sources of error during mQ trainings.

Installation quality appears to be consistent for systems commissioned with mQ, with an overall average 90.5% of total normalized capacity, 94.2% normalized sensible capacity, 0.55 TESP, 395.6 CFM/nameplate ton, and 76.9% of systems with correct charge. One contractor group had the lowest average total normalized capacity, lowest normalized sensible capacity, and lowest percentage of systems with correct charge. Excluding this one group, the averages ranged from 87.6%–103.8% of total normalized capacity, 94.2%–100.8% normalized sensible capacity, and 84.7%–95.9% of systems with correct charge. These results can be compared to the Building America residential HVAC fault baseline studies when published in 2024 to see if following the mQ installation workflow improves the installation quality of new air conditioning and ASHP systems.

A statistically significant average system performance improvement was found for all three metrics analyzed for tune-up/retrocommissioning workflow (3.3% increase in total normalized capacity, 5.4% increase in normalized sensible capacity, and 6.2% increase in EER). However, the small amount of valid pre and post tune-up snapshot pairs contained in the large data set (14.2% of the cleaned tune-up data set) indicates that most technicians were not using the workflow as intended to baseline the system with a test-in snapshot, follow the mQ diagnostics to identify faults, correct faults and document corrections, and test-out the retrocommissioned system with a final performance snapshot. To address this, mQ has created introductory workflows for training technicians that limit the options and force technicians to precisely follow the correct data entry and probe usage protocols.

There was a wide range in improvement using the tune-up/retrocommissioning workflow, with statistically significant performance improvement averages as high as 15.5% for one of the contractor groups and as low as 4.3% for another. However, there was enough variation within three of the nine contractor groups to cause their results to be statistically insignificant and pull the overall average improvement down to 5.4%. Therefore, the ceiling for performance improvement is high, but it is dependent on the individual technician and company. Further research is recommended to track and correlate performance improvements for correcting various fault types while using mQ so that savings can be estimated based on individual fault correction and so that best practices can be determined and implemented across contractor companies.

4.1.2 Non-Energy (Business) Impact Results Discussion

Although, anecdotally, at-large contractors and BPPs report mQ increases in the productivity of service contractors, specific reporting of KPI data was insufficient to support this finding. BPPs, even though they use business management software, were unable or unwilling to provide KPI data points for number of maintenance agreements, number of renewed maintenance agreements, number of service calls, average travel time for all call types, average labor time charged for all call types, number of new installs with mQ, and number of callbacks on new installs with mQ. The HVAC industry, across business sizes, needs improved business acumen in the use of business management software and the use of business KPIs to track performance. Any further research in this area will need to improve the value proposition for contractors to report on business KPIs. This could include incentivizing contractor businesses to report business KPIs or expanding the number of respondents for greater anonymity in aggregating responses.

Anecdotally, at-large contractors and BPPs generally indicate that mQ data improves customer receptivity to service work, but across the respondents, use of the mQ report with customers is low. Thus, the third-party nature and simplicity of the mQ report helps contractor businesses' relationships with customers and in closing sales, but greater facilitation of integrating mQ into business operations is needed. While the majority of respondents across at-large contractors and BPPs indicate they use and value the “just in time” education features in the mQ app, a majority of respondents also indicate “it takes time to learn” to use and integrate mQ into their business processes. To improve quality service and installation, there needs to be a continued development of real-time access to educational material, and flags and autocorrections of data entry errors.

4.2 Application of Findings

4.2.1 Feedback for Contractors and mQ App Improvements

As suggested in Section 4.1, many of the filters developed through the user error analysis (Section 2.2.1) have been incorporated back into the app, alerting current users of potential probe placement errors and measurement errors before a performance snapshot is taken. This is intended to decrease the number of snapshots containing user errors in the future and improve the accuracy of the average user's outputs. mQ has also introduced "guided workflows" in the software's 2.5 release, which provide simpler step-by-step directions, walking the technician through the process and limiting the mistakes that can be made. The user error analysis also led to feedback for the BPPs on their technicians' common errors and the training required to correct them. These lessons learned have been incorporated into general mQ training.

4.2.2 Estimate of Annual Cooling Electricity Savings and Cost Savings After a Tune-Up

An estimate of the annual cooling electricity and utility bill savings from an average air conditioning or ASHP tune-up using the mQ service workflow can be determined using the results from Section 3.1.3. This is meant to be a representative average example by climate zone, and we recommend using actual values from the specific equipment and location in question when estimating savings. The recommended method for estimating savings for the tune-up of an individual real-world system is to use equation b) below with the nameplate capacity, equivalent full-load cooling hours (EFLH) from the applicable technical reference manual or ENERGY STAR® ASHP Energy Savings Calculator, and field-measure the actual EER_{pre} and EER_{post} with mQ.

Savings can be estimated in two different ways: a) using the sensible capacity delta and b) the EER delta results, both from Section 3.1.3. The following equations are standard in technical reference manuals across the country for air conditioning tune-up measures:

$a)$ $$\Delta kWh/yr = SF \times CAP \times 12 \times \frac{1}{SEER} \times EFLH_C$$

$b)$ $$\Delta kWh/yr = CAP \times 12 \times \left(\frac{1}{EER_{pre}} - \frac{1}{EER_{post}}\right) \times EFLH_C$$

Where:

SF = savings factor, equal to the sensible capacity delta (%)

CAP = capacity of the unit (kBtu/hr)

12 = conversion from tons to kBtu/hr

$SEER$ = seasonal efficiency ratio of the unit in (kBtuh/kW)

EER_{post} , EER_{pre} = energy efficiency ratio before and after the tune-up (kBtuh/kW)

$EFLH_C$ = equivalent full load cooling hours for the region (hours).

Table 26 shows representative estimates using equation a). The *SF* is assumed to be equal to the delta normalized sensible capacity found in Section 3.1.3 (5.4%, from Table 15). The capacity (*CAP*) is the average capacity in each Building America climate zone for units in this study (Figure 10). SEER is assumed to be 13 for an existing system, because 13 SEER was the federal minimum beginning in 2006 and a publicly available baseline study from 2018 showed that the average for central air conditioning was 12.0 SEER.[19] $EFLH_C$ is the full load cooling hours from the ENERGY STAR ASHP Energy Savings Calculator, denoted in Table 26. The average electricity cost is from the September 2023 EIA Average Price of Electricity to Ultimate Customers by End-Use Sector for the census division in which the representative city resides.

Table 26. Representative Estimate by Climate Zone of Annual Cooling Electricity Savings and Cost Savings After a Tune-Up Using the mQ Workflow using Equation a)

Climate Zone	***CAP***	***Representative City***	***EFLH_C*[20]**	***kWh/yr Savings***	***Average $/kWh*[21]**	**$/yr Savings**
Hot-Humid	3.35 tons	Houston, TX	2,209	368.9	$0.1389	$51.24
Hot-Dry	3.83 tons	Phoenix, AZ	2,141	408.7	$0.1439	$58.82
Mixed Humid	2.72 tons	Louisville, KY	1,150	155.9	$0.1299	$20.25
Marine	3.88 tons	Portland, OR	379	73.3	$0.2430	$17.81
Cold	2.91 tons	Chicago, IL	683	99.1	$0.1600	$15.85

Table 27 shows representative estimates using equation b). The capacity (*CAP*) is the average capacity in each Building America climate zone for units in this study (Figure 10). The EER_{pre} and EER_{post} are equal to the average test-in and test-out EER found in

[19] 2018 Pennsylvania Statewide Act 129 Residential Baseline Study Final Draft. Submitted to: Pennsylvania Public Utility Commission. NMR Group, Inc. February 12, 2019. https://www.puc.pa.gov/Electric/pdf/Act129/SWE-Phase3_Res_Baseline_Study_Rpt021219.pdf

[20] From ENERGY STAR ASHP Energy Savings Calculator. Calculator last updated April 2009. https://www.energystar.gov/sites/default/files/asset/document/ASHP_Sav_Calc.xls

[21] EIA Average Price of Electricity to Ultimate Customers by End-Use Sector, September 2023. Residential Rates. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

Section 3.1.3 (11.8 and 12.5, from Table 17). $EFLH_C$ is the full load cooling hours from the ENERGY STAR ASHP Energy Savings Calculator, denoted in Table 27. The average electricity cost is from the September 2023 EIA Average Price of Electricity to Ultimate Customers by End-Use Sector for the census division in which the representative city resides.

Table 27. Representative Estimate by Climate Zone of Annual Cooling Electricity Savings and Cost Savings After a Tune-Up Using the mQ Workflow Using Equation b)

Climate Zone	*CAP*	*Representative City*	$EFLH_C$[22]	*kWh/yr Savings*	*Average $/kWh*[23]	$/yr Savings
Hot-Humid	3.35 tons	Houston, TX	2,209	421.4	$0.1389	$58.54
Hot-Dry	3.83 tons	Phoenix, AZ	2,141	467.0	$0.1439	$67.20
Mixed Humid	2.72 tons	Louisville, KY	1,150	178.1	$0.1299	$23.14
Marine	3.88 tons	Portland, OR	379	83.7	$0.2430	$20.35
Cold	2.91 tons	Chicago, IL	683	113.2	$0.1600	$18.11

Ultimately, the generalized results from both methods are within 12.5% of each other.

4.3 Future Work

Several suggestions for future work are offered above in Section 4.1 Results Discussion, but they have been collected and combined with other suggestions here for convenience. We recommend a published third-party study validating mQ calculations and outputs (see Table 2 and Section 2.2.3). Many of the calculations behind the output metrics are patented or trade secrets, so a validation of the outputs against alternative measurement techniques can increase contractor, technician, and building scientist confidence in the results. Specifically, we recommend a published comparison of the mQ airflow estimations with direct airflow measurements, such as the TEC True Flow grid. This can be expanded by comparing the accuracy of the estimation between invasive and non-invasive test modes within mQ.

[22] From ENERGY STAR ASHP Energy Savings Calculator. Calculator last updated April 2009. https://www.energystar.gov/sites/default/files/asset/document/ASHP_Sav_Calc.xls
[23] EIA Average Price of Electricity to Ultimate Customers by End-Use Sector, September 2023. Residential Rates. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

For more granularity on the performance improvement of fault correction with mQ, we recommend a limited, more controlled study of pre/post tune-up performance where faults and repairs are catalogued for each system. This would allow the performance improvement level to be correlated to fault type correction. When published, compare the current field baseline performance from the Building America residential HVAC fault baseline studies to the mQ new system commissioning results in Section 3.1.2.

The HVAC industry, across business sizes, needs improved business acumen in the use of business management software and the use of business KPIs to track performance. Any further research on HVAC contractor business practices will need to improve the value proposition for contractor business to report on business KPIs. This could include incentivizing contractor businesses to report business KPIs or expanding the number of respondents for greater anonymity in aggregating responses.

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