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Residential HVAC Installation Practices:

A Review of Research Findings

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List of Acronyms

AC	Air Conditioning
ACEEE	American Council for an Energy-Efficient Economy
ACCA	Air Conditioning Contractors of America
AFUE	Annual Fuel Utilization Efficiency
ASHP	Air-Source Heat Pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BPM	Brushless Permanent Magnet
CAC	Central Air Conditioning
CEC	California Energy Commission
CEE	Consortium for Energy Efficiency
CFM	Cubic Feet per Minute
COP	Co-efficient of Performance
DOE	Department of Energy
ECM	Electronically Commutated Motor
EER	Energy Efficiency Ratio
EM&V	Evaluation, Measurement and Verification
EPA	Environmental Protection Agency
FDD	Fault Detection and Diagnostics
FXO	Fixed Orifice
HP	Heat Pump
HVAC	Heating, Ventilation, and Air Conditioning
IESO	Independent Electricity System Operator
MERV	Minimum Efficiency Reporting Value
NASEO	National Association of State Energy Officials
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
PARR	Partnership for Advanced Residential Retrofit
PSC	Permanent Split Capacitor
STAC	State Technologies Advancement Collaborative
QI	Quality Installation

QIV	Quality Installation Verification
QM	Quality Maintenance
R&D	Research and Development
STAC	State Technologies Advancement Collaborative
TXV	Thermostatic Expansion Valves

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Introduction

This report summarizes relevant findings from available literature and research that were evaluated to better quantify the potential benefits of improving current installation practices for heating, ventilation, and air conditioning (HVAC) equipment in existing homes (i.e., equipment replacements). Although some of the findings may be informative and applicable to the new construction market, this report focuses on analyses specific to the single-family residential HVAC replacement market. The research findings summarized in this report reveal that improving the installation of central heating and air conditioning systems has the potential to decrease operating and maintenance costs, decrease equipment purchase price, improve indoor air quality and overall indoor comfort, and reduce household energy consumption by mitigating a variety of common system performance issues.

The US Department of Energy (DOE) produced this report in response to industry stakeholder input received during the May 2016 *Residential Central Air Conditioning and Heat Pump Installation Workshop Meeting*[1] (https://energy.gov/eere/buildings/downloads/residential-central-air-conditioning-and-heat-pump-installation-workshop). DOE hosted the stakeholder discussion workshop to identify and rank research and development (R&D) needs and critical knowledge gaps related to improving system design, selection, and installation (collectively "installation"). At the meeting, it was suggested that additional field research may be needed to supplement modeled and lab-based studies and develop a better understanding of both the prevalence of system performance faults and their cumulative impact.

One hallmark study from 2014 served as a foundation for this literature review. The National Institute of Standards and Technology's (NIST) *Sensitivity Analysis of Installation Faults on Heat Pump Performance*[2] study assessed the impacts of installation faults on the energy consumption of refrigerant-based residential heat pump equipment. The study used computer simulations and laboratory tests to quantify the impact of commonly observed individual faults, as well as certain combinations of faults. While the study provided unprecedented insight into the potential impact of improper HVAC installations and performance degradation, it also identified key knowledge gaps. This literature review, including examination of field-based studies, aims to fill those gaps:

- How would field data, collected under imperfect conditions, change the results?
- What research has been performed on the prevalence of installation faults, and how can the data and findings from this research inform the need for better HVAC system installation and performance?
- What are the impacts of the studied faults on other types of systems and other aspects of HVAC system performance (e.g., occupant comfort, indoor air quality, and equipment durability)?

DOE gathered and reviewed 44 reports, focusing primarily on field studies, produced by industry experts, utilities, and regional energy efficiency organizations that documented the energy performance impacts of common HVAC faults that occurred because of installation and/or maintenance issues. This collection includes reports published prior to the 2014 NIST study and more recent studies. Findings were supplemented by informal discussions with subject matter experts in the spring/summer of 2017, and the results of 13 interviews of HVAC industry stakeholders regarding common practices and the relative impacts of oversizing of HVAC equipment conducted by Oak Ridge National Laboratory staff in 2015-2016.

DOE's systematic review underscored that comfort and energy performance in the single family residential HVAC replacement market are impacted most by improper airflow, incorrect refrigerant charge, and duct performance

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[1] U.S. Department of Energy—Office of Energy Efficiency and Renewable Energy, Building Technologies Office. Residential Central Air Conditioning and Heat Pump Installation–Workshop Outcomes. U.S. Department of Energy: Washington, DC. November 2016. DOE/EE-1496. https://www.energy.gov/sites/prod/files/2016/11/f34/CAC-CHP%20Installation%20Workshop%20Report%20-%2011-30-16.pdf.

[2] U.S. Department of Commerce—National Institute of Standards and Technology, Energy and Environment Division. Sensitivity Analysis of Installation Faults on Heat Pump Performance. NIST Technical Note 1848. U.S. Department of Commerce: Washington, DC. September 2014. https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1848.pdf.

issues. It also revealed that the issues often inherent with existing ductwork (e.g., duct leakage, duct insulation, duct design, and exposure to outdoor conditions) complicate the overall load calculation and sizing process and interfere with the efficient operation of equipment, even when it is installed with correct airflow and refrigerant charge.

Additionally, the majority of studies reviewed found that the energy savings attributed to proper residential HVAC equipment sizing may be less than previously estimated for the majority of split-system HVAC equipment installed in single-family homes. Few studies, however, have addressed performance of advanced technologies or installations in highly efficient homes (such as low-load or zero net energy homes). Further, some studies show proper sizing can significantly reduce peak demand, which has benefits for the electricity grid and consumers by lowering overall energy costs. Under current industry practice, however, the majority of systems—especially those installed as emergency replacements—are installed without performing detailed load calculations.

Detailed load calculations tend to be imprecise and are likely to be distorted by inefficiencies in the existing duct system that can be difficult to accurately measure and costly to repair. Given the limited availability of equipment in sizing increments less than half a ton (6,000 Btuh), it may be difficult to justify the added time and cost of completing a detailed load and sizing calculation in the vast majority of retrofit installations that are triggered by equipment failure.[3] A more streamlined and accessible means of properly sizing equipment could help enable large-scale adoption of proper equipment sizing practices in retrofit applications. In specific applications where improper sizing has greater impact, detailed load calculations should continue to be used, such as low-load homes and homes where humidity control is a key consideration.

The availability of multi-stage and variable speed equipment offers a potential solution to the need for detailed load and sizing calculations in many replacement/retrofit applications. But additional research is needed to better understand the interplay between comfort, efficient equipment operation, distribution system losses, and optimized control strategies to support the development of updated sizing, equipment selection, and system design procedures.

This report presents the background and approach for the cited research and lists key findings and recommendations for further areas of study to promote industry adoption of improved HVAC installation practices. An annotated bibliography of the publications, reports, and documents considered for this review is included (see Appendix B). Results from this literature review will inform DOE's ongoing R&D, field validation, and communication on advancing the industry adoption of improved HVAC installation practices.

[3] Informal discussions with users of Manual J and other load calculation tools, indicate the time required to collect input data in the field and complete the data entry needed to produce a sizing estimate can range from 90 minutes to as much as 8 hours, depending on the complexity of the home and the experience level of the technician. The time and expense required to obtain load calculations further increases when visual observations are supplemented with diagnostic tests (e.g. blower door tests and duct leakage tests) to improve the accuracy of the input data.

Background and Approach

Building on NIST's work, DOE compiled and reviewed publications, reports, and industry studies that considered *in situ* HVAC performance and the impact of installation and maintenance faults. DOE obtained reports from existing resource repositories, including the Building America Solution Center, the Consortium for Energy Efficiency Resource Library, the California Energy Commission website, and DOE national laboratories, as well as from sources mentioned during interviews with industry experts. While the list of studies considered for this report is by no means exhaustive, it represents a good faith effort to review the existing knowledge base so as to accurately inform our findings and recommendations. The study addresses the following research topics:

1. Is there sufficient data available to accurately quantify the cost savings, energy savings, and other measurable benefits resulting from quality installation (QI)? Or, alternatively, is the data available to accurately quantify the penalty for installation or maintenance faults?

2. Is the research robust enough to extrapolate nationally? What limitations exist?

3. To what extent are technology solutions available in the market (i.e., fault-tolerant HVAC equipment, and/or automated field verification tools) that could mitigate installation faults?

4. Is there sufficient data to quantify the frequency of faults, by type, existing in the field? Are baseline studies or utility program data available to aid in determining the prevalence of those faults?

This search was coupled with outreach to regional energy efficiency organizations, utility HVAC programs, EPA's ENERGY STAR® Program, and subject matter experts, including many of the original authors of the cited research. DOE also gathered input from industry representatives attending DOE's Building Technologies Office Peer Review Meeting: *Smart Tools for Improving Installed Performance of Residential and Small Commercial HVAC Systems Expert Meeting* held on March 16, 2017.
[4] Based on analysis from an initial set of reports, DOE generated a list of questions (see Appendix C) to guide further input and identify additional source documents to be included in this review.

Analysis of Information Gathered

DOE identified and systematically reviewed 44 reports. DOE considered the evolution of the research, examining the reports chronologically to gauge how industry views on the relative impact of faults on HVAC performance have shifted over time as technologies and industry's understanding of the issues have changed. Studies researching the impact of improper installation on HVAC equipment performance date back to the early 1990s. Since that time, a number of technology innovations in heating and cooling equipment and diagnostic tools have come to market and, with some trial and error along the way, many lessons have been learned regarding the impact of sub-optimal installations. Advancements in HVAC technology innovations (e.g., TXVs, variable speed components, and modulating equipment) have enabled more energy efficient equipment to be installed in more homes. Appendix A presents the evolution of research on HVAC installations, categorized by topics addressed including fault detection methodologies, ducts, refrigerant charge, sizing and load calculations, airflow, peak demand, building shell (e.g., leakage rates), contractor concerns, and demand concerns (e.g., customer concerns). The testing methods are also included. Appendix B includes an alphabetized annotated bibliography for each of the reports reviewed.

Table 1 (below) summarizes our key findings based on the project's four research topics. A more detailed discussion of the frequency and net impact of installation and maintenance faults follows.

[4] Navigant Consulting, Inc. U.S. Department of Energy's Workshop on Smart Tools for Improving Installed Performance of Residential and Small Commercial HVAC Systems Stakeholder Workshop. Navigant Consulting, Inc.: Chicago, IL. March 16, 2017. https://www.energy.gov/sites/prod/files/2017/11/f46/bto-QI-HVAC-Systems-Stakeholder-Workshop-Discussion-Summary-11-2017.pdf.

Table 1: Key Findings by Research Topic

	Research Topic	Key Findings
1	Quantifying Benefits of Better Installations	• Sufficient data exists to support the need for improved installation and maintenance, but the level of energy and demand savings to be gained varies by fault type and climate zone. • Information about the prevalence of faults and the distribution of the magnitude of faults by type are also necessary to develop cost and savings estimates. Table 2 attempts to summarize these findings, but direct comparisons between studies are complicated by the use of varying metrics and measurement methods used by the researchers. • Findings across the studies reveal pervasive incidences of field performance issues—and savings opportunities—in refrigerant-based central cooling and heating systems.
2	Scope and Applicability of Existing Knowledge Base	• Available field studies cover hot-dry, mixed-dry, hot-humid, mixed-humid, cold, and very cold climates. • Most field studies are small in scale and a variety of metrics are used, making it difficult to make statistically valid extrapolations and to quantify the wide-scale impact of installation faults. However, consensus is strong that duct leakage is a nearly universal problem, and the vast majority of refrigerant-based systems suffer from airflow and/or refrigerant charge faults, regardless of the age of the HVAC system, or the house. • It is harder to pinpoint a specific energy or cost penalty, as the scale of the faults varies by study and the direction of the faults (over or under for sizing, airflow, and refrigerant charge) may vary by region.
3	Availability of Technology Solutions	• Researchers are starting to investigate the potential for multi-stage and variable speed equipment to mitigate sizing issues but these systems are still susceptible to common faults like refrigerant charge, airflow, and poor duct design and installation. • Early research suggests that complex interactions between the equipment, distribution system condition, and control settings have a significant impact on the success of optimizing the potential benefits of these technologies. • Automated verification system tools are suggested in one study [Appendix A: 44] as a potential remedy to mitigate installation faults as they occur.
4	Prevalence of Faults	• Duct leakage is the most common source of performance degradation of HVAC systems, with most studies finding 90-100% of systems tested needing sealing or repairs to the supply or return air ducts. • Low airflow is found more than 50% of the time in all regions studied, while high airflow is a problem in 8-15% of systems. • Refrigerant charge faults vary by study approach and region, but range between 29-78% undercharge and 4-50% overcharge. • The presence of non-condensables in refrigerant lines is a potentially common fault that has not been studied extensively. While at least one study [Appx A: 23] identified the presence of non-condensables as a potentially important problem, additional research is needed to better quantify the prevalence, magnitude, and relative impact on system performance of this fault type.

Research Topic 1: Quantifying Benefits of Better Installations

The literature provides sufficient data to support the need for improved installation and maintenance practices. However, the prevalence of specific faults can vary by region, and most studies are limited to a single region. There is general agreement that airflow and refrigerant charge are the key issues with AC/HP performance. However, quantifying the exact impact is difficult because the relative impact can vary by region due to climate and/or construction practices, and because interactions with leaky ductwork confound efforts to accurately predict potential savings. Occupant behavior also varies significantly, which further challenges predictions about the energy performance of installed equipment. For instance, for many homeowners in colder climates [Appx A: 18], commonly accepted assumptions for operating hours are incorrect, with discretionary use of AC resulting in total run times 25-33% lower than projected and peak afternoon events contributing up to 2.5% additional demand burden. Additionally, the practice of continuous fan operation has been found in multiple studies to be a significant factor in exacerbating both energy consumption and demand penalties stemming from installation and maintenance issues.

Potential benefits associated with repairing existing systems vary with the level of intervention, type of system (e.g., central air conditioning, heat pumps, fossil fuel furnaces, etc.), and climate demands. In all cases, duct performance represents a wild card in terms of being able to accurately predict and achieve energy savings targets. Potential benefits of repairing the studied faults include:

- Duct sealing and insulation: 33% increased cooling capacity, 16-41% increased seasonal system efficiency [Appx A: 1, 4]
- Duct sealing, insulation, airflow and refrigerant charge correction combined: 12-47% energy savings and 1.2 kW demand reduction [Appx A: 2, 3, 23, 44]
- Static pressure, capacity, efficiency, refrigerant charge, and thermal expansion valves (TXV) repairs: 24% efficiency improvement in AC/HP systems [Appx A: 21]
- Incremental savings from tuning up existing AC/HP systems are approximately 5% [Appx A: 18]
- Gas furnace tune-up with some duct improvements achieved 23% increased capacity [Appx A: 30].

Research Topic 2: Scope and Applicability of Existing Knowledge Base

The available research covers all major climate zones with the exception of marine climates. While most field studies are small in scale, the field data largely aligns with predictions based on simulations and lab tests. However, the condition of the distribution system (i.e., location, leakage rates, static pressure, etc.), occupant thermostat, and fan settings also greatly impact overall system performance. While additional field study is needed to better understand how to optimize advanced system design (e.g., ECM motors, multi-stage and variable speed equipment, and smart controls), it appears that the case has sufficiently been made that duct leakage, incorrect airflow, and incorrect refrigerant charge are pervasive faults in both new and existing equipment nationwide.

Research Topic 3: Availability of Technology Solutions

Research investigating the potential for advanced HVAC equipment to mitigate the penalties incurred from common faults is limited. One small-scale study [Appx A: 13] designed to determine the potential for dual-stage equipment to mitigate penalties incurred from oversizing found that field performance of the systems was significantly less than lab tests, with actual measured performance of central AC systems at 59-84% of rated SEER. The same study suggested that there may be both energy consumption and peak demand penalties associated with downsizing dual-stage equipment, but further study is needed in this area.

Research Topic 4: Prevalence of Faults by Type

Existing research dating back to the mid-1990s and continuing through 2016 indicate that 70-90% of AC/HP systems in homes have at least one performance-compromising fault incurred at installation or due to inadequate maintenance. When duct leakage is considered, these rates rise to 90-100%.

Gas furnaces are less susceptible to installation faults, with gas pressure being the primary adjustment. Low airflow (indicated by high temperature rise) can also be a problem for fossil fuel furnaces causing systems to cycle on the high limit, but there is minimal energy impact associated with these issues. The greater effect is on comfort and system durability.

It is also important to note that the studies do not provide sufficient data to reliably quantify the prevalence of multiple faults, or the impacts of faults occurring in combination.

Table 2 summarizes the field measured data by evaluated fault type.

Table 2: Field Measured Data by Fault Type

Fault Type	Reports	States	Recommended Range[5]	% of Systems Testing Higher than Recommended Range	% of Systems Testing Lower than Recommended Range
Equipment Sizing	Appx A: 1, 2, 3, 5, 8, 12, 13, 18, 24	AZ, CA (south), FL, NJ, NV, TX, WI	33-48% oversize compared to Manual J	31-93%	0-9%
Airflow	Appx A: 1, 2, 3, 8, 24, 44	AZ, CA (north and south), MN, NJ, NV, WI	Less than 350 CFM/ton	8-29%	50-93%
Refrigerant Charge	Appx A: 2, 3, 8, 24, 44	AZ, CA (north), NJ, NV, MN, WI	Exceeded manufacturer superheat or subcooling ranges	4-50%	29-78%
Duct Leakage	Appx A: 1, 2, 3, 4, 8, 23, 24	AZ, CA (north and south), NJ, NV, TX	100 CFM25 (to outside) or more	67-100%	N/A

[5] Varying methods and metrics were used to measure the studied faults. The information provided in the table represents the most commonly used metrics to determine out-of-compliance performance.

Summary of Findings and Recommendations

Based on the systematic review and analysis, DOE identified the following findings:

- **Continued pursuit and support of HVAC quality installation is needed, but new approaches may be required.** Despite extensive research, HVAC quality installation and maintenance practices have not been widely adopted throughout the HVAC industry. Research indicates that training and standards alone are insufficient to influence trade practices [Appx A: 38, 41] and consumers are driven primarily by low cost and fast service [Appx A: 8, 40, 42], particularly in retrofit scenarios. Technology solutions in the form of advanced equipment, controls, and automated verification tools hold promise but need support to engage the market. As such, collaboration with industry to research and field validate HVAC system performance is needed.

- **The prevalence and impact of non-condensables in the refrigerant lines is still unknown.** Additional field research is needed to better quantify the frequency with which systems are operating with non-condensable contaminants in the refrigerant line, the magnitude and range of the level of contamination, and the degree to which the system performance is compromised as a result.

- **More research is needed to determine the relative impact of faults on HVAC system performance beyond energy (e.g., occupant comfort, indoor air quality, and equipment durability).** Most studies have focused primarily on energy impacts of improper system design and installation practices. Taking the extra steps to make the necessary measurements and adjustments as a system is installed adds cost and time to the job. To justify this added burden on the contractor and customer, it would be worthwhile to better quantify the potential non-energy related benefits of a proper and verified installation. For example, which faults cause more wear and tear on the equipment, and to what extent do properly performing systems maintain more consistent comfort and health conditions?

- **Additional work is needed to improve duct system performance.** Ducts with enough leakage to require sealing can occur as frequently as 70-100% of existing systems, but duct leakage characteristics vary regionally and duct performance is increasingly dependent on housing vintage as codes (and enforcement) get better. In addition to leakage, some duct systems suffer from other design (e.g., restrictive duct capacity) or installation issues (e.g., incorrectly installed flex duct) which can also adversely impact system performance. These repairs are not a natural fit for any existing trade, the work can be difficult and labor-intensive, and there is no consumer market for these services. Technological advancements in duct materials, design, installation, and sealing techniques, as well as market breakthroughs, are needed to mitigate this issue.

- **Evolving sizing and equipment selection practices are needed to better address retrofit scenarios and support proper design of systems using advanced equipment and control technologies.** Efforts should focus on more accurately assessing the balance between sensible and latent loads for cooling, establishing procedures for selection of multi-stage and variable speed equipment, and developing methods or tools that speed up and simplify the load calculation process. Although studies have found that energy savings attributed to proper residential HVAC equipment sizing may be less than previously estimated, the number of studies with field-verified data on the impacts of sizing on energy efficiency and system performance is limited [Appx A: 12, 19]. Moreover, retrofit scenarios present unique challenges as obtaining accurate input data for load calculations can be complicated, time consuming, and subject to interpretation. In addition, better sizing, equipment selection, and system design guidance are needed when specifying multi-stage and variable speed equipment. In the case of basic retrofits, a quick assessment that estimates acceptable equipment sizing within the margins of what is available from the manufacturer would be sufficient to avoid gross oversizing without placing undue burden on the contractor or creating a false sense of precision by asking for detailed inputs that may not be available to the technician. In the case of multi-stage and variable speed equipment, sizing strategies should include consideration of interactions with existing duct systems and control strategies to optimize system performance. In addition, studies have emerged showing that:

- Even when using best practices, Manual J results can overestimate sensible loads by as much as 50% [Appx A: 5] and also underestimate latent loads [Appx A: 13]; and
- The level of effort and uncertainty associated with input assumptions required to complete a comprehensive load calculation and determine accurate sizing often outweighs the net benefit in retrofit situations.

The findings above provide the basis for the following recommendations to advance high performance HVAC installation practices.

- Develop and define a universally accepted set of methodologies and metrics for measuring the benefits of applying best installation and maintenance practices to enable more "apples to apples" comparisons among available field data sets.

- Focus market interventions on the following installation elements to improve performance in residential retrofits:

  - Ensure tools and guidance for proper system design and equipment selection are readily available and accessible to installers, especially when specifying multi-stage and variable speed equipment.
  - Ensure correct airflow by any means possible (i.e., fan speed adjustments are better than not doing anything even if ducts cannot be repaired) and verify through direct or indirect (i.e., static pressure drops combined with fan curve data) airflow measurements;
  - Ensure correct refrigerant charge using manufacturer recommended methods (i.e., sub-cooling or superheat); and
  - Address the duct system to be designed, sized, sealed, insulated, and constructed cost-efficiently.

- Promote technologies and processes that reduce deployment and implementation costs and make improved installation practices more accessible and cost-efficient (e.g., automated verification systems and on-board monitoring and fault detection).

- Develop Quality Control protocols to detect and minimize the opportunity for gaming of data inputs when using automated verification tools. At a minimum, ensure data checks exist to identify patterns indicating improper use of tools and intentional gaming.

- Promote high efficiency systems and those which are capable of adapting to varying building load conditions via multi-stage or variable speed technologies.

- Conduct further research to better understand elements related to load calculations and sizing, including:
  - The role of system sizing practices and advanced controls in managing peak demand and load curves; and
  - Identification of the scenarios in which sizing should be prioritized in relation to comfort and energy consumption reduction (e.g., low-load homes, high humidity conditions, and as part of an overall system redesign inclusive of ductwork).

- Define best practices for selecting, specifying, and installing advanced technologies (e.g., multi-stage and variable speed equipment) with intelligent controls. Coordinate these definitions with equipment manufacturers developing best practices for equipment sizing, selection, and installation when coupled with inadequate duct systems that adversely impact equipment and system performance and that cannot be repaired.

For more information on DOE's efforts to improve the energy efficiency of new and existing homes, visit the Residential Buildings Integration site.

Appendix A: Evolution of Research on HVAC Installations

Table 3 is organized chronologically to help the reader align each of the 44 reports DOE reviewed with the HVAC and diagnostic testing technology available at the time each study was completed. The chronological listing also helps demonstrate the evolution of how industry views have emerged over time in terms of the relative impact of heating and cooling equipment performance faults. Studies researching the impact of improper installation on HVAC equipment performance date back to the early 1990s. Since that time, a number of technology innovations in heating and cooling equipment and diagnostic tools have come to market and, with some trial and error along the way, many lessons have been learned regarding the impact of sub-optimal installations. Advancements in HVAC technology innovations (e.g., TXVs, variable speed components, and modulating equipment) have enabled more energy efficient equipment to be installed in more homes. In examining each report, DOE's analysis considered the testing methods applied and how each of the following topics were addressed:

- **Fault Detection Methodologies:** includes reports examining the methodology of measuring the performance of diagnostic tools (handheld and onboard sensors) and/or their accuracy
- **Ducts:** includes reports examining practices, impacts and/or prevalence of faults related to duct material, location, design, leakage, and insulation
- **Refrigerant Charge:** includes reports examining impacts and/or prevalence of improper refrigerant charge
- **Sizing and Load Calculations:** includes reports examining practices, impacts and/or prevalence of faults related to sizing and load calculations
- **Airflow:** includes reports examining practices, impacts, and/or prevalence of faults related to airflow
- **Peak Demand:** includes reports examining the impact of proper HVAC installation on peak demand
- **Building Shell:** includes reports that documented building airflow leakage rates (in cubic feet per minute, or CFM)
- **Contractor Concerns:** includes reports examining contractor concerns related to HVAC installation, verification, and maintenance practices
- **Demand Concerns:** includes reports examining homeowner concerns and interests related to HVAC installation practices

Table 3: Summary of Reviewed Research Studies on HVAC Installations

Ref #	Publication Date	Report	Topics Addressed									Testing Method			
			Fault Detection Methodologies	Ducts	Refrigerant Charge	Sizing & Load Calculations	Airflow	Peak Demand	Building Shell (Leakage Rates)	Contractor Concerns	Demand Concerns (Customer)	Modeled	Lab Testing	Field Testing	Survey
1	1995	Blasnik, M., Proctor, J., Downey, T., Sundal J., & Peterson, G. Assessment of HVAC Installations in New Homes in Southern California Edison's Service Territory		x	x	x	x	x	x			x		x	
2	1995	Blasnik, M., Proctor, J., Downey, T., Sundal, J., & Peterson, G. Assessment of HVAC Installations in New Homes in Nevada Power Company's Service Territory		x	x	x	x	x	x			x		x	
3	1996	Blasnik, M., Downey, T., Proctor, J., & Peterson, G. Assessment of HVAC Installations in New Homes in APS Service Territory		x	x	x	x	x	x			x		x	
4	1996	Jump, D., Walker, I., &, Modera, M. Field Measurements of Efficiency and Duct Retrofit Effectiveness in Residential Forced Air Distribution Systems		x			x		x					x	
5	1998	Proctor, J. Monitored In-Situ Performance of Residential Air-Conditioning Systems		x	x	x	x	x	x			x		x	
6	1998	Walker, I., Sherman, M., Modera, M., & Siegel, J. Leakage Diagnostics, Sealant Longevity, Sizing and Technology Transfer in Residential Thermal Distribution Systems		x			x		x					x	
7	2000	Siegel, J., Walker, I., & Sherman, M. Delivering Tons to the Register: Energy Efficient Design and Operation of Residential Cooling Systems		x		x	x	x	x			x			
8	2001	Xenergy New Jersey Residential HVAC Baseline Study		x	x	x	x			x	x			x	x

Ref #	Publication Date	Report	Topics Addressed									Testing Method			
			Fault Detection Methodologies	Ducts	Refrigerant Charge	Sizing & Load Calculations	Airflow	Peak Demand	Building Shell (Leakage Rates)	Contractor Concerns	Demand Concerns (Customer)	Modeled	Lab Testing	Field Testing	Survey
9	2002	Foster, R., South, M., Neme, C., Edgar, G., & Murphy, P. Residential HVAC Quality Installation: New Partnership Opportunities and Approaches				x				x					x
10	2003	Walker, I. Register Closing Effects on Forced Air Heating System Performance		x			x		x			x	x		
11	2004	Wilcox, B. & Larsen, J. Measured Cooling load, Energy, and Peak Demand Savings from High-Performance Glass in a California Production House						x						x	
12	2006	Sonne, J., Parker, D., & Shirley, D. Measured Impacts of Proper Air Conditioning Sizing in Four Florida Case Study Homes		x		x	x	x						x	
13	2006	Proctor, J., & Cohn, G. Two-Stage High Efficiency Air Conditioners: Laboratory Ratings vs Residential Installation Performance		x	x	x	x	x	x					x	
14	2006	Titus, E. Strategies to Increase Residential HVAC Efficiency in the Northeast		x	x	x	x	x	x	x	x	x		x	x
15	2006	Walker, I. Residential Furnace Blower Performance		x			x	x	x			x	x		
16	2007	Henderson, H., & Shirley, D. Closing the Gap: Getting Full Performance from Residential Central Air Conditioners		x		x	x		x			x			
17	2007	Wirtschafter, R., Thomas, G., Azulay, G., Blake, W. and Prahl, R. Do Quality Installation Verification Programs for Residential Air Conditioners Make Sense in New England?		x	x	x	x	x				x		x	
18	2008	Pigg, Scott Central Air Conditioning in Wisconsin: A compilation of recent field research.			x	x	x	x	x		x			x	x
19	2009	Proctor, J. AC Sizing, Electrical Peak, and Energy Savings				x		x				x		x	

Ref #	Publication Date	Report	Topics Addressed									Testing Method			
			Fault Detection Methodologies	Ducts	Refrigerant Charge	Sizing & Load Calculations	Airflow	Peak Demand	Building Shell (Leakage Rates)	Contractor Concerns	Demand Concerns (Customer)	Modeled	Lab Testing	Field Testing	Survey
20	2009	Talerico, T., & and Winch, R. Focus on Energy Evaluation: ECM Furnace Impact Assessment Report								x	x				x
21	2010	Kim, W. & Braun, J. Impacts of Refrigerant Charge on Air Conditioner and Heat Pump Performance			x								x		
22	2010	Hunt, Marshall, Kristin Heinemeier, Marc Hoeschele, and Elizabeth Weitzel HVAC Energy Efficiency Maintenance Study	x	x	x		x	x				x		x	
23	2011	Proctor, J., Chitwood, R., & Wilcox, B. Efficiency Characteristics and Opportunities for New California Homes (ECO) PIER Program Final Project Report		x			x		x					x	
24	2011	Rhodes, J. D., Stephens, B., & Webber, M.E. Using energy audits to investigate the impacts of common air-conditioning design and installation issues on peak power demand and energy consumption in Austin, Texas						x						x	
25	2012	Brand, L., & Rose, W. Measure Guideline: High Efficiency Natural Gas Furnaces				x			x				x		
26	2012	Heinemeier, K., Hunt, M., Hoeschele, M., Weitzel, E., & Close, B. Uncertainties in Achieving Energy Savings from HVAC Maintenance Measures in the Field	x		x								x	x	
27	2012	Walker, I., Dickerhoff, D., Faulkner, D., & Turner, W. Energy Implications of In-Line Filtration in California		x			x	x	x					x	
28	2012	Yuill, David P., and James E. Braun. Evaluating Fault Detection and Diagnostics Protocols Applied to Air-Cooled Vapor Compression Air-Conditioners	x										x		

Ref #	Publication Date	Report	Topics Addressed									Testing Method			
			Fault Detection Methodologies	Ducts	Refrigerant Charge	Sizing & Load Calculations	Airflow	Peak Demand	Building Shell (Leakage Rates)	Contractor Concerns	Demand Concerns (Customer)	Modeled	Lab Testing	Field Testing	Survey
29	2013	Kim, W. Fault Detection and Diagnosis for Air Conditioners and Heat Pumps Based on Virtual Sensors	x		x		x					x	x	x	x
30	2013	Yee, S., Baker, J., Brand, L., & Wells, J. Energy Savings from System Efficiency Improvements in Iowa's HVAC Save Program		x			x							x	
31	2014	Booten, C., Christensen, C., & Winkler, J. Energy Impacts of Oversized Residential Air Conditioners–Simulation Study of Retrofit Sequence Impacts.		x		x						x			
32	2014	Rhodes, J. D. Optimal Residential Energy Consumption, Prediction, and Analysis		x		x		x				x		x	
33	2014	Stephens, B. The impacts of duct design on life cycle costs of central residential heating and air-conditioning systems		x		x	x		x			x			
34	2014	Braun, James E., and David Yuill. Evaluation of the Effectiveness of Currently Utilized Diagnostic Protocols	x									x	x		
35	2014	Domanski, P. A. , Henderson, H.I., & W.V. Payne Sensitivity Analysis of Installation Faults on Heat Pump Performance	x	x	x	x	x					x	x		
36	2015	Brand, L., Yee, S., & Baker, J. Improving Gas Furnace Performance: A Field and					x						x	x	
37	2015	Cummings, J., Withers, C., & Kono, J. Cooling and Heating Season Impacts of Right-Sizing of Fixed and Variable-Capacity Heat Pumps with Attic and Indoor Ductwork		x		x	x	x	x			x	x		
38	2015	NMR Group, Inc. Baseline Characterization Market Effects Study of Investor-Owned Utility Residential and Small Commercial HVAC Quality Installation and Quality Improvement Programs in California		x	x		x		x	x	x			x	x

Ref #	Publication Date	Report	Topics Addressed									Testing Method			
			Fault Detection Methodologies	Ducts	Refrigerant Charge	Sizing & Load Calculations	Airflow	Peak Demand	Building Shell (Leakage Rates)	Contractor Concerns	Demand Concerns (Customer)	Modeled	Lab Testing	Field Testing	Survey
39	2015	Parmenter, K., Prijyanonda, J., & Dorton, D. The Coil & Blade Project: Combining Field Work and Interval Data to Measure Impacts		x	x							x		x	
40	2015	Steiner, E., & Malinick, T. California HVAC Quality Installation/Quality Maintenance Customer Decision-Making Study									x	x			x
41	2015	Sullivan, M., Smith, J., Afrat, K., & Bosco, P. Impacts of the OPA HVAC Installation Optimization Training Program on Realized Energy Efficiency in Retrofit AC Systems.					x					x		x	
42	2015	Vaidya, R., Fogel, C., Tolkin, B., & Poulin, B. Swimming Against the Tide–Gauging HVAC Quality Installation and Quality Maintenance Program Efforts to Establish a Foothold in the Market		x	x		x			x	x			x	x
43	2016	Mallay, D. Compact Buried Ducts in a Hot-Humid Climate House		x		x	x					x		x	
44	2016	Pigg, S., Cautley, D., & Koski, K. Improving Installation and Maintenance Practices for Minnesota Residential Furnaces, Air Conditioners and Heat Pumps		x	x	x	x	x		x	x			x	x

Appendix B: Annotated Bibliography

This annotated bibliography presents the evaluated reports with summary annotations (in alphabetical order for ease of reference). Annotations provided are primarily focused on consideration of the energy performance impacts of common HVAC faults driven by installation and/or maintenance issues for the single-family residential HVAC replacement market. If a study was conducted in a specific location, the location is noted after the report URL.

Table 4: Annotated Bibliography

Ref #	Report
3	Blasnik, Michael, Tom Downey, John Proctor, and George Peterson. *Assessment of HVAC Installations in New Homes in APS Service Territory.* Report no. 95.111. Proctor Engineering Group, Ltd: Phoenix, AZ April 22, 1996. http://www.proctoreng.com/dnld/95111.pdf (Phoenix, AZ) This study included a sample size of 28 HVAC systems in 22 newly built homes. Key findings include: duct leakage and existing duct insulation levels reduce overall cooling efficiency (reasonable improvements can save 16% of the cooling energy); air conditioners often have insufficient air flow across the indoor coil and are frequently undercharged (proper installation, following the manufacturers installation instructions, and testing would remedy these problems at a cost of about $70); a program that ensures tight, well-insulated ducts and properly installed air conditioners could reduce cooling usage by approximately 42% and diversified peak demand by 1.2 kW (the additional cost is estimated to be $210 per unit).
1	Blasnik, Michael, John Proctor, Tom Downey, Jim Sundal, and George Peterson. *Assessment of HVAC Installations in New Homes in Southern California Edison's Service Territory.* Report no. 94.113. Proctor Engineering Group, Ltd: Palm Springs, CA January 1995. http://www.proctoreng.com/dnld/94113.pdf (Palm Springs, CA) This investigation involved field testing duct systems, air handlers, and building shells in ten houses in Southern California Edison's service territory. Key findings include: duct leakage and low duct insulation levels cause an average effective cooling capacity loss of 33%; and air conditioners often have insufficient air flow across the indoor coils and are frequently undercharged due to improper installation procedures. A program that ensures tight, well-insulated duct systems along with properly installed air conditioners can reduce cooling usage by approximately 47% and peak demand by 1.2 kW. In addition, these modifications can reduce the specified size of installed systems, potentially leading to an additional 0.4 kW demand savings. The report also includes recommendations for improving program design to improve cooling efficiency and reduce peak demand.
2	Blasnik, Michael, John Proctor, Tom Downey, Jim Sundal, and George Peterson. *Assessment of HVAC Installations in New Homes in Nevada Power Company's Service Territory*. Final Report. Proctor Engineering Group, Ltd: Palm Springs, CA. January 1995. http://www.proctoreng.com/dnld/94113.pdf (Palm Springs, CA) This study covered 40 HVAC (AC) systems in 30 newly built homes. Key findings include: duct leakage and low duct insulation levels cause an average loss of 37% in overall cooling efficiency; and air conditioners often have insufficient air flow across the indoor coils and are frequently undercharged due to improper installation procedures (the problem can be remedied for approximately $68 per house). A program that ensures tight, well-insulated duct systems along with properly installed air conditioners can reduce cooling usage by approximately 44% and peak demand by 1.2 kW. In addition, these modifications can reduce the specified size of installed systems, potentially leading to an additional 0.4 kW demand savings.

31	Booten, C., C. Christensen, and J. Winkler. *Energy Impacts of Oversized Residential Air Conditioners–Simulation Study of Retrofit Sequence Impacts*. Report no. NREL/TP-5500-60801. National Renewable Energy Laboratory: Denver, CO November 2014 https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/energy-impacts-residental-ac.pdf This report presents a simulation-based study examining the impacts of oversizing. Key findings include: energy penalties for oversizing are minimal; energy penalties in single speed systems have more to do with parasitic power consumption than oversizing; and oversizing penalties are reduced when connected to a system with duct losses.
25	Brand, L., and W. Rose. *Measure Guideline: High Efficiency Natural Gas Furnaces.* Report no. DOE/ GO-102012-3684. National Renewable Energy Laboratory: Denver, CO. October 2012. https://www.nrel.gov/docs/fy13osti/55493.pdf This document is a guideline for practitioners and is based on Partnership for Advanced Residential Retrofit (PARR) lab-based research. It includes key statements regarding gas furnace sizing, including: high efficiency furnace annual fuel utilization efficiency (AFUE) (for closed combustion furnaces) is relatively insensitive to oversizing based on lab testing in the 70% to 120% oversizing range. Even in separating the technologies (single speed vs modulating), the differences are minimal. For furnaces with permanent split capacitor (PSC) motors that are connected to tight ducts (high external static pressure above 0.5 inches of water column), there is a slight decrease in AFUE. For modulating furnaces connected to overly tight/small ducts, there is a slight increase in power to operate the circulating air blower (more power to overcome the high static pressure).
36	Brand, L., S. Yee, and J. Baker *Improving Gas Furnace Performance: A Field and Laboratory Study at End of Life*. Report no. DOE/GO-102015-4626. National Renewable Energy Laboratory: Denver, CO. February 2015. https://www.nrel.gov/docs/fy15osti/63702.pdf This report presents a field- and lab-based study investigating the impacts of common installation practices and age-induced equipment degradation on the installed performance of gas furnaces over the life of the product. Twelve furnaces of various ages and efficiencies were retrieved from Iowa homes and tested for efficiency in the lab. Prior to their removal, system airflow, static pressure, equipment temperature rise, and flue loss measurements were recorded for each furnace as installed in the house. Results indicate that steady-state efficiency in the field was 6.4% lower than that measured for the same furnaces under Standard 103 in the lab. The study indicates that equipment performance did not significantly decrease over 15-24 years of operation.
34	Braun, James E., and David Yuill. *Evaluation of the Effectiveness of Currently Utilized Diagnostic Protocols*. Purdue University: West Lafayette, IN. February 18, 2014. http://www.performancealliance.org/Portals/4/Documents/HVAC%20Research/EffectivenessOfFDDProtocols-Purdue-2014-02 pdf This paper presents lab and simulation data evaluating the performance of four fault detection diagnostic (FDD) protocols. This paper also presents an evaluation and findings regarding a fifth protocol. Key findings include: there is a question of accuracy regarding the protocols' field testing capabilities. The results produced high false alarm rates (60-100% overall, with most categories over 95%), high misdiagnosis rates, high no diagnosis rates, and low missed detection rates (which would suggest the protocols may be too sensitive). The results also provide some context for what range of performance might be expected from FDDs.

37 Cummings, James, Charles Withers, and Jamie Kono. *Cooling and Heating Season Impacts of Right-Sizing of Fixed- and Variable-Capacity Heat Pumps With Attic and Indoor Ductwork*. Report no. DOE/GO-102015-4678. National Renewable Energy Laboratory: Golden, CO. June 2015. https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/variable-capacity-heatpumps-indoor-ductwork pdf

A study funded through the Building America Partnership for Advanced Residential Construction that examined the impact of sizing on heating and cooling energy efficiency performance (including during peak demand) for both variable-capacity and fixed-capacity heat pumps. The research from this study finds that oversizing residential HVAC systems can be beneficial. Key findings include: oversizing residential central air conditioning (CAC) and air-source heat pump (ASHP) systems can be beneficial when using variable speed equipment; oversized variable-capacity systems can save substantial heating and cooling energy, the benefits of which are even more pronounced with a well-sealed duct system, and they can also substantially reduce both heating and cooling peak demand. Short-cycling was not found to be a problem. Heat pump system oversizing diminishes the number of hours per year that the system goes into electric resistance backup heating.

35 Domanski, Piotr A., Hugh I. Henderson, and W. Vance Payne. *Sensitivity Analysis of Installation Faults on Heat Pump Performance*. National Institute of Standards and Technology Technical Note 1848. U.S. Department of Commerce: Washington, DC. September 2014. http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1848.pdf

A study was conducted by NIST to assess and better understand the impacts that heat pump installation faults have on equipment electricity consumption in a single-family residential house application. This study used computer simulations and laboratory tests to quantify the impact of common faults. It includes a literature review of related studies in which the authors note that many field studies are not designed with the technical rigor (and resulting confidence intervals) that are commonly achieved in a lab environment. Key findings include: duct leakage, refrigerant undercharge, oversized heat pump with nominal ductwork, low indoor airflow due to undersized ductwork, and refrigerant overcharge have the most potential for causing significant performance degradation and increased annual energy consumption. Additionally, the impact of simultaneous faults was found to be additive.

9 Foster, Rebecca, Mia South, Chris Neme, George Edgar, and Patrick Murphy. *Residential HVAC Quality Installation: New Partnership Opportunities and Approaches*. ACEEE 2002 Summer Study on Energy Efficiency in Buildings, Volume 6. American Council for an Energy-Efficient Economy: Washington, DC. 2002. http://aceee.org/files/proceedings/2002/data/index.htm

This paper provides a historical snapshot of the progress of quality installation (QI) efforts around the country (at both Federal and local levels): the Consortium for Energy Efficiency's (CEE) 2000 QI Specification, the ENERGY STAR Cool Change Promotion, New Jersey's QI Program, and the Wisconsin QI Program. QI discussed in this paper presents a model that is very focused on sizing (and avoiding oversizing) and training, but not necessarily on delivered efficiency savings (capacity delivery).

26 Heinemeier, Kristin, Marshall Hunt, Marc Hoeschele, Elizabeth Weitzel, and Brett Close. *Uncertainties in Achieving Energy Savings from HVAC Maintenance Measures in the Field*. University of California, Davis: Davis, CA. June 2012. http://wcec.ucdavis.edu/wp-content/uploads/2013/07/Kristin-Heinemeier- ASHRAE-2012 pdf

This paper provides an analysis of the uncertainties in the measurement of common variables (such as dry bulb, wet bulb, refrigerant temperatures, refrigerant pressures, airflow and power) as measured in the lab by evaluation, measurement, and verification (EM&V) teams, by participants in maintenance programs, and by typical contractors. The uncertainties were combined in calculating sub-cooling, superheat, energy efficiency ratio (EER) and annual kWh values. A key finding is that savings vary widely.

16 Henderson, Hugh I., Jr, and Don B. Shirey, III. *Closing the Gap: Getting Full Performance from Residential Central Air Conditioners*. University of Central Florida Florida Solar Energy Center: Orlando, FL. April 27, 2007. http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1716-07.pdf

This report provides a summary of the National Association of State Energy Officials (NASEO)/State Technologies Advancement Collaborative (STAC) Task 4 to develop specifications for a residential air conditioner system optimized for hot-humid climates. The project complements efforts by the California Energy Commission (CEC) and the New York State Energy Research and Development Authority to develop residential AC systems optimized for hot-dry and norther climates, respectively.

Key findings include the following. When a conventional CAC with a seasonal energy efficiency ratio (SEER) of 13 was used to condition modeled houses, the periods of low sensible heat ratios resulted in high indoor humidity. Indoor humidity levels were higher for high-efficiency homes (compared to standard homes) because AC run times were reduced. Adding continuous ventilation (ASHRAE 62.2 standard) significantly increased the amount of time the indoor humidity was high (above 60% relative humidity) because outdoor humidity was introduced into the houses at an accelerated rate. Oversizing increased comfort (decreased supply fan runtime lead to decreased outdoor air that was introduced to the building enclosure through leaky ducts). Comfort was increased (with relative humidity dropping below 60%) when the thermostat was set lower and the AC supply airflow was lowered to 300 CFM. A small standalone dehumidifier was found to be a cost-effective way to reduce indoor relative humidity.

22 Hunt, Marshall, Kristin Heinemeier, Marc Hoeschele, and Elizabeth Weitzel. *HVAC Energy Efficiency Maintenance Study*. Report no. SCE0293.01. University of California, Davis: Davis, CA. December 29, 2010. http://www.calmac.org/%5C/publications/HVAC_EE_Maintenance_Final.pdf

This study examines the question of appropriate savings attributes, especially as they relate to the EM&V deemed savings processes. The study reviews six EM&V studies that raised questions about the design and efficacy of the implementation of programs focused on single measure rebate programs for refrigerant charge, airflow, and ducts (testing and sealing) vs. implementation with a holistic QI approach. The study includes a summary review of key publications and reports from past 20+ years and analyzed laboratory test data from HVAC systems operated with and without faults.

4 Jump, David A., Iain S. Walker, and Mark P. Modera. *Field Measurements of Efficiency and Duct Retrofit Effectiveness in Residential Forced Air Distribution Systems*. Lawrence Berkeley National Laboratory: Berkeley, CA. 1996. http://aceee.org/files/proceedings/1996/data/papers/SS96_Panel1_Paper15.pdf (Sacramento, CA)

This report includes a field study of 24 California homes to determine the potential savings and improved delivery efficiency from air sealing and insulating ductwork that exists outside of the conditioned space (e.g., ducts in attics). The study included tests for infiltration, register airflows, fan air flow, duct leakage, and home characteristics. For several metrics, they measured before and after insulating/air sealing the ductwork. The mean cost to retrofit was between $635 and $1,069 (and does not include travel time fixed costs); labor was 77% of the total cost. The average reduction in energy consumption (due to sealing and insulation) was 18%.

29 Kim, Woohyun. "Fault Detection And Diagnosis For Air Conditioners and Heat Pumps Based On Virtual Sensors." PhD dissertation. Purdue University: West Lafayette, IN. 2013. http://docs.lib.purdue.edu/open_access_dissertations/153

This study attempts to quantify the impact of installation faults in refrigerant based HVAC systems. Using simulations and virtual sensors, simple models were developed to estimate energy consumption penalties of various faults (and costs using fixed sensors).

21	Kim, Woohyun and Braun, James E., "Impacts of Refrigerant Charge on Air Conditioner and Heat Pump Performance." *International Refrigeration and Air Conditioning Conference.* Paper 1122. Purdue University: West Lafayette, IN. 2010. http://docs.lib.purdue.edu/iracc/1122This report studies the impact of improper refrigerant charging on cooling capacity, heating capacity, and efficiency. Key findings include the following. Undercharge or overcharge can reduce air conditioner life, capacity, and efficiency. For systems with a fixed orifice (FXO), there is a rapid reduction in both cooling capacity and energy efficiency with decreasing refrigerant charge level. For systems with TXVs, both capacity and co-efficient of performance (COP) do not decrease significantly until the refrigerant charge level reaches around 70%; when the charge level is under 70%, the TXV becomes fully open and then the system acts like a system having a FXO. Based on the situations that are commonly encountered in the field, refrigerant undercharging in the range of 12-19% can lead to an average reduction of 12.87% in cooling capacity and 7.6% in energy efficiency.
43	Mallay, D. *Compact Buried Ducts in a Hot-Humid House*. Report no. DOE/GO-102016-4796. National Renewable Energy Laboratory: Golden, CO. January 2016 https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/compact-buried- ducts-hot-humid pdf A report that outlines research activities by Home Innovation, a U.S. Department of Energy Building America team with the project goal of developing an alternative buried duct system that performs effectively as ducts in conditioned space—ducts that are durable, energy efficient, and cost-effective—in hot humid climates (International Energy Conservation Code warm-humid Climate Zone 3A). Key findings include: compact buried duct layout can be a practical alternative to installing ducts inside conditioned space (inside the air barrier); most savings are achieved by a simpler (reduced length) duct layout that limits leakage, conduction loses and pressure drops (static pressure); minimum recommendation of R-8 duct insulation and R-30 attic insulation.
38	NMR Group, Inc. *Baseline Characterization Market Effects Study of Investor-Owned Utility Residential and Small Commercial HVAC Quality Installation and Quality Improvement Programs in California*. CALMAC Study ID CPU0102.01. California Public Utilities Commission: San Francisco, CA. January 14, 2015. http://www.calmac.org/publications/CPUC_HVAC_Baseline_Market_Study_Final_Report.pdf This study established a baseline of current installation and maintenance practices using information from a variety of sources (including other studies, utility staff interviews, a survey of 500+ customers, a survey of 245+ contractors, and HVAC distributor interviews). Key findings include: 42% of residential contractors were aware of Air Conditioning Contractors of America (ACCA) Standard 5 and only 14% say they adhered to it; 10% say they adhere to ACCA Standard 4 Quality Maintenance (QM), but none of the 13 techs observed in the field (for an ancillary study) were knowledgeable of ACCA Standard 4.
39	Parmenter, Kelly, Joe Prijyanonda, and Donney Dorton. *The Coil & Blade Project: Combining Field Work and Interval Data to Measure Impacts*. International Energy Program Evaluation Conference: Madison, WI. 2015. https://www.iepec.org/wp-content/uploads/2015/papers/089.pdf (Oklahoma) This study included field data collection that incorporated spot measurements and data logging of HVAC system components to measure the impacts of key maintenance measures as a function of the sequence in which they were performed. Key findings include: a methodology to apply field data to recommend a set of deemed savings, and demonstration of using interval data to disaggregate the HVAC equipment from the rest of the loads in the home by directly comparing the logged data of the HVAC system components with whole-home 15-minute interval data.
18	Pigg, Scott. *Central Air Conditioning in Wisconsin: A Compilation of Recent Field Research*. ECW Report Number 241-1. Focus on Energy: Madison, WI. May 2008. https://focusonenergy.com/sites/default/files/centralairconditioning_repot.pdf (Wisconsin) This report summarizes the results of several Wisconsin field studies. Key findings include the following. One field study of 2- versus 3-ton systems indicated the effect of downsizing on energy savings or humidity control was inconclusive. One of the sites showed no difference in weather-normalized energy consumption (reduced power requirements were almost exactly offset by increased run time).

44 Pigg, Scott, Dan Cautley, and Karen Koski. *Improving Installation and Maintenance Practices for Minnesota Residential Furnaces, Air Conditioners and Heat Pumps*. Report no. COMM-201305222-72623. Minnesota Department of Commerce, Division of Energy Resources: St. Paul, MN September 30, 2016 http://mn.gov/commerce-stat/pdfs/card-improving-insullation.pdf (Minnesota)

This report examines the savings potential (and program strategies) associated with QI and maintenance of residential CACs, ASHPs and natural gas furnaces in Minnesota. The study includes field based research (100 systems), market research, interviews with installation actors (contractors, distributors, utilities and others), and a telephone survey of 700 homeowners. Key findings indicate that price and reputation drive consumer decisions, and that consumers have little awareness, concern for, or understanding of installation issues that affect the performance of the systems they purchase. "Quality" is judged by the technology of the equipment and the cleanliness and professionalism of the servicing technician. More than half of surveyed households report having their heating and/or cooling system serviced in the last five years; 25% have a maintenance service contract; and nearly 50% of households practice continuous air circulation at some point during the year. Field testing reveals nine out of ten HVAC systems have an installation or maintenance issue that could be corrected with an average improvement of 12% (± 3) or roughly 100 kWh. Most cooling system opportunities are related to refrigerant charge and airflow adjustments. Methods for measuring airflow do not always agree. CACs in new homes appear to run about 50% more hours and use nearly 70% more energy on average than CACs in older homes. The higher energy consumption is mainly due to house size (new homes on average are a third larger). Higher operating hours for new homes may reflect lack of shade and/or a greater propensity for occupants to use their cooling systems. The study showed occupants of newer homes use their CACs on average 14 more days than occupants in older homes).

19 Proctor, John. *AC Sizing, Electrical Peak, and Energy Savings*. Report no. 92.086. Proctor Engineering Group, Ltd.: San Rafael, CA. June 2009. http://www.proctoreng.com/dnld/ACSizingElectricalPeakandEnergySavings pdf

A key finding of this study is that there are only very small energy savings available to homeowners from downsizing CACs, but downsizing can produce sizable peak reductions for utilities. Therefore, a case could be made that downsizing should be a high priority for society (even if the benefit to an individual is limited). One way this can be achieved is by accounting for both peak kW and kWh in cost effectiveness calculations (whereas typically just kWh is accounted for).

5 Proctor, John. *Monitored In-Situ Performance of Residential Air-Conditioning Systems*. Report no. SF-98-30-4. Proctor Engineering Group, Ltd.: San Rafael, CA. http://www.proctoreng.com/dnld/97501B.pdf

This report examines three measured factors that affect performance: cooling load, capacity, and attic temperatures. Key findings include: most common calculations for sensible heat load gain are overestimated by 50%, and airflow and refrigerant charge installation issues were found in the systems reviewed.

23 Proctor, John, Rick Chitwood, and Bruce A Wilcox. *Efficiency Characteristics and Opportunities for New California Homes (ECO).* Report no. CEC-500-2012-062. California Energy Commission: Sacramento, CA. March 2011. http://www.energy.ca.gov/2012publications/CEC-500-2012-062/CEC-500-2012-062 pdf Northern California)

This report presents results of a two-phase field study of 80 homes meant to develop a baseline to support more accurate life cycle cost and energy savings calculations. Key findings include: average AC system performed well below expectations, experiencing problems such as high static pressures in return ducts, low sensible capacity and efficiency, and issues with TXV and refrigerant charge. AC system issues were particularly severe in zoned systems and combined hydronic systems. Phase Two showed that post-repair measurements on upgrades to nine HVAC units resulted in an average efficiency improvement of 24%.

13	Proctor, John, and Gabriel Cohn. *Two-Stage High Efficiency Air Conditioners: Laboratory Ratings vs. Residential Installation Performance.* American Council for an Energy Efficient Economy: Washington, DC http://aceee.org/files/proceedings/2006/data/papers/SS06_Panel1_Paper20.pdf (Atlantic region) This project monitored four high SEER air conditioners with dual-stage compressors, TXV metering devices, and high efficiency air handlers with ECM fans. One system with a single- stage compressor was also monitored. Data included capacity, power consumption, EER, indoor/outdoor temperature and relative humidity. The data were analyzed to assess the relationship between laboratory testing and real world performance. The performance of installed systems was significantly lower than their rated performance, especially when the fan was set to operate "continuously." Additionally, there may be energy and peak load penalties if dual-stage air conditioners are downsized to meet the home's actual load.
32	Rhodes, Joshua Daniel. "Optimal Residential Energy Consumption, Prediction, and Analysis " PhD dissertation. University of Texas: Austin, TX. 2014. https://repositories.lib.utexas.edu/handle/2152/33342 This study examined a database of 4,971 energy audits on single-family homes in Austin, Texas. Key findings include: there is a need for better performing (installed) HVAC systems, and inefficiencies associated with poor residential air-conditioning performance aggregated across a city can be significant, especially during peak periods.
24	Rhodes, Joshua D., Brent Stephens, and Michael Webber. "Using Energy Audits to Investigate the Impacts of Common Air-Conditioning Design and Installation Issues on Peak Power Demand and Energy Consumption in Austin, Texas." *Energy and Buildings* 43 (2011): 3271-278. http://built-envi.com/publications/rhodes_etal_eb_2011 pdf (Austin, TX) This study analyzes the dataset from 4,971 energy audits performed on homes in Austin, Texas from 2009–2010. The study seeks to quantify the prevalence of typical air-conditioner design and installation issues such as low efficiency, oversizing, duct leakage, and low measured capacity, and estimate the impacts that resolving these issues would have on peak power demand and cooling energy consumption. Key findings include: air-conditioner use in single-family residences currently accounts for 17–18% of peak demand, and improving equipment efficiency alone could save up to 205 MW, or 8%, of peak demand. The study estimated 31% of systems were oversized, leading to up to 41 MW of excess peak demand. Replacing oversized systems with correctly sized higher efficiency units has the potential for further savings of up to 81 MW. The study estimates that the mean system could achieve 18% and 20% in cooling energy savings by sealing duct leaks and servicing their air-conditioning units to achieve 100% of nominal capacity, respectively.
7	Siegel, Jeffrey, Iain Walker, and Max Sherman. *Delivering Tons to the Register: Energy Efficient Design and Operation of Residential Cooling Systems*. Lawrence Berkeley National Laboratory: Berkeley, CA. May 1, 2000. http://escholarship.org/uc/item/9mn7j9fp This paper examines bringing the HVAC system inside the thermal and air leakage envelope, locating it in a conditioned attic that is insulated and sealed at the roofline and is well connected to the house. A key finding is that both field measurements and simulation results show that houses with ducts located in conditioned attics have dramatically increased cooling performance and lower energy consumption than houses with ducts in conventional attics. However, the marginal benefit of improving an air conditioning system once it is in a conditioned attic is small; the largest part of energy savings come from insulating and sealing the attic.

12 Sonne, Jeffrey K., Danny S. Parker, and Don B. Shirley, III. *Measured Impacts of Proper Air Conditioning Sizing in Four Florida Case Study Homes*. Report no. FSEC-CR-1641-06. University of Central Florida Florida Solar Energy Center: Orlando, FL. October 25, 2006. http://www.fsec.ucf.edu/en/ publications/pdf/FSEC-CR-1641-06.pdf (Cocoa, FL)

This paper presents a summary of the NASEO/STAC Task 3.2 project examining the benefits of proper sizing through field testing of four case study homes in Florida (and additional homes tested in Wisconsin). Of four right-sized systems, only one saw lower energy use; however, that house's system was not appropriately installed for a hot-humid climate. The authors observed that loads were increased on two of the systems in the afternoons (late day heat gain), which the authors attribute to return side duct leakage. Systems that are right-sized (lower compared to oversized) need to run longer to dehumidify. However, if there is return duct leakage of hot/humid outdoor air can overwhelm system performance and may cause increased energy use (the location of the return ducts can influence this effect, such as return ducts located in the attic). Energy savings had more to do with technology upgrades and SEER performance than with right-sizing.

40 Steiner, Ellen, and Todd Malinick. *California HVAC Quality Installation/Quality Maintenance Customer Decision-Making Study*. EMI Consulting: Seattle, WA. April 15, 2015. http://www. emiconsulting.com/assets/CDM-Report-2015-04-15-FINAL.pdf

This study presents anecdotal evidence of how QI (and HVAC in general) are perceived in the marketplace from a homeowner/customer perspective and presents the information on customer's relationship with the HVAC marketplace. The purpose of this study is to better understand the customer perspective, and how industry could use this understanding to improve QI market penetration.

33 Stephens, Brent. "The Impacts of Duct Design on Life Cycle Costs of Central Residential Heating and Air-Conditioning Systems." *Energy and Buildings* (2014) http://built-envi.com/wp-content/uploads/2012/04/ stephens-2014-enb-lcc-duct-design-unformatted pdf

This report presents simulation-based and predictive modeling studies of two typical new single-family homes for two separate climates: Austin, Texas and Chicago, Illinois. The study tries to predict the impacts of various external static pressure ductwork designs from independent HVAC contractors (using both flexible and rigid sheet metal ductwork materials). A key finding is that lower pressure ductwork is generally more efficient, particularly in homes with PSC blowers.

41 Sullivan, Michael, Jesse Smith, Kausar Afrat, and Phil Bosco. *Impacts of the OPA HVAC Installation Optimization Training Program on Realized Energy Efficiency of Retrofit AC Systems*. International Energy Program Evaluation Conference: Madison, WI. 2015. https://www.iepec.org/wp-content/uploads/2015/papers/087.pdf

This report supports the need for QI. Key findings include: contractor training (a one-day, eight-hour) did not improve installation practices; about 20% of the efficiency of newly installed air conditioners is lost at the time of installation.

20 Talerico, Tom, and Rick Winch. *Focus on Energy Evaluation: ECM Furnace Impact Assessment Report*. Focus on Energy: Madison, WI. January 12, 2009. https://focusonenergy.com/sites/default/files/ emcfurnaceimpactassessment_evaluationreport pdf

This paper describes a study in Wisconsin designed to update a previous impact analysis report for furnaces with ECMs. The authors interviewed homeowners (participants and non- participants) and contractors. Key findings include: many homeowners with furnaces with an ECM increase the frequency of operating their furnace fan continuously; advice from HVAC contractors plays a pivotal role in homeowner's decision to increase fan operation; and HVAC contractors are more likely to tell homeowners to increase their fan operation if they install an ECM furnace versus a non-ECM furnace.

14 Titus, Elizabeth. *Strategies to Increase Residential HVAC Efficiency in the Northeast*. Northeast Energy Efficiency Partnerships: Lexington, MA. May 2006. https://forum.cee1.org/system/files/library/1330/508.pdf

Recommendations from this report include: continue central AC rebates but in conjunction with a quality installation verification (QIV) requirement, and provide QIV for all central AC installations.

42 Vaidya, Rohit, Cathy Fogel, Betty Tolkin, and Beth Poulin. *Swimming Against the Tide–Gauging HVAC Quality Installation and Quality Maintenance Program Efforts to Establish a Foothold in the Market*. NMR Group: Somerville, MA2016. http://www. nmrgroupinc.com/wp-content/uploads/2016/03/Swimming-Against-the-Tide.pdf

This study estimated the proportion of contractors adhering to QI and QM practices, gauged customer and contractor awareness of QI, identified barriers to QI, and examined contractor QI and QM compliance via field observation. Key findings include the following. The field study (for impact evaluations) found that the baseline assumptions (for oversizing, duct leakage, and system airflow) were generally not as poor as assumed by the QI program. The study did not include examination of verification of refrigerant charge. Findings suggest that compliance with, awareness of, and willingness to pay for QI/QM is weak. Customers tend to favor contractors who do the job the fastest and for the least amount of money. In California, it was estimated that a quarter of the 15,000-19,000 contractors are unlicensed, and that licensed contractors are therefore "caught between the pincers of a supply side and demand side squeeze." On the demand side, customers are not demanding (nor willing) to pay for QI. On the supply side, licensed contractors are competing with unlicensed contractors in the "race to the bottom."

10 Walker, Iain S. *Register Closing Effects on Forced Air Heating System Performance*. Report no. LBNL-54005. Lawrence Berkeley National Laboratory: Berkeley, CA. November 1, 2011. https://www.osti.gov/scitech/biblio/822806

A laboratory study that that used a test chamber to evaluate the impact of closing registers on duct pressures, duct leakage, air handler airflow, air handler power consumption, and envelope pressure. The study found that closing registers generally does not save energy, unless the ducts are very tight and the envelope is fairly pourous.

15 Walker, I.S. *Residential Furnace Blower Performance*. Report no. LBNL-61467. Lawrence Berkeley National Laboratory: Berkeley, CA. October 2006. https://eta.lbl.gov/sites/default/files/publications/lbnl-61467.pdf

This study assessed the performance of furnace blowers and the potential cost-effectiveness of setting performance standards in California and changing motor technologies from PSC blowers—dominant in the market—with a brushless permanent magnet (BPM) blower. The benefits of BPM motors depend strongly on interactions with the rest of the duct system. A key finding is that potential energy savings for BPM blowers may not be realized because of existing ductwork, e.g., the high static pressures that are prevalent in existing residential duct distribution systems. The existing high static pressures are difficult to reduce, due to the presence of filters and cooling coils that account for more than half of the system static pressure. For both heating and cooling, pressure reductions can be achieved through these key duct distribution improvements:

- Use of larger or multiple returns
- Use of low pressure filters – promote the use of 4-inch deep pleated filters
- Use of larger air conditioning coils to reduce coil pressure drop
- Use of more compact duct systems with shorter duct runs
- Careful installation: reduce number of elbows and make duct runs as straight as possible
- Encourage use of sheet metal duct instead of flexible duct

27	Walker, Iain, Darryl Dickerhoff, David Faulkner, and Will Turner. *Energy Implications of In-Line Filtration in California*. Report no. CEC-500-2013-081. California Energy Commission: Sacramento, CA. June 2012. http://www.energy.ca.gov/2013publications/CEC-500-2013-081/CEC-500-2013-081.pdf This study performed measurements in ten California houses to determine the effects of filter performance on the energy use of central heating and cooling systems. Multiple filters were evaluated covering a range of filter effectiveness. Generally, the higher minimum efficiency reporting value (MERV) correlates to higher airflow resistance (but filter depth can complicate that general statement). Per the findings, general recommendations are: • Recommended MERV 11 or less – (moderate energy impact: less than 5%) • Recommended MERV 16 only be used in low leakage duct systems as it pushes blower to the limit and causes excess noise • Thickness: 4-inch filters fare better than 1- or 2-inch filters
6	Walker, I., M. Sherman, M. Modera, and J. Siegel. *Leakage Diagnostics, Sealant Longevity, Sizing and Technology Transfer in Residential Thermal Distribution Systems*. Lawrence Berkeley National Laboratory: Berkeley, CA. January 1998. https://www.osti.gov/biblio/650258-leakage-diagnostics-sealant-longevity-sizing-technology-transfer-residential-thermal-distribution-systems A study of 17 homes in which measured duct leakage (to outside of the conditioned space) and sealant longevity. A key finding is that there was a large range of duct leakage from house to house, even in the new houses that all had the same house and HVAC system design, and in some cases the same HVAC contractor. This large variation indicates that the specific installation rather than system design is the determining factor for duct leakage and implies that any test for duct leakage used for compliance or screening purposes must be able to distinguish between individual systems.
11	Wilcox, Bruce A., and James Larsen. *Measured Cooling Load, Energy, and Peak Demand Savings from High-Performance Glass in a California Production House*. ASHRAE: Washington, DC. 2004. http://web.ornl.gov/sci/buildings/conf-rchive/2004%20B9%20papers/129_Wilcox.pdf This study examines the impacts of glass glazing and HVAC system size in two production houses in California. For one production house, the AC system was downsized (by one ton), but the ducts were not replaced (leaving them as oversized). Results indicated losses from the extra surface area (of the oversized ducts) slightly reduced the efficiency of the new smaller system. Static pressure and fan energy could have been reduced with the smaller system, but the better glass actually increased the relative fan energy.
17	Wirtshafter, Robert M., Greg Thomas, Gail Azulay, William Blake, and Ralph Prahl. *Do Quality Installation Verification Programs for Residential Air Conditioners Make Sense in New England?* International Energy Program Evaluation Conference: Madison, WI. 2007. https://www.iepec.org/conf-docs/papers/2007PapersTOC/papers/111_1114_ab_648.pdf This study examined the effectiveness of QIV programs as they relate to peak demand savings opportunities in New England. The study concluded that QIV programs cannot be justified unless the AC systems have excess capacity at system peak, a situation that only occurs in simulations for systems that are more than 40% oversized according to Manual J. If systems have insufficient capacity at system peak, efficiency gains produced by air flow and refrigerant charge will not reduce peak demand.

8 XENERGY, Inc. *New Jersey Residential HVAC Baseline Study*. NJ Clean Energy Program, New Jersey Board of Public Utilities: Trenton, NJ November 16, 2001. http://njcleanenergy.com/files/file/Library/Xenergy%20HVAC.pdf (New Jersey)

A baseline study conducted in New Jersey on the supply and demand sides of the HVAC market for energy efficiency savings. The study includes field data, customer decision making data, and contractor segmentation data. The key findings include:

- Efficiency: On average, cooling systems were oversized by 23%; 53% of measured airflows were less than the manufactures recommendation of 350 cubic feet per minute (CFM) per ton. Duct leakage data analysis for this study estimated an average outdoor air leakage rate of 329 CFM25; 68% of systems were not charged properly (47% were undercharged and 21% were overcharged). Results of the on-site visits clearly show that the greatest potential to save energy is through reduction of duct leakage to outdoors and refrigerant charge correction.
- Contractor/Customer Relationship: 62% of sample customers reported that they solicited bids from only one contractor (and 55% identified their contractors through recommendations from friends and family). At the same time, 71% reported that their contractor was the only source of information they used in making their equipment selection decisions and additionally 91% selected the model recommended by the contractor. Ninety-four percent of customers reported they were satisfied with the equipment installation services they received (even though most customers surveyed could not technically define quality installation).
- Contractor Segmentation: The largest 39 contractors (representative of 2% of the contractor network) install nearly 30% of the systems. Ninety-four percent of the contracting companies have nine or fewer employees (and represent the two smallest buckets as far as number of installations per company). As a whole, these companies account for 58% of the installations.

30 Yee, S., J. Baker, L. Brand, and J. Wells. *Energy Savings from System Efficiency Improvements in Iowa's HVAC SAVE Program*. Report no. DOE/GO-102013-4164. U.S. Department of Energy, Building Technologies Office: Washington, DC. August 2013. https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/iowa_hvac_save_project.pdf

A report on a pre- and post-furnace repair field study of 48 homes, examining installation faults and their prevalence. A more in-depth study of ten of the homes with tune-ups or replaced/modified ducts was also conducted. Key findings include the following. Delivering up to 23% more energy from the furnace to the conditioned space via system tune-ups with or without furnace upgrades is possible. Delivering 80%-90% of furnace-generated heat to the conditioned space is possible. Residential HVAC equipment should be tested and improved as a system rather than a collection of distinct components.

28 Yuill, David P., and James E. Braun. *Evaluating Fault Detection and Diagnostics Protocols Applied to Air-Cooled Vapor Compression Air-Conditioners*. Purdue University: West Lafayette, IN. 2012. http://docs.lib.purdue.edu/cgi/viewcontent. cgi?article=2306&context=iracc

This paper presents lab data from 13 air conditioning systems to evaluate how well FDD protocols in tools perform, particularly in the absence of any standard method of measuring the performance of FDD. Key findings include the following. As there is no standard method (protocol) for creating and evaluating faults, the authors recommend a standard protocol be developed. Since tools use different and varying protocols to diagnose FDD, assessing a tool's performance is complicated. Because there is no FDD protocol, the tools being deployed in the market do not measure the same things with the same accuracy, which is leading to false alarms, misdiagnosis alarms, missed detection alarms, and no alarms when conditions indicated an alarm should have posted.

Appendix C: Questions on HVAC Installation Practices for Industry Stakeholders

DOE gathered input from industry representatives attending DOE's Building Technologies Office Peer Review Meeting: *Smart Tools for Improving Installed Performance of Residential and Small Commercial HVAC Systems Expert Meeting* held on March 16, 2017. A list of questions was distributed to stakeholders at that meeting as an aid to guide further input and identify additional source documents to be included in this review. The table below includes the questions posed during that search process.

Table 5: Questions on HVAC Installation Practices for Industry Stakeholders

1	Are there resources published prior to September 2014 that were not included in NIST's report and would add supplementary information to DOE's current efforts?
2	Are there resources published subsequent to September 2014 that would supplement the NIST findings and DOE's current efforts?
3	Are there limitations or concerns with the methodologies used in existing research studies that DOE should consider when assessing the results and applying regional results nationally?
4	Field data regarding the prevalence of specific HVAC system performance degradation in existing homes is not widely available. Are there relevant sources of field data that would provide additional clarity around this gap?
5	How resilient is today's HVAC equipment? Can technology advancements (e.g. variable speed/capacity equipment) help mitigate the impact of various faults on electricity consumption or other performance issues?
6	The majority of research, study, and evaluation has focused on the supply side (contractors and programs) A recent study by NMR in CA identified a need for more demand side work to better understand the barriers and drivers of customers' HVAC purchasing decisions Is this approach being pursued in other regions?
7	The issue of quantifying savings remains, are there alternative means by which EM&V can be improved to help in cost effectiveness tests?
8	Ducts – how important are they and when (and where) are they the most important? 2018 IECC includes buried ducts and some studies suggest savings are greater for encapsulating ducts (bringing in the thermal envelope) than through QI measures (at least in certain climate zones).
9	Sizing – how is equipment sizing addressed by the HVAC industry? Has the industry's approach to sizing been updated to reflect findings from research on HVAC quality installation practices?

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