U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Barriers to Broader Utilization of Fault Detection Technologies for Improving Residential HVAC Equipment Efficiency

April 2022

Disclaimer

This work was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, its contractors or subcontractors.

Authors

The authors of this report are:

- Jon Winkler, National Renewable Energy Laboratory (NREL)
- Jeff Munk, Oak Ridge National Laboratory (ORNL)
- Walt Hunt, Pacific Northwest National Laboratory (PNNL).

Acknowledgments

This report was prepared by NREL, ORNL, and PNNL for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Office. The authors acknowledge Mr. Eric Werling and Mr. Marc LaFrance, technology managers U.S. Department of Energy Building Technologies Office, for their support and guidance for this research. We would also like to acknowledge all the stakeholders and peer reviewers for providing valuable insight used to develop the content of this report.

List of Acronyms

AFDD	automated fault detection and diagnosis
DOE	U.S. Department of Energy
FDD	fault detection and diagnosis
HVAC	heating, ventilating, and air conditioning
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory

Table of Contents

List of Tables

1 Introduction

Faults in residential heating, ventilating, and air-conditioning (HVAC) equipment may occur due to poor installation practices or develop over time, and these faults can negatively impact system efficiency, thermal comfort, and equipment lifespan (EERE 2018). Automated fault detection and diagnosis (AFDD) technologies identify energy-wasting HVAC faults, such as low indoor airflow and improper refrigerant charge, and guide technicians in making equipment or system changes that can improve system efficiency.

For residential HVAC, AFDD is implemented through a range of fault detecting and diagnosis capabilities, sensor configurations, and target applications. AFDD technology can either be permanently installed by the original equipment manufacturer (OEM) using embedded sensors or as an add-on product either during or after installation of the HVAC equipment. Additionally, several advanced installation tools and refrigerant gauge sets include AFDD features for temporary use during equipment installation and tune-ups. Some technologies can detect a fault but have limited diagnosis capabilities. For example, a single-point measurement from the home's thermostat or energy monitor can provide certain fault detection capability by analyzing the equipment runtime or energy consumption. These technologies, though limited at determining the cause of a given fault, may have significant energy savings potential due to their low cost and prevalence in the residential HVAC market (ENERGY STAR® 2020).

Despite the potential benefits, fault detection technologies face many technical and market barriers preventing broad adoption (Butzbaugh et al. 2020). Beyond the cost barriers due to the added sensor requirements and technology development, fault detection technologies face implementation and adoption barriers such as installer training, customer awareness, standardized communication protocols, and methods of test for evaluating accuracy.

1.1 Overview

The purpose of this report is to characterize market and technical barriers impeding broader utilization of fault detection technology for residential HVAC energy efficiency applications. Section 2 provides additional background information and describes the faults and methods. Section 3 categorizes fault detection technology types and their corresponding features, and Section 4 describes the market and technical barriers impeding broader AFDD adoption and utilization for residential HVAC energy efficiency applications. During the development of this report, input was collected from a range of stakeholders including AFDD technology manufacturers and relevant industry organizations.

1.2 Scope of Characterization

Given the broad spectrum of fault detection technology types and capabilities, the scope of this report focuses on applications with the highest potential for energy savings. The characterization includes a broad range of fault detection approaches applicable for only the following equipment and applications:

- *Equipment Type*: Electric air conditioners and air-source heat pumps.
- *Application*: Central HVAC systems in residential applications.
- *Equipment Design*: Fault detection approaches applicable to conventional 24 VAC controlled HVAC systems and/or high-end, digitally communicating HVAC systems.

2 Background and Definitions

2.1 Fault Detection, Diagnosis, and Automated FDD

A fault detection and diagnosis (FDD) algorithm implements a two-step process that uses available data/measurements to determine faulty operation (fault detection) and then uses a series of rules/relationships to identify the possible cause (fault diagnosis). Faults can be defined based on an undesirable physical condition (e.g., low refrigerant charge), undesired behavior (e.g., evaporator coil ice buildup), or when a quantifiable outcome deviates from the expected value (low coefficient of performance; see Frank et al. 2019). AFDD is a technology or tool that implements the FDD process and communicates the presence of a fault to the user. AFDD can utilize either short-term data, such as that obtained during the installation or commissioning process, or a continuous data stream to detect faults throughout the equipment's lifespan. In general, AFDD technology incorporates sensors or data collection, local or cloud-based data processing for determining faults, and alert messaging to the AFDD user.

To summarize, FDD generally refers to algorithms or methods, and AFDD refers to the technologies that implement the FDD process and communicate fault status to the end user.

2.2 Add-On and OEM-Embedded AFDD

OEM-embedded AFDD utilizes on-board refrigerant-side and/or air-side sensors, installed during the manufacturing process, to perform fault detection. In contrast, add-on AFDD utilizes sensors that are not installed at the factory by the OEM but instead are installed by the homeowner or a contractor after the HVAC equipment has been installed at a residence. For both categories, FDD information can be provided locally on equipment or remotely through a cloud-based platform.

For OEM-embedded AFDD, the sensors supporting fault detection are permanently installed in the HVAC equipment. For add-on AFDD, the sensors supporting fault detection may be designed for either a permanent or temporary installation on the HVAC system. Add-on AFDD technologies, which are intended to be temporarily installed for fault detection, are referred to as smart diagnostic tools. Smart diagnostic tools are generally Bluetooth-enabled refrigerant-side and air-side sensors that connect to an AFDD application on a smart phone or tablet.

2.3 Installation/Service Faults and Operational Faults

Faults can result from poor installation or service practice or can develop over time because of poor maintenance or normal wear and tear. Certain faults, such as refrigerant overcharge and the presence of non-condensable gases, can be caused by the technician not following industry-recommended practices during installation or while servicing the equipment. Operational faults resulting from poor maintenance, such as fouled heat exchangers, are generally correctable. However, other operational faults from normal wear and tear on the system, such as compressor valve leakage, are typically not easily fixed. Some operational faults, such as a capacitor or blower motor failure, prevent the system from operating and result in a contractor service call to fix the system. Several types of faults, such as refrigerant undercharge and low indoor airflow rate, can be categorized as either installation or service related or operational depending on the root cause. For example, a system could be low on charge due to improper charging during installation, slow refrigerant leaks in factory or field-made braze joints, or leaks that develop over time due to corrosion or vibration. Similarly, the indoor airflow rate could be low because of an incorrect blower setting (installation fault) or a clogged filter (operational fault).

We distinguish between installation/service faults and operational faults, because certain FDD methods cannot be applied to both types. Table 1 lists several example faults and their corresponding categories.

Table 1. Example Fault Types and Categories

Example Fault Type	Installation/Service	Operational
Indoor unit airflow rate	X	X
Outdoor unit airflow rate		X
Refrigerant undercharge	X	X
Refrigerant overcharge	X	
Presence of non-condensable gases	X	
Liquid line restriction	X	
Compressor valve leakage		X

Improper equipment sizing, poorly insulated ducts, leaky ducts, or undersized ducts could also be considered faults that result in energy waste and/or occupant discomfort. However, these issues are generally very costly or challenging to correct and are best addressed by proper design and assessment prior to the installation of new HVAC equipment. Therefore, the focus of this paper is on faults related to the installation or operation of the HVAC equipment itself.

2.4 Fault Detection Methods

There are multiple methods for detecting potential HVAC faults. This paper discusses three methods: trend analysis, defined parameter thresholds, and performance monitoring.

Trend Analysis

The trend analysis method for detecting faults relies on the identification of changes in system operation. This method can monitor any parameter related to the HVAC system operation that would likely change as the result of a fault and can include non-invasive monitoring of equipment parameters (e.g., equipment runtime as monitored by a smart thermostat) as well as more direct measurements (e.g., compressor current). Depending on the parameter monitored, it may or may not be possible to determine the likely cause of the change in performance. One challenge associated with this method is that it cannot identify faults present at the time of deployment of the AFDD technology. The method requires past data to develop a baseline for identifying changes, so any degraded performance due to previously existing faults will be integrated into the baseline data. Existing faults must be identified using an alternative method at the time the trend analysis fault detection system is deployed to ensure a fault-free baseline.

Defined Parameter Thresholds

The defined parameter thresholds method relies on measuring key performance parameters and defining an acceptable, "no fault," range for the given measurement. If a measurement falls outside of the acceptable range, a fault is triggered. For example, the amount of refrigerant subcooling at the condenser outlet is a parameter that can be used as an indication of proper charge in an air conditioner equipped with a thermostatic expansion valve. In this example, the measured subcooling would be compared to an acceptable range of values (e.g., 5°–15°F), and a measurement outside of the acceptable range would trigger a fault. This approach typically allows for some insight into potential causes of the fault, depending on the parameters being monitored.

Performance Estimation

The performance estimation method relies on measuring system parameters to estimate the system capacity and/or efficiency and comparing it to the expected no-fault performance at the same conditions. For fault detection that is focused on identifying energy waste associated with faults, this is the most direct approach. The previous two methods, trend analysis and defined parameter thresholds, do not estimate system performance because both methods analyze a specific set of parameters to trigger faults.

The accuracy of this fault detection method depends on the accuracy of (1) the estimated performance metric, (2) the measured current operating conditions (e.g., indoor temperature, outdoor temperature, and indoor/outdoor humidity), and (3) the no-fault performance model. One benefit of this method is that it can identify any fault or combination of faults that measurably affect the equipment performance. However, the method has two important drawbacks. First, estimating capacity or efficiency requires more sensors than the other two methods. Additionally, detailed information on indoor and outdoor pairing is required to estimate the no-fault performance. FDD algorithms utilizing the performance estimation approach could include thorough diagnosis using the same sensors required to estimate system performance. However, multiple low-intensity faults could be challenging to diagnose even if they result in a significant overall performance penalty.

Indirect and Direct HVAC FDD Approaches

For add-on AFDD, fault detection can be accomplished using an indirect FDD approach, direct FDD approach, or a combination of both. A direct HVAC FDD approach uses refrigerant-side and/or air-side measurements directly on the HVAC system to identify faults. For example, using refrigerant temperature and pressure sensors to measure the superheat and subcooling of an HVAC system to check for proper refrigerant charge is a direct HVAC FDD approach. An indirect HVAC FDD approach may include measurements such as HVAC power consumption, HVAC run time, or indoor temperature, which are impacted by HVAC performance but not direct refrigerant-side or air-side measurements of the system. Indirect HVAC FDD approaches generally use trend analysis to detect faults over time based on a change from baseline performance.

Communicating and Non-Communicating Systems

Conventional systems that operate based on the presence or absence of 24 VAC signals from the thermostat are considered non-communicating because the control signal only goes in one direction. Systems that feature two-way digital signals between the outdoor unit, indoor unit, and/or thermostat are considered communicating systems. Many variable-speed systems are communicating because it allows the compressor speed and system capacity to be modulated in response to the indoor air temperature measured by the thermostat. Some premium two-stage systems are also communicating and use this to offer additional features to the homeowner, such as display of fault notifications on the thermostat. A standard communication protocol between components of an HVAC system does not yet exist, and all manufacturers currently use proprietary digital communication signals. Therefore, a communicating system cannot use components from different manufacturers while maintaining the features and capabilities that are dependent on the digital communication between components.

3 AFDD Types and Characteristics

This section includes a description of the five fault detection technology types that fall into three main categories—smart diagnostic tools, add-on, and OEM-embedded. Add-on technology is defined as any fault detection technology that is not installed at the factory by the OEM. The add-on and OEM-embedded technologies are further divided into two subcategories each.

AFDD technologies comprise five technology types:

1. Smart diagnostic tools are an add-on AFDD approach that utilizes temporarily installed sensors to directly measure refrigerant-side and/or air-side characteristics of an HVAC system. This approach generally utilizes Bluetooth-enabled sensors, which communicate data to an AFDD application on a smart phone or tablet. Smart diagnostic tools are utilized by an on-site technician either during an HVAC system installation or during a scheduled system check. Smart diagnostic tools offer remote data viewing and data logging functionality while the technician and tools are on-site, but this AFDD technology is temporary and is removed from the HVAC system by the technician at the completion of the service visit. Thus, smart diagnostic tool FDD algorithms must use the operating conditions present during the site visit and cannot wait for favorable conditions or a fault persistence criterion to be satisfied. Smart diagnostic tools typically use parameter thresholds on a single measurement or combination of measurements, such as refrigerant subcooling, supply air temperature, refrigerant pressures, etc., to communicate the status of the system to the on-site technician. Several smart diagnostic tools also include estimates of system performance, such as capacity, sensible heat ratio, and/or energy efficiency ratio. Because smart diagnostic tools are temporarily installed, one set of tools can provide fault detection for many residential HVAC systems, allowing the capital cost of the tools to be amortized over their lifespan.
2. Add-on, indirect HVAC AFDD utilizes one or more sensors or devices that are not directly monitoring the HVAC system components. Examples of these sensor or devices include a home's smart thermostat or an energy monitor located in the electric panel. This approach generally uses cloud-based trend analysis to detect the presence of faults by continuously analyzing equipment runtime or energy use, but diagnostic capabilities are limited due to a lack of baseline performance data and/or HVAC equipment-specific measurements. The lack of baseline performance data also prevents the technology from detecting existing faults unless they continue to alter the system operation. Furthermore, existing smart thermostats or home energy monitors could be leveraged to provide FDD capability through cloud-based computing or a software update without changing the primary functionality of the device.
3. Add-on, direct HVAC AFDD generally requires a contractor to install sensors directly on the HVAC system. This approach uses air-side sensors, refrigerant-side sensors (temperature and/or pressure), voltage and current measurements, and/or thermostat signals to continuously monitor the system for faults. Because sensors are installed

directly on the HVAC system, parameter threshold fault detection is possible. However, trend analysis is likely the primary fault detection method since the add-on AFDD technology may not be programmed with performance data for the specific system it is installed on. Some add-on, direct HVAC AFDD technologies utilize information from a smart diagnostic tool to provide baseline performance data (Emerson 2020).

4. OEM-embedded, parameter threshold AFDD utilizes sensors installed on the equipment at the factory to identify faults when sensor measurements exceed a predetermined value or range. Because of the additional cost of the sensors, this approach is commonly only found on premium products. On many of those products the sensors are used to aid in control of an electronic expansion valve or a variable-speed compressor, and fault detection is not the primary purpose of the sensors. Though the approach inherently includes some diagnosis capability since individual parameters are being used for fault detection, the technology may miss detecting impacts due to multiple faults. A review of installation and service manuals of many premium products indicated that the parameter threshold approach was mainly used to ensure reliable operation of the equipment. However, this approach could also be used to detect faults that are potentially decreasing system efficiency with the appropriate measurements and thresholds.
5. OEM-embedded, performance monitoring AFDD utilizes sensors installed on the equipment at the factory to estimate the performance of the system compared to the expected no-fault performance. A fault is triggered if the measured performance exceeds an allowable tolerance relative to the no-fault performance. Since system performance is used to trigger a fault, the approach detects degradation due to any combination of faults. Currently, no products on the market include this FDD type. However, it was identified as a feasible approach that could utilize many of the same sensors as the OEM-embedded, parameter threshold FDD approach and could more directly identify performance degradation of the system (Winkler et al. 2020).

Though we describe and characterize five unique AFDD technology types, a combination of technologies can be utilized to improve AFDD accuracy and usefulness. For example, coupling a smart diagnostic tool with an add-on, direct HVAC AFDD technology provides the add-on, direct HVAC AFDD technology with additional baseline information that could not be collected without the additional sensors included with the smart diagnostic tool. Additionally, since both OEM-embedded technology types listed above would likely utilize a similar suite of sensors, a performance monitoring AFDD technology would likely continue to use parameter thresholds to identify certain faults.

Table 2 compares the five technology types, target markets, features, and pros and cons. The following subsections define and expound on the technology characteristics of Table 2.

3.1 Description and Market

The five technology types addressed in this paper have unique features and characteristics that affect their suitability for different markets. In this section we will compare the five AFDD technologies in Table 2 and highlight differences in their respective markets and applications.

The smart diagnostic tool and add-on AFDD approaches can be applied to either existing or new HVAC equipment installations, whereas OEM-embedded AFDD approaches utilize factory-installed sensors and are therefore limited to only new installations. However, due to hardware and service plan costs, add-on direct HVAC AFDD technology is currently applied primarily to newly installed HVAC systems. Customers are more likely to purchase add-on direct AFDD technology as part of a new installation, because the AFDD technology costs can be incorporated into the overall cost of the system and represent a small relative increase in price. The cost of the added sensors, controls, and communications may preclude OEM-embedded AFDD approaches from being broadly utilized in low- and mid-tier products in the current market. Additionally, OEMs consider embedded AFDD technology to be an advanced, high-tech feature to differentiate premium systems from low- and mid-tier products.

There are two primary technology users: HVAC contractors and building occupants. HVAC contractors refer to the workers that are physically on-site servicing, maintaining, or installing the equipment or the overall business entity. The primary technology users for smart diagnostic tools are HVAC contractors, which includes the on-site technician and the possibility for more experienced technicians to view the data remotely. Add-on, indirect AFDD technology is not directly linked to an HVAC contractor or OEM, and AFDD features of the technology are currently only used by building occupants. Add-on direct HVAC AFDD has two primary customers/users—HVAC contractors and building occupants. The technology is typically used by contractors to sell upgraded service contracts and perform remote check-ins to monitor performance. However, building occupants must make a specific decision to purchase the technology.

The technology users of OEM-embedded AFDD technologies can vary depending on whether the system is a communicating system or non-communicating system and how the OEM chooses to handle faults. Non-communicating systems tend to indicate faults using flashing lights or seven-segment displays located on the equipment control board. The HVAC contractor is likely the only technology user because these indicators are not easily visible to building occupants. Communicating systems can communicate faults from the HVAC equipment components to the thermostat, providing a pathway for notifying the building occupant directly. However, manufacturers may choose to only notify the building occupant of severe faults, while retaining a history of minor faults for future reference. Additionally, many communicating systems have internet-connected thermostats that allow faults to be communicated directly to the building occupant or to the servicing HVAC contractor.

Add-on and OEM-embedded AFDD technologies use a variety of approaches to communicate alerts and the operational status to building occupants, such as periodic emails, smart phone application notifications, and thermostat messages. Add-on, direct HVAC and OEM-embedded AFDD technologies may also send alert notifications to the HVAC contractor. Smart diagnostic tools typically include automated report generation features for technicians to provide to the building occupants, but it is unclear how often these features are used.

Residential HVAC AFDD technology has three primary use cases—ensuring equipment reliability/safe operation, ensuring the equipment is operating with the expected efficiency, and helping HVAC contractors retain customers through service contracts. Smart diagnostic tools help to ensure long-term reliable operation by comparing certain measured parameters to the expected values; however, this comparison is only conducted while the tool is connected to the system during installation or a service call. Add-on, indirect HVAC AFDD technologies analyze trends in equipment runtime and/or energy use and are therefore inherently focused on detecting issues affecting energy use, such as clogged filters or inadvertently opened windows. However, AFDD capabilities of add-on, indirect HVAC technologies, such as smart thermostats, are not often marketed by the manufacturer, have not always been enabled by default, and do not likely drive consumers to purchase the product. OEM-embedded sensors included with premium systems are currently utilized for on-board controls and to ensure equipment is not operating in a state that could jeopardize equipment reliability or lifespan. OEM-embedded AFDD could be utilized for energy efficiency applications if the current thresholds to trigger alerts were reduced or if the sensors were used to calculate system performance metrics, such as capacity and coefficient of performance. However, sensors used to calculate system performance metrics for detecting operational faults need to remain accurate over the equipment's lifespan.

3.2 Technology Features

The types of sensors used for FDD are dependent on the fault detection method. The trend analysis method may rely on runtime measurements from a smart thermostat or energy use trends from a home energy monitoring system. More direct measurements can also be used to identify faults, such as thermostat control signals, compressor current, return and supply air temperatures, and refrigerant temperatures and pressures. The parameter thresholds method may use refrigerant pressure and temperature sensors to detect improper system charge or low indoor and outdoor airflow.

OEM-embedded AFDD technologies can ensure that sensors are placed at the best locations for identifying a particular fault, because a location may be more accessible prior to final assembly at the factory. OEMs also have design information that could be important when determining the best sensor location. For example, a relatively inexpensive approach to measure refrigerant subcooling, which can be used to detect refrigerant charge faults, is to directly measure the refrigerant saturation temperature. However, determining the best location on the heat exchanger for this measurement is not easily accomplished in the field and the optimum location is often not accessible without significant disassembly. Sensor locations for add-on, direct HVAC AFDD technologies are often limited by accessibility. Additionally, field-installed refrigerant pressure measurements introduce potential for refrigerant leaks, while OEM-embedded pressure measurements can be factory-brazed into the system and/or leak checked.

Table 2. Fault Detection Technology Characteristics and Features

	Characteristic/Feature	Smart Diagnostic Tools	Add-On		OEM-Embedded	
			Indirect HVAC	Direct HVAC	Parameter Thresholds	Performance Monitoring
	Fault Detection Method(s)	Parameter threshold	Trend analysis	Trend analysis, Parameter threshold	Parameter threshold	Parameter threshold, Performance estimate
Description and Market	**Target HVAC market**	Quality installation, Equipment tune-ups	All compatible HVAC equipment	New HVAC installations	Premium HVAC equipment	Premium HVAC equipment
	Primary technology users	HVAC contractor	Building occupant	HVAC contractor, Building occupant	HVAC contractor	HVAC contractor
	Informs occupants of faults	No	Yes	Yes	Yes	Yes
	Requires technician on-site for fault detection	Yes	No	No	No	No
	Primary technology use cases	Equipment reliability, Energy efficiency	Energy efficiency	Customer retention, Equipment reliability	Equipment reliability	Equipment reliability, Energy efficiency
Technology Features	**Sensors**	Refrigerant pressure & temperature, air temperature & humidity, electrical meter	Thermostat (runtime), Home energy monitor	Refrigerant & air temperatures, Voltage and current, Control signals	Embedded refrigerant sensors, Voltage and current	Embedded refrigerant sensors, Voltage and current
	Ability to capture installation faults	Yes	No	No	Yes	Yes
	Ability to capture operational faults	No	Yes	Yes	Yes	Yes
	Includes diagnosis/guidance on specific faults	Yes	No	Yes	Yes	Yes
	Dependent on no-fault baseline data	No	Yes	Yes	No	No
	Includes calculations of capacity and efficiency	Yes	No	No	No	Yes
	Technology Pros	- Detailed performance information while technician is on-site - Low relative cost as one tool set can serve many homes	- Continuous monitoring - Could utilize existing market penetration of smart thermostats	- Continuous monitoring - Routine performance reports sent directly to occupant	- Existing reliability-focused FDD could be modified to capture efficiency degradation - Includes diagnostics	- Detects degradation due to any combination of faults
	Technology Cons	- No continuous monitoring - Requires technician on-site for fault detection - Additional setup time vs. conventional tools - Manual, error-prone data entry process - May miss impacts due to multiple faults	- Limited sensing locations - Does not capture installation faults - Limited diagnosis capabilities	- Requires professional installation - May include additional cost for service contracts - Requires baseline data - Manual, error-prone data entry process	- May miss impacts due to multiple faults - Currently only available in premium products	- New approach requiring research and development

4 AFDD Adoption Barriers

In this section, we identify the key barriers associated with the broader adoption and utilization of the five AFDD technology types. Table 3 lists five categories of barriers and denotes which individual barriers are considered minor or major depending on level of effort estimated to remove the barrier.

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.

Similar to Section 3, the following subsections further describe the particular technology barriers that require additional explanation.

4.1 Evaluation Barriers

A set of barriers that affect all AFDD technologies is associated with a lack of a standardized method of test to evaluate their performance, and it is challenging to promote adoption of a technology without a means to objectively quantify its performance. Different technologies may identify different types of faults or may indicate faults at different levels of severity. These characteristics are critical to understanding the utility of an AFDD technology. A standardized method of test could provide a means to assess the effectiveness and performance of an AFDD technology. Additionally, a standard method of test could assess the types and severity of faults that can be identified by the technology and the rate of false positives, false negatives, and misdiagnoses. The results from a standard method of test could be used to inform stakeholders of the effectiveness of a certain AFDD technology and allow for more thoughtful pairing of different technologies to create a more comprehensive AFDD package.

A standard method of test would likely require a standardized set of fault types and fault levels that an AFDD technology would be evaluated against, which would also provide AFDD developers with clear design targets, potentially decreasing development time associated with uncertain performance targets.

Evaluation methods are considered a major barrier for all the AFDD technologies. Addressing this barrier through development of standard methods of test and establishing standardized fault types and thresholds will likely vary for each technology type and the application. For example, technologies that utilize trending analysis, such as thermostats, will need to be evaluated differently than technologies that use parameter thresholds, such as smart diagnostic tools. Evaluation methods for add-on, indirect HVAC AFDD technologies could be simpler than the other AFDD technology types since standardized fault intensities will not be necessary. However, trending or learning based methods could be challenging to evaluate and, in the case of a thermostat, excessive runtime thresholds will have to be defined.

4.2 Justification Barriers

Establishing the prevalence of specific faults and their associated energy-penalty in today's residential HVAC landscape could provide a justification for deploying AFDD technologies. For today's central air-conditioner and heat pump market, there is a limited understanding of fault prevalence and severity and the corresponding energy penalty for individual faults and combinations of faults. Additionally, there are limited data on the effectiveness and energy saving potential of available AFDD technologies. Addressing these barriers would enable the justification of AFDD to be examined for specific system types and climate regions in the residential market. Data collected to address the first two justification barriers in Table 3 would be applicable to all five AFDD technology types.

A review of past research on the fault prevalence with central air conditioners and heat pumps indicates that 70%–90% of systems have a performance-compromising fault (EERE 2018). Legacy field studies on fault prevalence and the associated energy penalty of faults have largely focused on individual faults and been concentrated in a specific region. Two ongoing field studies funded by DOE's Building America program are aiming to fully characterize the prevalence and severity of faults in newly installed central air-conditioner and heat pump systems (University of Central Florida N.D.; University of Nebraska Lincoln N.D.). Both field studies are examining the prevalence of the following residential HVAC installation faults: improper indoor airflow, improper refrigerant charge, duct leakage, presence of non-condensable gases, and equipment oversizing. These field studies cover multiple regions of the United States with plans to survey field sites until statistical validity is reached for fault prevalence. Because these two studies are evaluating newly installed HVAC systems, fault prevalence and severity data in older, existing HVAC systems will remain uncertain.

AFDD technology has been available in the residential market for several years, but there is a limited understanding of the effectiveness and energy-savings potential. Another ongoing field study funded by DOE's Building America program is aiming to examine the impact and effectiveness in deploying AFDD technology (Southface Energy Institute N.D.). This field study is primarily focused on characterizing the effectiveness of smart diagnostic tools, but the effort is also examining add-on, direct HVAC AFDD monitoring.

These ongoing field projects exploring the prevalence and severity of faults, energy penalty of faults, and effectiveness of AFDD technology are aiming to address the justification barrier for AFDD technology in residential HVAC.

4.3 Cost Barriers

There are three primary types of cost barriers associated with AFDD technology—hardware costs, installation and operational labor costs, and subscription fees paid by the building occupant. Hardware costs depend on the AFDD technology type, such as a contractor purchasing a smart diagnostic tool or the additional sensors and control boards for OEM-embedded AFDD technology. Labor costs can be due to the installation of AFDD sensors and/or the operation of the AFDD technology by the contractor while on-site. Building occupant subscription fees are currently only associated with add-on, direct HVAC AFDD technology, but subscription fees may become a cost component of other AFDD technologies as capability expands in the future.

Hardware cost is considered a minor barrier to smart diagnostic tool adoption mainly because the additional cost compared to a standard technician tool set is amortized over years of use and spread out over many HVAC system installations and/or tune-ups. However, smart diagnostic tools are significantly more expensive compared to conventional tools and may be a barrier for newly hired technicians expected to purchase their own tools. Several electric utilities offer incentives to help offset the hardware and training costs to improve smart diagnostic tool adoption in their service territory (PNNL 2021).

Hardware costs are considered a major barrier for add-on, direct HVAC and OEM-embedded AFDD technologies because of the relative cost increase of the technology compared to the cost of standard HVAC equipment. For add-on, direct HVAC AFDD technology currently on the market, the HVAC contractor purchases the hardware from the supplier and then determines how the hardware costs are passed down to the consumer. Hardware and subscription costs for add-on, direct HVAC AFDD are commonly rolled into the purchase of the new HVAC system. For OEM-embedded AFDD technologies, the manufacturer hardware cost for refrigerant-side sensors and controls for refrigerant charge monitoring was estimated to be $116 (personal communication, HVAC OEM, 2020). This would result in a 11%–14% increase in the manufacturer production cost of a 3-ton, 14 SEER system depending on air handler configuration and whether it is an air conditioner or heat pump (Regulations.gov 2015). This does not include any additional labor costs to install the sensors and controls on the assembly line or any increase in markup to recoup AFDD development costs.

Hardware cost is not a barrier to add-on, indirect HVAC AFDD technology, because there is minimal cost associated with the addition of AFDD products in this category (e.g., smart thermostats and home energy monitors). Although the price of smart thermostats is considerably higher than conventional thermostats, they offer additional features, such as smart home integration, automatic set point scheduling, and smart phone application support, that generally drive purchasing decisions. The hardware cost of smart thermostats is not limiting their projected sales growth, as the market size is forecasted to increase by six-fold from 2019 to 2027 (Allied Market Research 2021). Similarly, home energy monitors are generally purchased for managing home energy use or tracking solar production, and AFDD would be an additional feature that would not require additional hardware.

HVAC contractor labor cost is a minor barrier for smart diagnostic tools and OEM-embedded AFDD technology. Smart diagnostic tools generally use more sensors than a traditional refrigeration gauge set, such as air duct temperature and humidity probes, discharge line refrigerant temperature, and outdoor unit current, which take additional time on-site to locate and install. It also takes the HVAC contractor additional time to enter the system information in the smartphone application and diagnose and resolve any identified faults. HVAC equipment manufacturers are somewhat concerned embedded AFDD technology could lead to additional time on-site and/or difficulties commissioning the equipment. If equipment is known to be more challenging to install compared to equipment without AFDD technology, HVAC contractors may be less likely to upsell the equipment to building occupants.

Subscription costs are only a barrier for add-on, direct HVAC AFDD and can prevent building occupants from renewing the service contract after the first term expires. Thus, it's important for building occupants to recognize the value of the technology when it comes time to renew the contract. Though several smart diagnostic tools charge HVAC contractors a small fee per system data set uploaded to the cloud for access during future site visits, this cost generally does not deter HVAC contractors from using the technology.

4.4 Implementation Barriers

Implementation barriers include technological challenges and any additional effort that is required to ensure successful deployment of the AFDD technologies.

One minor technological challenge for OEM-embedded AFDD is the need to communicate data between the components of the system. This can create challenges for multiple reasons. First, the primary locations for embedded sensors are in the outdoor unit and the air handler. Neither of these components are typically installed in a convenient location for communicating faults, either through direct display or via Wi-Fi (because they are often located outside of the living space). On current products, faults are generally communicated via the thermostat display and/or to the cloud via an internet-connected thermostat. Second, communicating data between units requires a digital communication protocol. Currently, manufacturers use proprietary communication protocols, requiring all components (including the thermostat) to be from the same manufacturer. This makes it impossible to mix and match components from different manufacturers without sacrificing the features offered via communications. With the recent increase in popularity of third-party smart thermostats, the inability to use these thermostats with a communicating HVAC system may hinder adoption.

Another technical challenge associated with AFDD technologies is the need for accurate no-fault targets for the monitored data. To identify a fault condition, AFDD technologies must have a no-fault target for comparison with its monitored data. Additionally, the no-fault targets must allow for expected deviations in operation due to component and assembly tolerances, installation-specific differences, and sensor accuracy to help mitigate the risk of falsely identifying a fault when none exists. This has been identified as a major barrier for the OEM-embedded performance monitoring approach because it requires accurate performance predictions across a wide range of indoor and outdoor operating conditions. The add-on, indirect HVAC technologies rely on trend analysis, which introduces two challenges related to no-fault targets. First, the system needs to be fault-free when the AFDD technology is commissioned to ensure that it can establish a baseline data set that is not influenced by faults. Second, it may be challenging to determine whether changes in operation are caused by faults or changes in the environment (e.g., outdoor temperature, solar irradiance, indoor temperature, or indoor humidity) or occupant behavior (e.g., thermostat set point schedules or internal heat loads). For those reasons, the add-on, indirect HVAC approach received a major barrier designation for this category. The other AFDD technologies generally rely on parameter thresholds for identifying faults, and it may be easier to identify an appropriate no-fault target for specific measured parameters on the HVAC system. Therefore, those technologies received minor barrier designations for this category.

The need for installer/contractor training is a barrier for all AFDD technologies except for add-on, indirect HVAC AFDD technology. For OEM-embedded approaches, this is considered a minor barrier because some limited training will be necessary for contractors to familiarize themselves with the AFDD features of the system and learn how to properly read fault codes and utilize them to diagnose the problem. There is significantly more training required to properly use smart diagnostic tools and to install and configure add-on, direct HVAC AFDD technology, resulting in a major barrier notation for these technologies (PNNL 2021). The accuracy of both approaches relies on the proper placement and installation of sensors and proper use of the associated software. Proper use of the software often requires technicians to manually input a significant amount of data about the HVAC system. The performance of smart diagnostic tools and add-on, direct HVAC systems is dependent on the accuracy of this information, and this has been marked as a major barrier accordingly.

4.5 Market Barriers

The primary market barrier to broad AFDD adoption is a lack of awareness and/or demand for the technology. DOE launched the Smart Tools for Efficient HVAC Performance Campaign (PNNL N.D.) in 2021 to promote awareness of smart diagnostic tools and provide key resources for stakeholders, which should help to address the minor barrier indicated in Table 3. Lack of technology awareness and demand is considered a minor barrier for add-on, indirect HVAC AFDD for several reasons. Though smart thermostats have been installed in millions of U.S. homes, many of these devices do not include AFDD features, or the AFDD features that are included have not always been enabled by default. AFDD features included on add-on, indirect HVAC technologies likely do not influence consumers purchasing decisions.

The major market barrier for adoption of add-on, direct HVAC AFDD technology revolves around business challenges associated with the distribution chain. Add-on, direct HVAC AFDD technology reaches the consumer through the HVAC contractor, and remote monitoring of the HVAC system may not align with the HVAC contractor's conventional business practices, which can involve multiple site visits per year to build customer relationships and sell other services. Additionally, the HVAC contractor may view add-on, HVAC direct AFDD technology as extending the life of the HVAC system, which is counter to their interest in selling replacement equipment. Medium-sized HVAC contractor businesses are most likely to adopt add-on, direct HVAC AFDD technology in their business practice, because they are more flexible, and the business owners are still engaged with hands-on activities. Small HVAC contractor businesses do not have the bandwidth to overcome the challenges required to adopt new technology, such as contractor training and remote monitoring, and often do not understand the technology's value proposition. Large HVAC contractor businesses are not well-suited or interested in adopting a new technology that requires significant change management.

OEM-embedded, parameter threshold AFDD technology has seen little market adoption because the high-end, premium HVAC systems that currently include the technology are not a significant percentage of units sold (Regulations.gov 2015). High-end, premium HVAC systems are often purchased because of their high efficiency, improved comfort control, and lower noise levels rather than the embedded AFDD technology.

Residential, central HVAC systems are typically sold to consumers by HVAC contractors, not by the OEM, and thus the HVAC sales chain disconnects the OEM from the homeowner. HVAC contractors are the OEMs' sales team and ultimately determine the features to emphasize while reviewing cost proposals with the homeowner. HVAC contractors may choose to emphasize features such as system efficiency, thermal comfort, noise level, or Wi-Fi connectivity because they consider these features to be more important to the homeowner. Additionally, OEM-embedded AFDD features are a greater benefit to the building occupant than the contractor and could lead to longer installation times for the contractor. Thus, homeowners may be unaware of embedded AFDD technology and not understand the benefits the technology may have on the operational efficiency of the system.

Because there are a limited number of differentiators in low- and mid-tier HVAC equipment products, OEMs often market equipment based on reliability and lifespan. Touting product reliability while trying to upsell AFDD features to detect performance issues is a challenging proposition for HVAC contractors, and HVAC contractors admitting equipment may have performance-robbing faults in the future is contrary to OEM marketing strategies.

Table 3. Key AFDD Adoption Barriers

	Barrier Description	Can DOE Help Remove Barrier?	Smart Diagnostic Tools	Add-On		OEM-Embedded	
				Indirect HVAC	Direct HVAC	Parameter Thresholds	Performance Monitoring
Evaluation	No standard method of test exists to establish FDD performance and accuracy	Yes	XX	XX	XX	XX	XX
Evaluation	No standard exists to establish fault types and fault thresholds that should be detected	Yes	XX	XX	XX	XX	XX
Justification	Limited data on the energy-penalty of specific faults with specific system types *	Yes	XX	XX	XX	XX	XX
Justification	Limited data on prevalence of installation and operational faults *	Yes	XX	XX	XX	XX	XX
Justification	Limited field deployment data verifying energy savings with AFDD implemented	Yes	XX	XX	XX	XX	N/A
Cost	Sensor hardware cost	Yes	X		XX	XX	XX
Cost	HVAC contractor labor cost	No	X		XX	X	X
Cost	Subscription service fee required for monitoring	No			XX		N/A
Implementation	Data needs to be communicated between the indoor unit, thermostat, or outdoor unit	Yes				X	X
Implementation	Requires accurate no-fault targets	Yes	X	XX	X	X	XX
Implementation	Requires installer/contractor training	Yes	XX		XX	X	X
Implementation	Relies on data entry by technicians	Yes	XX		XX		N/A
Market	Technology awareness/demand	Yes	X	X	XX	XX	N/A
Market	Potentially undermines HVAC contractor maintenance subscription business	No			X		N/A
Market	HVAC sales chain disconnects the OEM from the homeowner	No				X	X
Market	Selling AFDD features contradict OEM marketing product reliability	Yes			X	XX	XX

*Efforts to remove barrier would apply to all five fault detection technologies.

Note: "X" denotes minor barriers and "XX" denotes major barriers relative to the other FDD technology types where:

- Minor Barrier = Significant progress toward overcoming barrier could be achieved with a 1- to 2-year focused effort by select organization(s), and
- Major Barrier = Significant progress toward overcoming barrier could be achieved with a 2+ year focused effort with industry-wide engagement

5 Conclusions

The purpose of this report is to characterize market and technical barriers impeding broader utilization of fault detection technology for residential HVAC energy efficiency applications. We describe five main AFDD technology types—smart diagnostic tools, add-on indirect HVAC, add-on direct HVAC, OEM-embedded parameter threshold, and OEM-embedded performance monitoring. Table 2 compares the five technology types, target markets, features, and pros and cons. We identify the key barriers associated with the broader adoption and utilization of the five AFDD technology types by indicating the key evaluation, justification, cost, implementation, and market barriers. Table 3 lists five categories of barriers and denotes which individual barriers are considered minor or major depending on level of effort estimated to remove the barrier. We concluded that DOE funded research can address most of the barriers we identified.

References

Allied Market Research. 2021. "Smart Thermostat Market by Technology (Wi-Fi, Bluetooth, Zigbee, and Others), Application (Air Conditioning, Heating, and Ventilation) and End User (Residential, Commercial, Industrial, and Others): Opportunity Analysis and Industry Forecast, 2020–2027." https://www.alliedmarketresearch.com/smart-thermostat-market.

Butzbaugh, J., Tidwell, A. and Antonopoulos, C. 2020. *Automated Fault Detection & Diagnostics: Residential Market Analysis*. Pacific Northwest National Laboratory. Prepared for the U.S. Department of Energy.

EERE. 2018. *Residential HVAC Installation Practices: A Review of Research Findings*. https://www.energy.gov/sites/prod/files/2018/06/f53/bto-ResidentialHVACLitReview-06-2018.pdf.

Emerson. 2021. "Sensi Predict: Brining smart technology to HVAC systems." https://manuals.plus/m/f86d8d59d778a98823badbe5f22ea3e9b703d6cb594dbe378809febc5dab6908_optim.pdf.

ENERGY STAR®. 2020. "Smart Thermostat Best Practices Guide." https://www.energystar.gov/sites/default/files/asset/document/ES_ST_BP-Guide%20FINAL.pdf.

Frank, S. M., Lin, G., Jin, X., Singla, R., Farthing, A., Zhang, L., & Granderson, J. (2019). *Metrics and methods to assess building fault detection and diagnosis tools* (No. NREL/TP-5500-72801). National Renewable Energy Lab., Golden, CO.

Personal communication with HVAC OEM. March 23, 2020.

PNNL. 2021. *Smart Diagnostic Tools are a "Game Changer" for HVAC Contractors*. PNNL-SA-165813. Pacific Northwest National Laboratory. https://www.pnnl.gov/sites/default/files/media/file/SDTC%20Contractor%20Case%20Study.pdf.

PNNL. N.D. "Smart Tools for Efficient HVAC Performance Campaign." https://www.pnnl.gov/projects/residential-hvac-smart-diagnostic-tools-campaign.

Regulations.gov. 2015. "2015-08 NODA Technical Support Document: Energy Efficiency Program for Consumer Products: Residential Central Air Conditioners and Heat Pumps." https://www.regulations.gov/document/EERE-2014-BT-STD-0048-0029.

Smart Thermostat Market by Technology (Wi-Fi, Bluetooth, Zigbee, and Others), Application (Air Conditioning, Heating, and Ventilation) and End User (Residential, Commercial, Industrial, and Others): Opportunity Analysis and Industry Forecast, 2020–2027. https://www.alliedmarketresearch.com/smart-thermostat-market.

Southface Energy Institute (Building America). N.D. "Optimizing Residential HVAC Performance using Quality Installation Verification and Monitoring Tools." https://www.energy.gov/eere/buildings/optimizing-residential-hvac-performance-using-quality-installation-verification-and.

University of Central Florida (Building America). N.D. "Investigation of the Prevalence and Energy Impacts of Residential Comfort System Faults – Hot-Humid and Hot-Dry Climates." https://www.energy.gov/eere/buildings/investigation-prevalence-and-energy-impacts-residential-comfort-system-faults-hot.

University of Nebraska Lincoln (Building America). N.D. "A Field Study to Characterize Fault Prevalence in Residential Comfort Systems." https://www.energy.gov/eere/buildings/field-study-characterize-fault-prevalence-residential-comfort-systems.

Winkler, J. and Munk, J. 2020. "Development of Technical Specifications and Evaluation Methods for Embedded AFDD in Residential HVAC Equipment – Summary of Key Project Findings." *DOE Internal Document*.

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

For more information, visit:
energy.gov/eere/buildings

DOE/GO-102022-5697 • April 2022