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Review of Residential Comfort Control Products and Opportunities

December 2017

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S Goyal
MC Baechler

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Richland, Washington 99352

Executive Summary

Buildings consume about 40% of total energy used in the United States, and residential buildings account for more than half of the energy consumed in buildings.

Researchers have shown that about 60% of heating, ventilation, and air-conditioning (HVAC) systems have installation, commissioning, and performance problems, leading to as much as a 30% increase in annual energy consumption (Lstiburek 2010; Domanski 2014). The efficient design and improved operation of HVAC systems in homes could lead to significant energy reduction.

The development of commercially available sensors and control-related software in the past decade has resulted in a rapidly growing and changing HVAC control industry. Several papers describe parts of the HVAC controls space (Maasoumy, 2016, DOE 2016b, DOE 2016d, Wang and Goins, 2015). However, the objective of this paper is to fill a remaining need to help researchers capture a snapshot of HVAC control product capabilities and remaining opportunities that save homeowners and technicians' time, money, and energy. By developing a taxonomy around the interaction between HVAC sensor and control technology, the current state-of-the-art product capabilities can be organized and summarized.

This paper begins by discussing the interaction of each major component in advanced sensor and control applications related to HVAC equipment. Figure ES.1 shows how each of these components interacts with each other to form appropriate inputs and outputs for a given application.

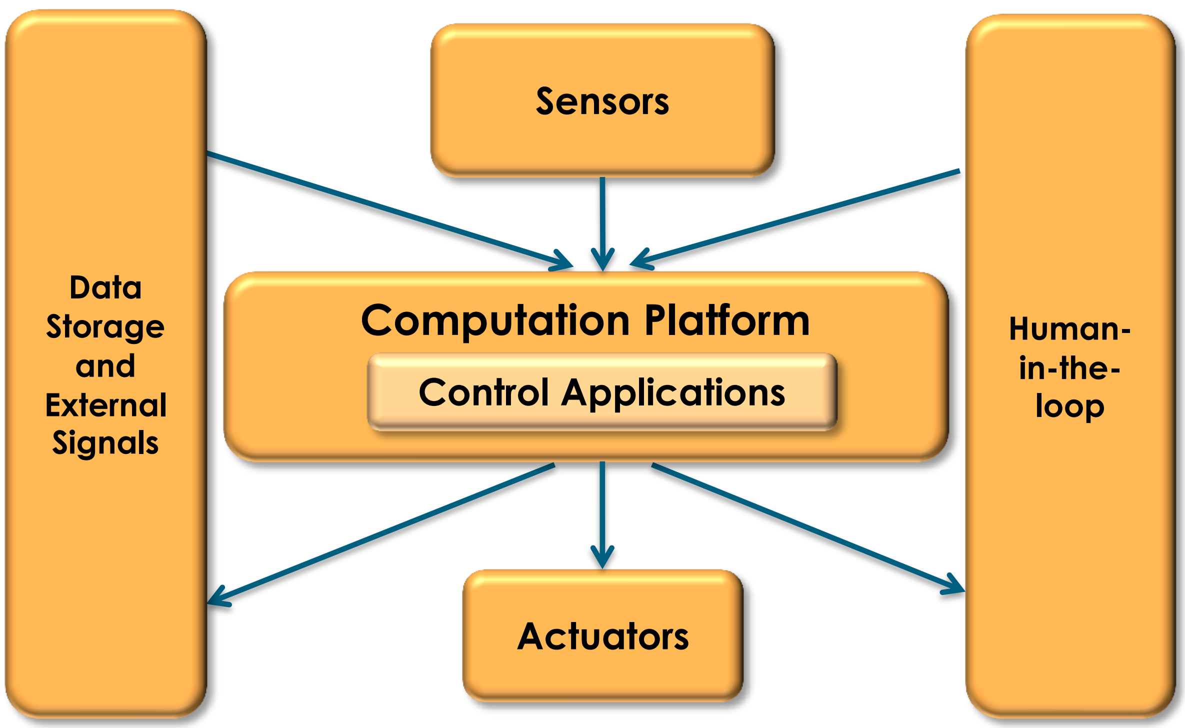

Figure ES.1. Interactions between Several Component Technologies in an HVAC Control System (blue lines represent communication.)

The paper also looks at the applications of these components to commissioning, maintenance, and operations of the HVAC equipment in residential buildings. This paper assumes that commissioning is conducted by the same contractor who installed the HVAC system (or possibly by a third-party verifier). Scheduled maintenance, or retro-commissioning, are also included in this section. An overview of major commissioning applications—including the current state-of-the-art, the benefit of improving that current technology, and the possible missed opportunities associated with each application—is shown in Figure ES.2.

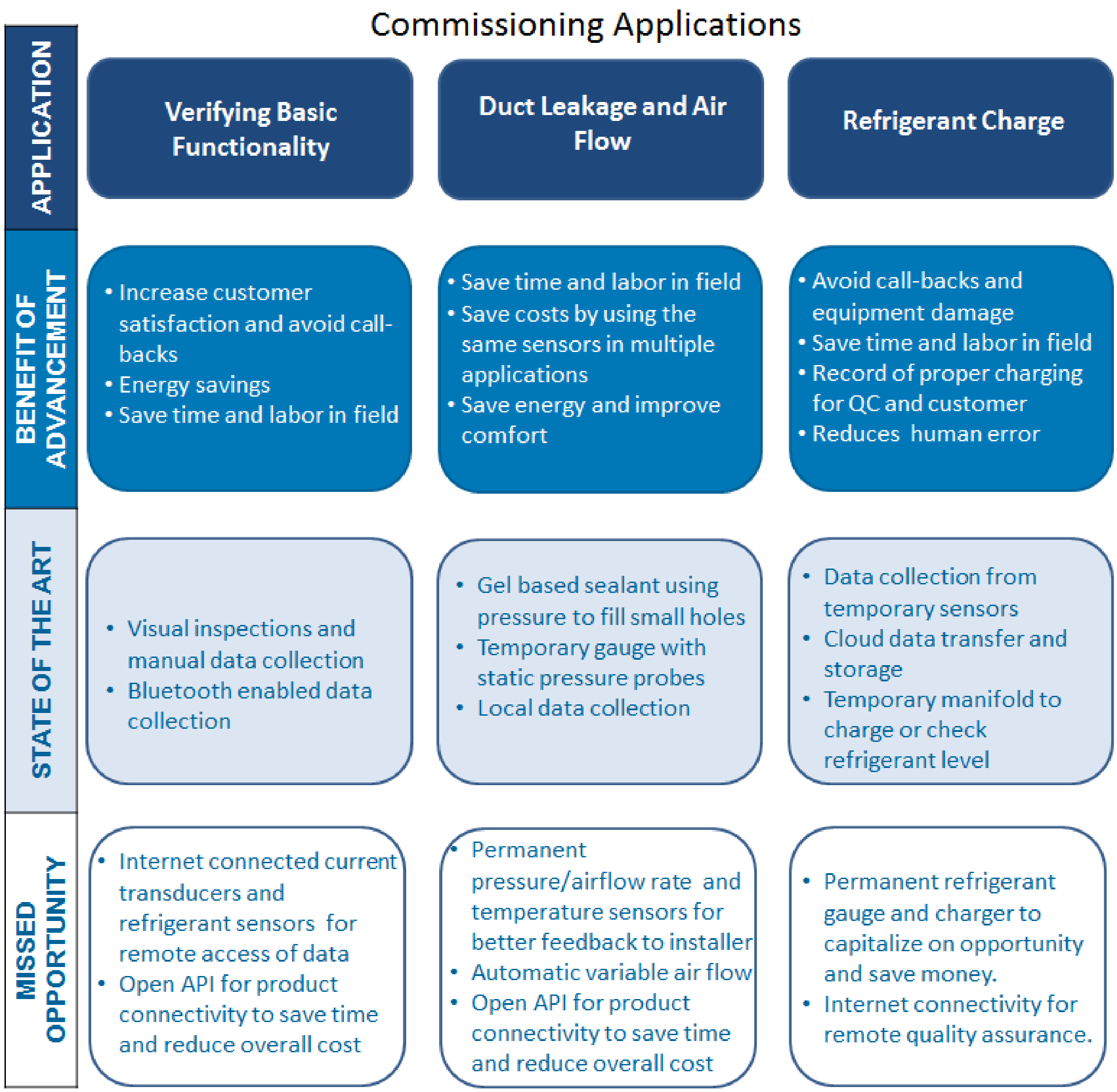

Figure ES.2. An Overview of State-of-art, Technical Gaps, and Benefits of Commissioning Applications

Maintenance is likely performed by an HVAC contractor. This is usually initiated by the homeowner, although some homeowners opt for a service contract providing biannual inspections and tune ups. A summary of the major maintenance applications is shown in Figure ES.3.

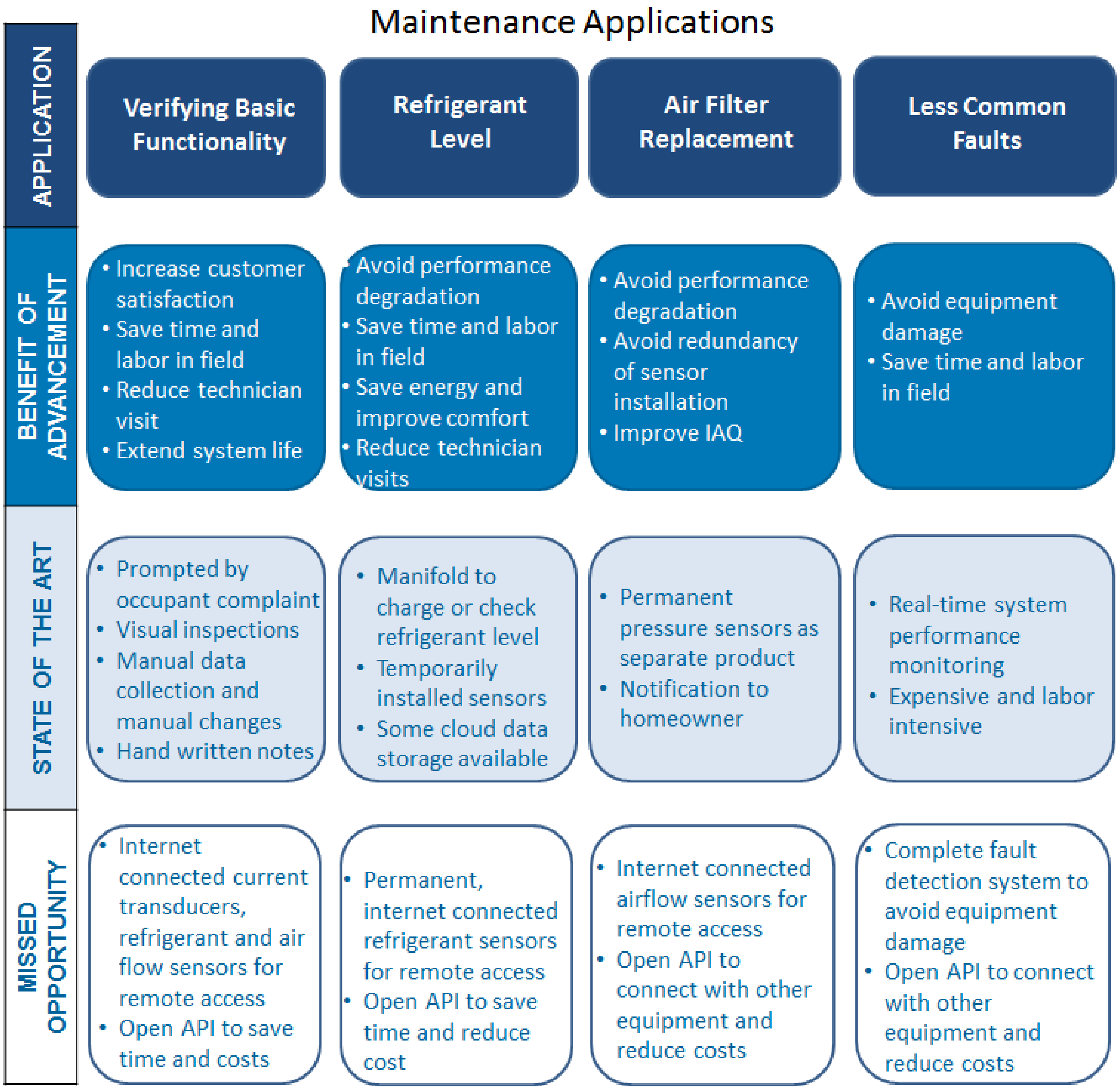

Figure ES.3. An Overview of State-of-art, Technical Gaps, and Benefits of Maintenance Applications

HVAC operation revolves around the interaction of occupants and HVAC systems. Improving this interaction is a major objective of emerging intelligent controls. An overview of operations and optimization applications is shown in Figure ES.4.

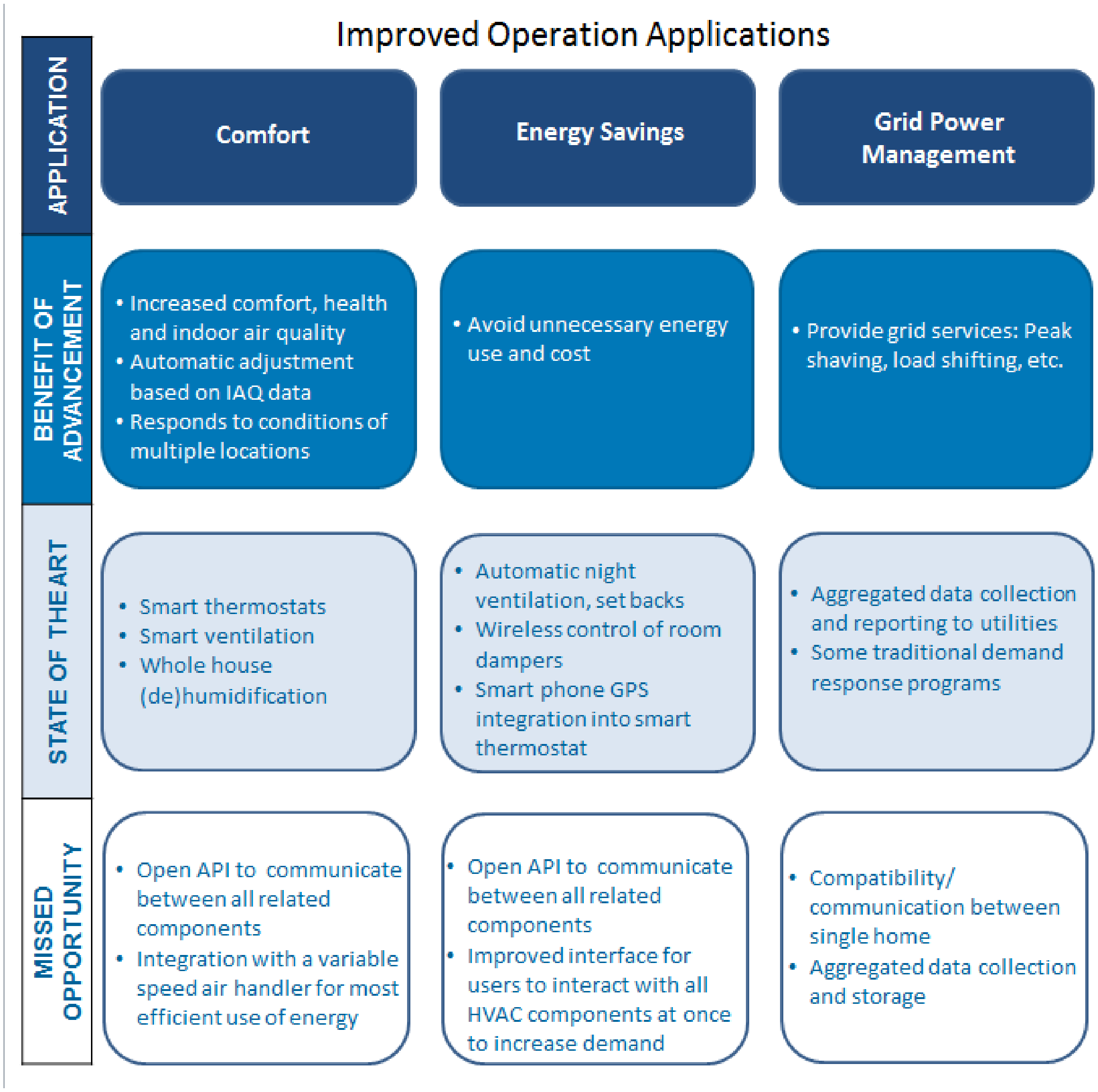

Figure ES.4. An Overview of State-of-art, Technical Gaps, and Benefits of Operation Applications

A summary of state-of-the-art product features is also provided. These products are categorized through their primary application type (commissioning/maintenance or operation) and the features are categorized by component type (sensors, data storage, human-in-the-loop, communication, and controls).

A common theme that emerges from this study is the importance of connectivity *between* product categories. There are many manufacturers of sensors and many manufacturers of controls, but the power to save time and money through automation of any application comes with the ability to connect those manufacturers together through a standardized application programming interface (API).

Two reoccurring opportunities to help save energy also appear throughout the paper. First, the use and control of variable speed motors throughout many components of the HVAC system would help take advantage of opportunities where full power is not necessary. Second, permanent and internet-connected sensors could help quickly diagnose and alert homeowners and technicians of non-optimal operating conditions so they can be remedied (e.g., dirty filters).

Acknowledgments

This paper would not have been possible without funding from the U.S. Department of Energy's Building America Program. The authors acknowledge and thank Eric Werling and Lena Burkett from the U.S. Department of Energy for their enthusiastic management of the Building America Program as well as their invaluable dedication to this paper. The authors also gratefully acknowledge help from Rosemarie Bartlett, Michael Brambley, Joshua Butzbaugh, Paul Ehrlich, Cory Fox, and Nora Wang for providing relevant information and excellent reviews.

Acronyms and Abbreviations

API	application programming interface
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTU	British thermal unit(s)
CO	carbon monoxide
CO_2	carbon dioxide
EPA	U.S. Environmental Protection Agency
ERV	energy recovery ventilation
FDD	fault detection and diagnostics
GPS	Global Positioning System
HRV	heat recovery ventilation
HSRS	HVAC Smart Relay Switch
HVAC	heating, ventilation, and air-conditioning
IAQ	indoor air quality
IFTTT	If This Then That
kWh	kilowatt-hour(s)
NA	not applicable
PIR	passive infrared
PM	particulate matter
RECS	Residential Energy Consumption Survey
RH	relative humidity
UV	ultraviolet
VFD	variable frequency drive
VOC	volatile organic compounds

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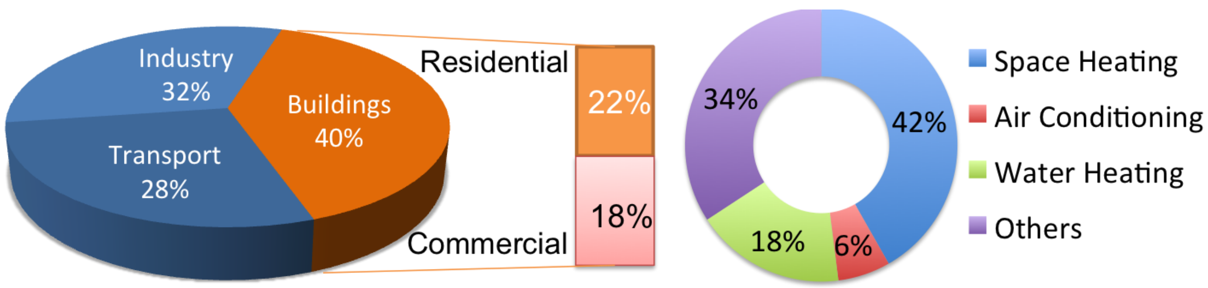
1.0 Introduction

Buildings are one of the major energy consumers across the world. In the United States, they contribute approximately 40% to the total energy consumption (EIA 2015). According to the Residential Energy Consumption Survey (EIA 2009), residential buildings account for more than half of the energy consumed in buildings.

Figure 1 shows the total energy consumption in the United States by end-use sector and the energy consumption in homes by their end usage. As shown in the figure, heating and cooling consume about 48% of the energy usage in residential buildings. A small percentage of energy savings in the residential heating, ventilation, and air-conditioning (HVAC) systems can have high economic and environmental impacts.



a) Energy Consumption by End-use Sector   b) Energy Consumption in Residential Buildings by End Usage

Figure 1. U.S. Energy Consumption by Sector and End Usage (EIA 2015 and EIA 2009)

To date, the majority of HVAC system sales have been replacement units that moved through a single distribution channel (EERE 2011). The manufacturer designs and builds the HVAC equipment, sells it to a distributor, who sells it to an HVAC contractor, who installs the unit for the end consumer. HVAC controls, such as thermostats and programmable thermostats, have typically been installed concurrently with the rest of the HVAC system. Now, more and more of these control devices are available at retail stores. This gives consumers more choices and pushes manufacturers to provide features that are valuable (e.g., saving time, money, or energy) for consumers.

Researchers have shown that about 60% of HVAC systems have installation, commissioning, and performance problems, leading to as much as a 30% increase in annual energy consumption (Lstiburek 2010; Domanski 2014). The efficient design and improved operation of HVAC systems in homes could lead to significant energy reduction. (As of 2015, there were approximately135 million households in the United States (EIA 2015), and the average annual electricity consumption for a U.S. residential customer is about 12,000 kWh. If 60% of homes in the U.S. were wasting 30% of their HVAC energy on performance issues that could be fixed with fault detection and diagnostics (FDD), about 146 billon kWh or 0.5 quads could be saved overall with better HVAC controls.)

While seven manufacturers (UTC/Carrier, Goodman/Amana, Trane/American Standard, Lennox, Rheem, York, and Nordyne) dominate the HVAC equipment market, they are not the market leaders in external HVAC controls. This disconnect between the equipment and controls manufacturers has left the market disjointed and flooded with options for consumers.

The objective of this paper is to capture a snapshot in time for this fast-moving industry. This paper will identify the current state-of-the-art sensing and control technologies, applications, and products. With this information and a review of recent literature, remaining opportunities to save homeowners and technicians time, cost, and energy are summarized. Although this paper touches on connected buildings and the "Internet of Things," it does not provide a comprehensive review of those industries as some other review papers do (Maasoumy, 2016, DOE 2016b, DOE 2016d, Wang and Goins, 2015). This paper is different from other review papers because it focuses solely on potential advancements in residential HVAC control applications.

The organization of the paper is shown in Figure 2. It shows the topic for each section and indicates what question each section is attempting to answer. Section 2.0 reviews the existing state-of-the-art sensors and controls/actuators, communication strategies, computation platforms, and interfaces related to residential HVAC systems. A description of advanced sensing and control applications is presented in Section 3.0. Section 4.0 presents a national energy savings impacts assessment and market barriers evaluation of the applications and associated technologies. Section 5.0 quantifies the potential impact of each technology advancement on the overall energy use of U.S. housing stock and prioritizes gaps based on these estimates.

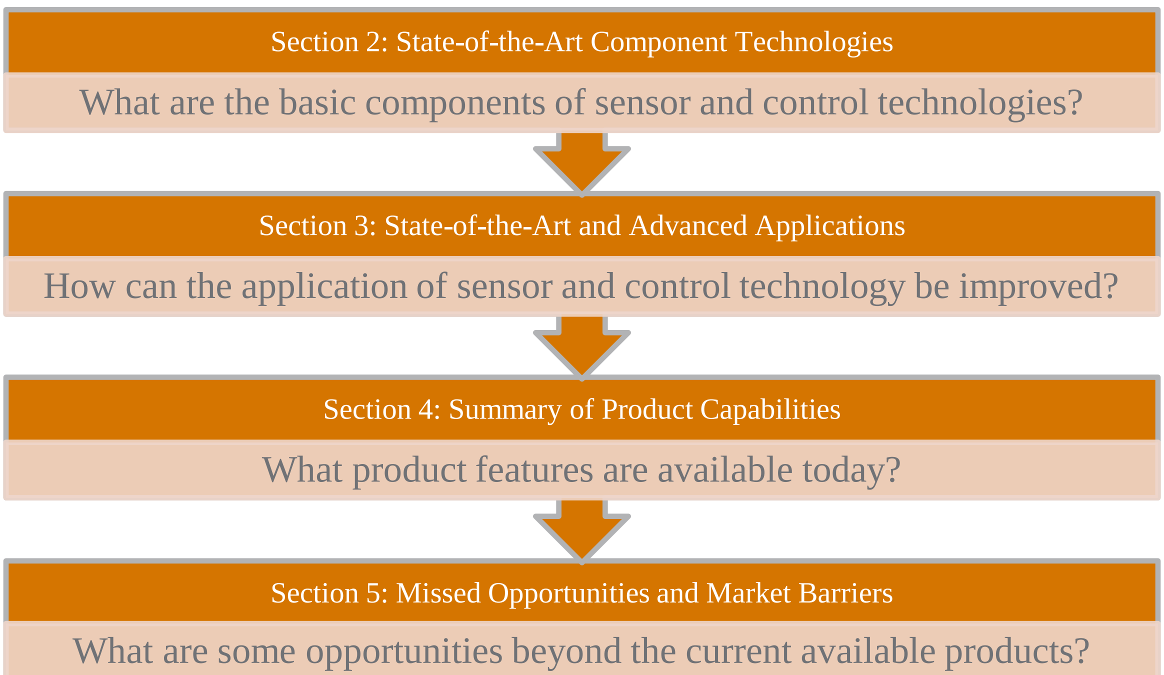


Figure 2. Outline of Paper

2.0 State-of-the-Art Component Technologies

A successful control system for implementing a basic or advanced control application may include up to six major components: (1) sensors, (2) data storage and external signals, (3) human-in-the-loop, (4) communication between components, (5) computation platform with control applications, and (6) actuators. Figure 3 shows interactions between these components.

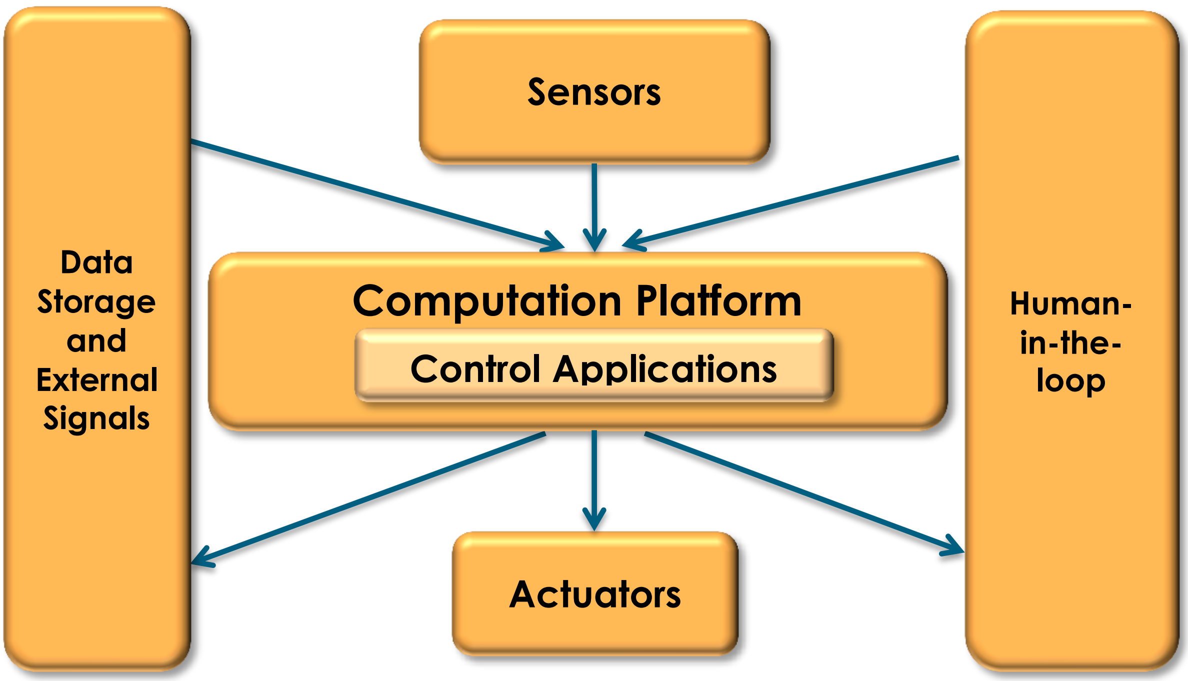


Figure 3. Interactions between Several Components in an HVAC Control System (Blue lines represent communication.)

2.1 Sensors

Sensors are devices used to produce electrical, digital, or optical signals to measure physical parameters and detect environmental events. Over the past few decades, the sensor and communications market has grown significantly with the development of temperature, humidity, occupancy, light, and CO_2 sensors. However, use of these sensors for HVAC control has still not reached its maximum potential in residential buildings for four main reasons: (1) high cost, which can be due to a combination of equipment expense, installation, and maintenance; (2) lack of computational capabilities; (3) inability of HVAC systems to effectively use the data from the sensors; and (4) the need to have sensors at multiple locations. Note that in Table 1 the sensors are listed at the component level. Multiple sensors (along with communication sensors) can be combined together to create products that are of potential use for HVAC systems. Such products are described later in the section. Table 1 provides an overview of available sensors that are either used in existing residential HVAC systems or that are capable of being used in the HVAC systems.

On-board sensors and diagnostics are common in HVAC equipment. However, those systems tend to be proprietary, and ultimately help diagnose internal issues with the equipment. Usually, this type of fault helps the equipment be capable of running at all. This paper goes above and beyond the baseline functioning of the system and focuses on ways in which external sensors and controls can help homeowners and technicians save time, money and energy. Therefore, on-board sensors will not be discussed further in this paper.

Table 1. Advantages, Disadvantages, and Applications of Several Types of Sensors

Sensor Types	Applications, Advantages & Disadvantages
Temperature	Applications: Outdoor, rooms, ducts
Thermocouples	Advantages: Inexpensive. Simple. Self-powered. Large temperature range. Rapid response time. Durable. Disadvantages: Not very accurate or stable. Signal conditioner needed.
Thermistors	Advantages: Inexpensive. Highly accurate. Stable. Rapid response time. Disadvantages: Fragile. Require voltage excitation. Overheating in certain models.
Resistance-temperature devices (RTDs)	Advantages: Long lasting. Accurate. Very stable. Easy to recalibrate. Disadvantages: Expensive. Slower response time. Require current excitation.
Humidity	Applications: Outdoor, dew point, rooms
Resistive Relative Humidity Sensor	Advantages: Small size. Low cost. Long-term stability. Field interchangeable. Disadvantages: Accuracy is inadequate at low relative humidity RH values. Can shift values if exposed to condensation. Significant temperature dependencies. Exposure to chemical vapors will lead to premature failure.
Capacitance Relative Humidity Sensor	Advantages: Stable. Resistant to chemical vapors. Disadvantages: Accuracy decreases as temperature deviates from calibration temperature. Field interchangeability requires computer-based recalibration for many models. Distance between sensing element and signal conditioning circuitry is limited to <10 feet. Selection of sensor and transmitter combination is important for proper application.
Thermal Conductivity Absolute Humidity Sensor	Advantages: Very durable. Resistant to chemical vapors. Disadvantages: Accuracy is dependent on ambient temperature. Respond to any gas that has thermal properties different from those of dry nitrogen.
Air Quality	Applications: Rooms, ducts
Photoionization Detectors (PIDs)	Advantages: Accurate. Reliable. Immediate. Can detect multiple types of volatile organic compounds (VOCs). Portable or permanent installation. Can log data. Disadvantages: More expensive than other indoor air quality (IAQ) sensor types.
Infrared Carbon Dioxide Monitors	Advantages: Portable or permanent installation. Disadvantages: Acts as a secondary measurement tool for IAQ because CO_2 is an indicator of poor IAQ, not a contaminant. Does not measure VOCs from building materials, furniture, and contamination.
Metal Oxide Sensors (MOS)	Advantages: Simple. Inexpensive. Can detect multiple types of VOCs. Disadvantages: Limited sensitivity. Slower to react. False positives in response to moisture or temperature.
Air Pressure	Applications: Ducts
Variable Resistance Transducers	Advantages: Simple. Inexpensive. Accurate. Reliable. Durable. Repeatability. Disadvantages: Amplifier is needed to amplify and condition signal to prevent interference. Changes in temperature may necessitate recalibration.

Sensor Types	Applications, Advantages & Disadvantages
Capacitance	Advantages: Can measure small differential pressure changes even with high static pressure. Stable. Repeatability. Disadvantages: High temperature sensitivity. High impedance output.
Power Sensors	Applications: HVAC equipment
Thermistors	Advantages: Inexpensive. Highly accurate. Stable. Rapid response time. Disadvantages: Fragile. Require voltage excitation. Overheating in certain models.
Occupancy	Applications: Indoor occupancy, outdoor motion, garage safety
Passive Infrared Sensors	Advantages: Simple. Disadvantages: Relies on movement to indicate occupancy. Local in scope. Fairly coarse grained.
Ultrasonic	Advantages: Can detect motion in any part of a space. Reliable. Typically contain both sensing and circuitry components. Disadvantages: Relies on movement and sound to indicate occupancy. Can be overly sensitive, responding to HVAC airflow.
CO_2	Advantages: Inexpensive. Stable. Rapid response time. Disadvantages: Not yet accurate in residential applications.
Energy Flow Meters	Applications: Metering HVAC, co-generation, water heaters
BTU Meter	Advantages: Matched sensors make data collection process simpler and maintain data consistency. Output flexibility. Connectivity to common control networks. Disadvantages: Flow measurement accuracy is dependent on model, calibration and installation.
Full Bore Magnetic Meter	Advantages: Very accurate, even at low flow rates. Long lasting. Reliable. Low maintenance costs. Disadvantages: Expensive. Reverse eddy currents can cause inaccurate readings.
Vortex Shedding Meters	Advantages: Common. Simple. Inexpensive. Disadvantages: Not accurate at low flows.
Ultrasonic Meters	Advantages: Noninvasive. Ideal for retrofit applications. Disadvantages: Installation details are critical. Installation error is more common, leading to inaccuracy.

One of the key shortcomings in control technology is that most residential buildings have only one sensor (interior temperature) per HVAC system. This sensor is typically in the thermostat, which is usually centrally located in a home, but does not capture the temperature variations throughout a home. Using multiple temperature sensors could improve both comfort and energy efficiency in homes (Siemann 2010). Similarly, despite the low cost of occupancy (presence/absence) sensors, they are not widely deployed for controlling HVAC systems in residential buildings. Certain thermostats (e.g., NEST, Ecobee) have a built-in passive infrared (PIR) sensor and have been deployed in several million homes. However, their use for efficient, optimized control is still unclear because it is quite challenging to detect occupancy status (occupied/unoccupied) of an entire home based on a single PI sensor at only one location. More examples of sensor applications are described in Section 4.0.

Smart/Intelligent Sensors: “Smart” sensors are sensors with small memory and standardized physical connection to enable communication with the processor and data network. A smart sensor could also be a combination of sensors with signal conditioning, embedded algorithms, and a digital interface. A smart sensor combines a sensing element, analog interface circuit, an analog-to-digital converter, and a bus interface in one unit. It usually provides functions beyond those necessary for generating correct representation of a sensed quantity.

Examples of smart sensors that are currently available include digital thermometer with thermocouple probes, multi-meter, infrared sensor/temperature gun, thermo-hygrometer, thermal-imaging temperature gun, and refrigerant pressure gauge. Examples of products that contain smart sensors include iManifold, Comfort Guard, AirAdvice, and FooBot. These products are discussed in more detail in Section 4.0.

2.2 Data Storage and External Signals

Data storage plays a key role in verifying, validating, and improving the commissioning, maintenance, and operation of an HVAC system. Historical data can be processed to learn user behavior and adapt control algorithms accordingly to deliver energy-efficient solutions that improve thermal comfort and IAQ inside homes. There are three options for storing data: (1) on the cloud over the internet, (2) on an on-board device as a part of the existing control system (e.g., smart thermostat), and (3) on a local device that is connected to the existing equipment controllers or thermostats, but not considered to be a necessary part to operate the system (e.g., local gateways and servers).

Several services and products that store data on the cloud are available in the market (e.g., Oracles, Opower). However, these products do not use the stored data for active control purposes; instead they focus on monitoring, diagnostics, and other services that identify potential energy saving measures. Although some devices, like smart thermostats (discussed further in Section 2.6), offer on-board data storage and a little computational power for local control purposes, only some thermostats and some cloudstorage providers offer open interface to access data and control functions. If the connection between these devices is open and easily accessible, the computational power and storage capacity of the entire control system can be significantly increased.

External data signals (e.g., utility pricing, weather, incentive signals) can be considered valuable inputs when deciding the control actions for the HVAC system. If This Then That (IFTTT) is an example of an application that can send external signals to computation platforms like smart thermostats. More use cases for data storage and external signals are discussed further in Section 3.0 of this paper.

Many of the technologies described in this paper incorporate connectedness with the web or the cloud. Consumers may view this connectivity as introducing risk to devices that formerly had none. A report from the California Energy Commission (Ghansah 2012) highlights a few cyber security and privacy issues that are possible by using current programmable communication thermostats and advanced metering infrastructure. The need for cyber security is not exhaustively described in this paper because the issue is ancillary to the actual control functions and applications. However, this need is so fundamental that it is included in the final set of recommendations included in Chapter 5.0.

2.3 Human-in-the-Loop

Human-in-the-loop is the term this paper uses to describe any user’s interaction (e.g., occupants, HVAC technicians, utility operators, etc.) providing input or receiving output from the computation platform. The interface for this interaction can be mechanical (e.g., a physical dial), digital (e.g., a computer screen), or internet-based (e.g., a phone application, tablet, etc.).

One example of a human-in-the-loop is an application that notifies the homeowner when a filter needs to be replaced (e.g., FilterScan). There are also interfaces that a utility control center could use to inform operators of peak events and manipulate many residential HVAC systems at once (e.g., Opower). Those interfaces would likely be part of a much more complex software program for demand response (Somasundaram et al. 2014). These systems could also include third-party vendors that gather data and have a control capability, but offer control services to either a utility or to the consumer (Baechler and Hao 2016).

An example of a human-in-the-loop interface that did not deliver its full potential benefit was the programmable thermostat. According to the Energy Information Administration's 2009 Residential Energy Consumption Survey (EIA 2009), 43% of heating systems and 48% of cooling systems in residential buildings use a programmable thermostat to control them. Unfortunately, many of the programmable thermostats that have been installed are not properly operated. Of the consumers who own a programmable thermostat, many struggle to properly understand or program its functions. A recent study by Callaway et al. (2014) indicates that programmable thermostats are difficult for users to understand, which has led to ineffective usage or even abandonment. Due to misuse, households with programmable thermostats sometimes have higher HVAC energy consumption on average than those with manual controls. As a result of this finding, the U.S. Environmental Protection Agency (EPA) suspended the ENERGY STAR programmable thermostat program in 2009. The ENERGY STAR program has since initiated a label for certified "smart thermostats" that are proven to save energy compared to a typical thermostat[1].

2.4 Communication Between Components

Communication functions allow data transfer between sensors, actuators, controllers, processors, storage, and user interfaces/devices. Communication between these sensors and controls can either be hard-wired, or wireless (local or through the internet). In the direct hard-wired case, a sensor is physically connected using a metal wire, which usually transmits a voltage or current signal, through a computation platform, to a control device and/or actuator. In the local wireless option, sensor data are sent to a control device and/or actuator using a local wireless network. Both the sensor and the control device are required to have a wireless relay installed and configured (e.g., Bluetooth). The internet is not needed in this case. In the internet wireless option, sensor data are transmitted to a control device and/or actuator over the internet. Both sensors and control devices are required to have a wireless sensor installed and be connected to the internet. In this case, the data is usually routed to the device through a server, which can be relatively slow and less reliable compared to any hard-wired connection.

2.5 Computation, Controllers and Actuators

Controls change system operation using both software and hardware. Software receives data from sensors, performs computations, and sends a signal to other external sources. Hardware physically responds to a stimulus control signal. Most control hardware is in the form of an actuator. Historically residential HVAC control systems operated using binary (on/off) actuation. Many newer systems support variable capacity outputs for evaporator and condenser fans as well as for gas burners and compressors. The movement to variable capacity has increased both comfort and efficiency. Common actuators are described in Table 2.

Table 2. Actuation Parameters Used for Controlling the HVAC Systems

Actuation Parameters[(a)]	Description
Cooling on/off	A binary signal is sent to turn on or off the cooling mode of operation. This parameter is usually available for both automatic and manual control in most existing systems.

[1] https://www.energystar.gov/products/heating_cooling/smart_thermostats/key_product_criteria

Actuation Parameters[a]	Description
Heating on/off	A binary signal is sent to turn on or off the heating mode of operation. This parameter is usually available for both automatic and manual control in most existing systems.
Fan on/off	The fan is turned on or off, which can be independent of the heating/cooling mode of operation.
Damper position	The damper position is manipulated to change airflow rate in different rooms of a building. This is not usually prevalent in existing systems.
Fan speed	The fan speed can be adjusted in systems with electronically commutated motors to change the total supply airflow rate.
Compressor speed	The compressor speed can be changed in HVAC units with inverter driven compressors.
Refrigerant outlet temperature	The outlet temperature of refrigerant is changed, which is achieved by changing the outdoor blower speed or compressor speed.

(a) Actuation parameters can be changed automatically or manually (by a technician or consumer) during the commissioning, FDD, operation, maintenance, or control stages.

2.5.1 Smart/Intelligent Controllers and Actuators

Smart controllers and actuation devices typically have wider flexibility than traditional controllers and actuators. These devices are capable of integrating themselves easily into HVAC systems (or their smart sensors or intelligent sensing devices) to provide better performance. Examples of smart controllers include variable vent flow devices (e.g., Ecovent), variable speed fans (e.g., Concept 3 motor), and multi-stage refrigeration units (e.g., Carrier's Infinity® 18VS Heat Pump 25VNA8). Details of these products are discussed further in Section 4.0.

2.6 Integrated Sensors and Controls

Integrated sensors and controls are devices consisting of a combination of sensors and controls that physically receive a signal, do some type of computation, and send a signal to the HVAC equipment. An example of a simple integrated sensor and control is a thermostat (basic, programmable, or smart). A thermostat receives data (mostly room temperature) from sensors and sends an actuation signal to operate the HVAC equipment. Basic thermostats are traditional electrical/mechanical devices that measure temperature and control the on/off state of an HVAC system. Programmable thermostats are digital electronic thermostats with an ability to switch between temperature set points based on the time of day (e.g., unoccupied hours during weekdays) or day of the week (e.g., weekends) as set by the user. Connected thermostats offer enhanced communication, improved interface, and simplified schedule setting (DOE 2016b). Smart thermostats are a type of connected thermostat that contain computation features, and thus are capable of supporting advanced software tools to monitor system performance, detect faults, and ensure correct installation and operation. Smart thermostats (a.k.a learning thermostats,) offer enhanced sensing/communication/computation features, and thus are capable to support advanced software tools to monitor system performance, detect faults, and ensure correct installation and operation. As compared to traditional or programmable thermostats, smart thermostats offer users much more flexibility in the development and implementation of advanced control strategies.

3.0 State-of-the-Art and Advanced Applications

In the previous section, components including sensors, data storage, human-in-the-loop, computation platforms, and controls/actuators were each discussed individually. This section describes integrated applications made up of multiple components that provide a service to an end user. These applications are divided into three use-case categories: commissioning, maintenance, and improved operation. In residential buildings, commissioning is likely conducted by the same contractor who installed the HVAC system, or possibly a third-party verifier. This step is sometimes performed as part of the installation. Commissioning can also be performed on existing HVAC systems and equipment, which is referred to as retro-commissioning. An HVAC contractor likely performs maintenance, which is usually initiated by the homeowner, although some homeowners opt for a service contract providing biannual inspections and tune ups. Operation of the system revolves around occupants, and improving this interaction between the occupant and the HVAC system is the subject of Section 3.3. In the future, there would ideally be products that perform tasks across all three categories.

Advanced FDD methods discussed in the sections below can detect faults and prevent catastrophic failures before they happen, thereby saving energy and money while increasing occupant comfort and maximizing the lifespan of the equipment. Advanced controls can use sensor data to operate a system at its optimal performance level based on system specifications, user inputs, and surrounding conditions. Moreover, stored data can also be used to inform and educate occupants and contractors about system operation and design weaknesses, which may result in improved performance by altering the system design or upgrading the system components.

3.1 Commissioning

HVAC commissioning ensures that the installed performance and operation of each component of the HVAC system meet the desired specifications outlined in construction documentation. Ensuring a proper installation requires the following: (1) sensors to measure airflow rate, refrigerant level, refrigerant temperature, zone temperature, etc.; (2) a computation platform to collect the sensors' data and perform calculations; and (3) a software to process the data and indicate whether the system is installed and configured correctly. These three components together are sometimes referred to as FDD.

Commissioning applications discussed in this section of the report focus on times when an HVAC technician would already be coming to a home, either for initial installation, or for scheduled maintenance (a.k.a. retro-commissioning).

An overview of major commissioning applications, including the current state-of-the-art, the benefit of improving that current technology and the major gaps associated with each application are show in Figure 4.

The detailed analysis of each major application is described in more detail in the subsections below. The tables that discuss the technology gaps of each application include a description of the state-of-the-art technology, potential technology advancements, and a summary of technology gaps. Each table also refers to "inputs," which include all inputs that help the application complete its task. These can include sensor measurements, manual input/inspection, or stored data from the cloud. The "outputs" refer to all of the outputs that the application provides. These can include a control action, a user notification, or even data sent to the cloud.

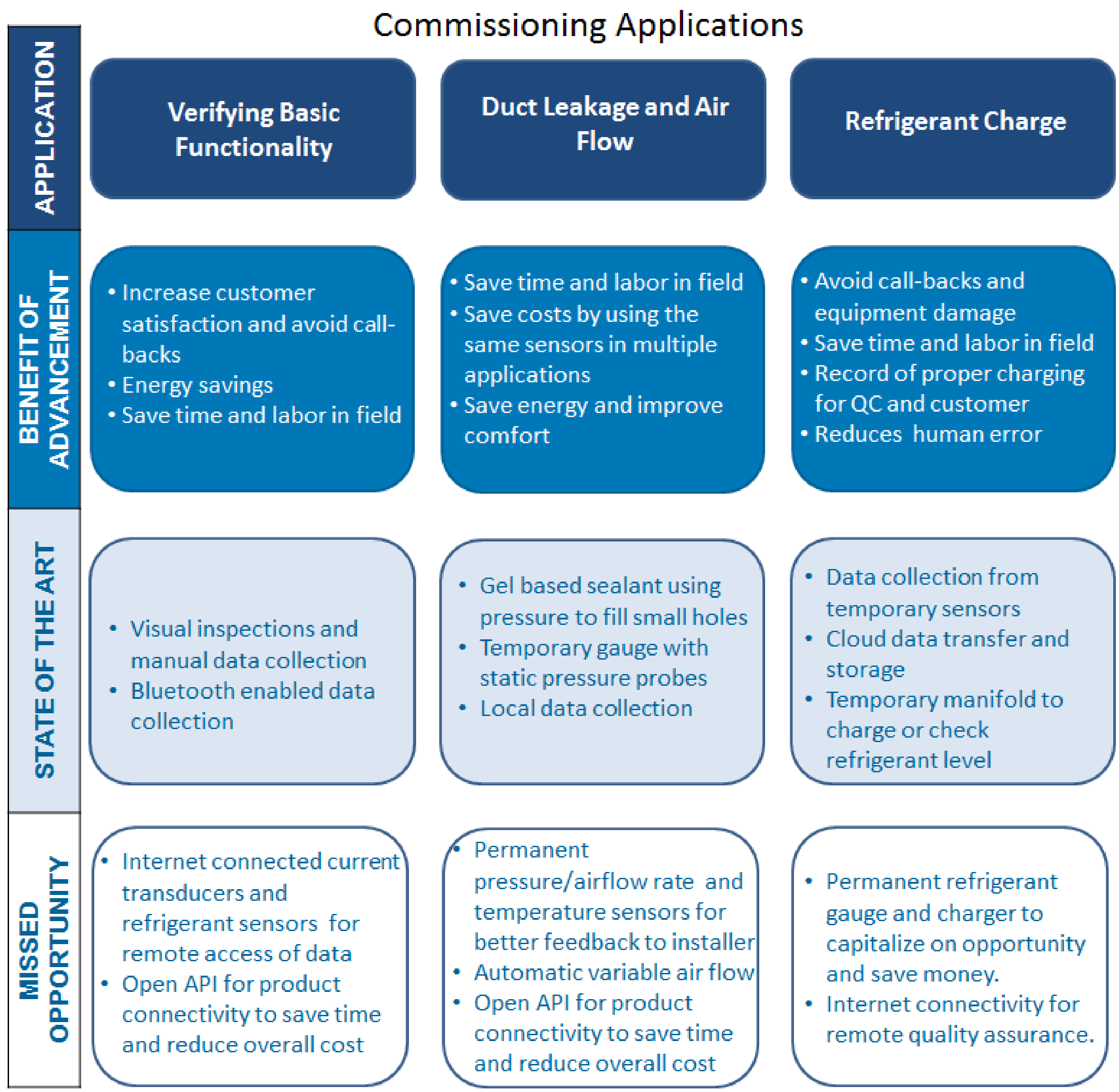


Figure 4. An Overview of State-of-art, Technical Gaps, and Benefits of Commissioning Applications

3.1.1 Verifying Basic Functionality

In residential buildings, the basic functions of an HVAC system are typically checked by the onsite technician who is installing the system. Checking the basic functionality of the system typically requires a person to turn the system and thermostat on, and visually inspects each of the components. Some of the items a technician would check to ensure basic functionality include: system turns on/off, is each component generally functioning (compressor, fan, burners, sensors, etc.), thermostat signal from equipment. Specific measurements that are taken to determine if there is a fault in the system include: power flowing to equipment, power flowing between equipment components, refrigerant charge, air flow, and connectivity between components. Current state-of-the-art processes and potential technologies are listed in Table 3 below.

Table 3. Remaining Opportunities to Reduce Time, Cost and Human Error Associated with Verifying the Basic Functionality of HVAC Systems

	Description	Inputs	Output
Current State-of-the-Art	HVAC system on/off	Visual inspection	NA
	Components functioning	Manual temperature measurement at grills, on-board diagnostics.	NA
	Thermostat on/off	Visual inspection	NA
	Thermostat settings	NA	NA
Potential Technology	HVAC system on/off	Wireless detection of HVAC system	Notification sent to contractor if HVAC equipment is undetectable.
	Components functioning	Current transducers throughout system and temperature sensors.	Notification sent to contractor if any power or temperature measurements are out of range.
	Thermostat on/off	Wireless detection of thermostat	Notification sent to contractor if thermostat is undetectable.
	Thermostat settings	Wireless timestamp capability. Smart algorithm to determine HVAC type based on signal, or additional current transmitter sensor.	Notification sent to contractor if HVAC type is undetectable.
Remaining Opportunity	Internet-connected current transducers and temperature sensors for remote access of data. Open application programming interface (API) for product connectivity to save time and reduce overall cost.		

3.1.2 Duct Leakage and Air Flow

In this application, we first focus on the air flow rate side of the system, which is divided into three parts: (1) detecting any leakage through the duct (and possibly sealing the leakage), (2) ensuring that air flow supplied to a home is close to its designed value, and (3) ensuring that the air flow is well distributed to different parts of the home.

Duct leakage is typically tested using a duct blaster device (e.g., Minneapolis Duct Blaster®). Once leakage is detected in the ductwork, it can be sealed using Aeroseal, which detects small holes and seals them without manual labor for each hole, or more traditional methods if the ducts are accessible. This process is already fairly automated and there are no further controls-related advancements for this particular commissioning application.

For air balancing and total air flow commissioning, an HVAC contractor will typically use a magnehelic gauge with two static pressure probes to test air flow rate near the air handler. A calculation is then conducted to convert the pressure difference into an airflow measurement. A flow hood (e.g., Alnor Flow Hood) that is typically used for measuring the air flow at each register can also be used on the return side to measure the whole-building airflow, but this is not common practice. Variable speed fans can enhance the ability to make automatic changes in the operation if enough air is not supplied to the home.

Balancing air flow rate should primarily be accomplished through good house layout and ductwork design. That said, there is some balancing that can occur through the tuning of grills or manual dampers. There is potential for automatic air balancing and grill tuning using products that are on the market today;

however, those products have not been tested by a third party and have not been developed for this specific purpose. Although, more expensive, true multi-zone systems can provide pressure and damper position measurements, which can be used to detect and correct slight balancing issues as well.

Table 4 highlights the largest area for improvement in this application of sensors and controls - the integration of static air pressure sensors into the air handler and duct system. There are few options currently available for inexpensive sensors (both in number and types) available in the market. Permanently installed pressure/airflow rate sensors would provide more accurate and more detailed feedback to installers, who may not be able to fix all of the problems they find with these measurements, but it could help reduce future errors by giving installers the power of data. If permanent sensors were installed, it would also provide an opportunity for a variable speed motor to adjust automatically depending on furniture placement or closed grills, providing better comfort and energy savings.

The open application programming interface (API) connection of any system needs to be managed through some computational platform. One example of a convenient computational platform that could be used for this and other applications is the thermostat.

Table 4. Remaining Opportunities to Reduce Time and Cost Associated with Measuring Duct Leakage and Air Flow

	Description	Inputs	Output
Current State-of-the-Art	Automatic duct leakage measurement/sealing (e.g., Aeroseal)	Duct leakage	Digital display and sealed holes
	Total air flow measured with two static pressure probes across air handler	Temporary static pressure probes	Digital display
	Measurements taken at each register	Temperature and pressure sensors at each register	Temperature control in each room
Potential Technology	Total air flow measured with two static pressure probes across air handler	Permanent pressure probes/gauge	Automatic adjustment of variable fan speed to match total air flow
	Auto-balancing of air-side system	Permanent pressure probes in air handler and at registers	Auto-balanced air-side of HVAC system
Remaining Opportunity	Permanent pressure/airflow rate and temperature sensors for better feedback to the installer and automatic adjustment of variable speed motor. Open API for product connectivity to save time and reduce overall cost		

3.1.3 Refrigerant Charge

In this application, sensors detect problems with the refrigerant side of an HVAC system—such as overcharging, undercharging, and leakage—which can be immediately resolved onsite.

The most common way to measure refrigerant charge during the commissioning process is to use a temporary data acquisition system (e.g., iManifold, Testo, Sporlan). Some products integrate an actuation into the device, such as the "Mastercool 99661-A Digital Manifold Gauge Set," which can automatically charge refrigerants to an optimized level. These products (1) detect the pressure of the refrigerant, (2) automatically stop the charging when the desired set point is reached, and (3) continuously transmit the information to a digital display (wired or wireless) or to the technician's smart phone or tablet during the entire process.

The potential technology described in Table 5 includes a set of permanent manufacturer-installed sensors in the outdoor unit of a system that uses refrigerant. The benefit of permanent sensors and chargers is that it could save time and money for future applications. Internet connectivity of sensors like this would provide an opportunity for remote quality assurance.

Table 5. Remaining Opportunities to Reduce Time, Cost and Human Error Associated with Charging Refrigerant

	Description	Inputs	Output
Current State-of-the-Art	Temporary data collection and automatic shutoff of charging system (e.g., Mastercool 99661)	Refrigerant temperature and pressure	Digital display, auto-shutoff when desired pressure is reached
Potential Technology	Permanent sensor installation with automatic flow shutoff when fully charged	Refrigerant temperature and pressure	Digital display, auto-shutoff when desired pressure is reached
Remaining Opportunity	Permanent refrigerant gauge and charger to capitalize on opportunity and save money for future use. Internet connectivity of sensors like this would provide an opportunity for remote quality assurance.		

3.2 Maintenance

Maintenance is necessary to ensure the ongoing performance of HVAC systems, equipment, and related components. Preventative maintenance (a.k.a. retro-commissioning) focuses on tune ups or other actions that are based on a timeline, rather than a physical trigger or fault. Reactive maintenance is based on a physical measurement or fault that signals that something is not performing as it should. Herein, reactive maintenance is referred to simply as maintenance in this report.

As discussed in Section 3.1, FDD can be used to identify, isolate, and correct or avoid faults that develop over time in existing HVAC systems. Although there is overlap between preventative maintenance and reactive maintenance, this section focuses on reactive maintenance, where permanently installed (and internet-connected) sensors could help reduce the time and cost associated with unexpected HVAC faults.

An overview of major maintenance applications, including the current state-of-the-art, the benefit of improving that current technology, and the major gaps associated with each application is shown in Figure 5. The detailed analysis of each major application is described in more detail in the subsections below.

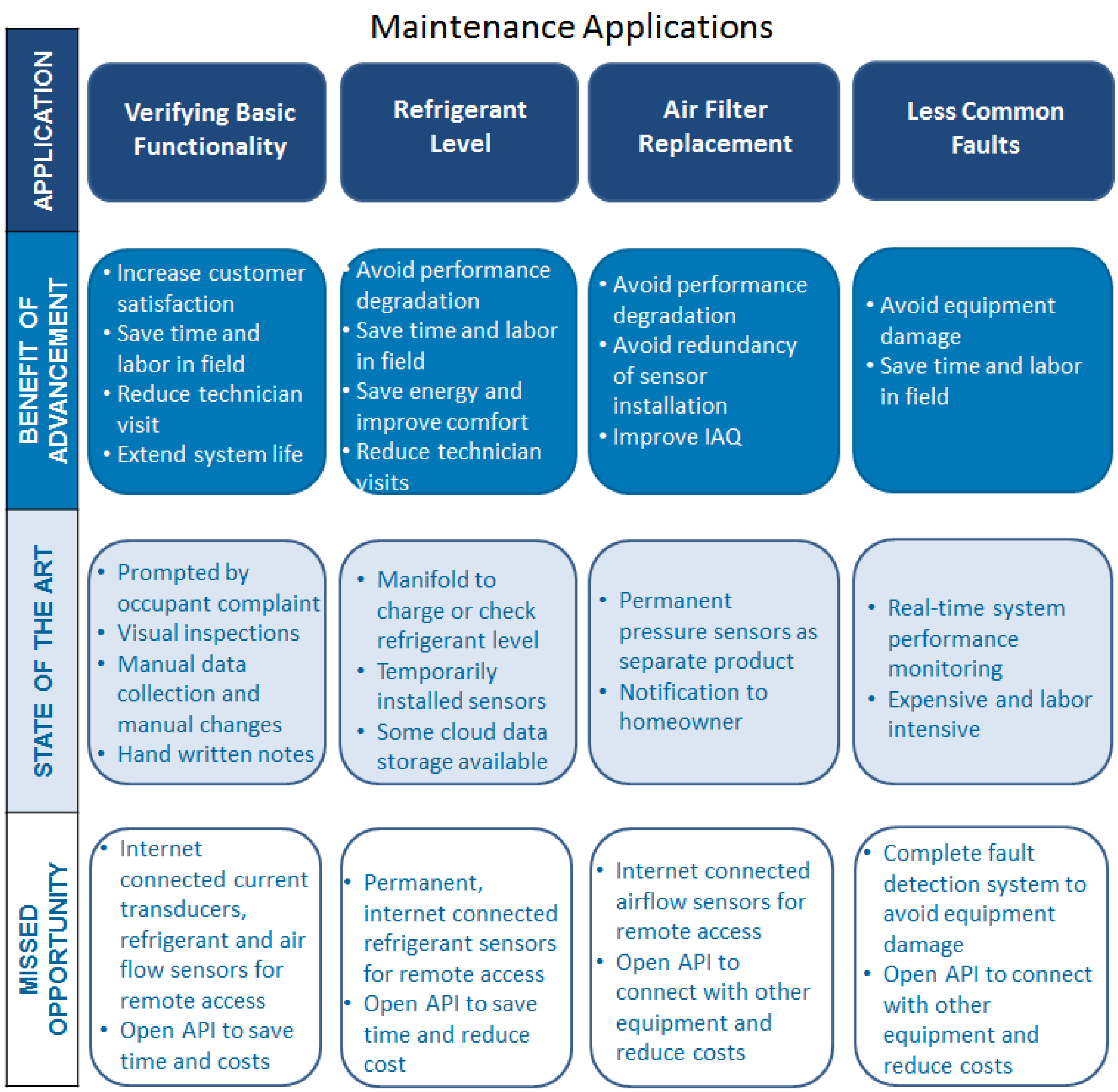


Figure 5. An Overview of State-of-art, Technical Gaps, and Benefits of Maintenance Applications

3.2.1 Verifying Basic Functionality

The basic functionality of the system can be monitored and corrected using the same approach as is discussed in Section 3.1. In this case, data storage may be a helpful addition to the gaps previously mentioned. Data storage either locally or on the cloud could help determine if measurements are changing over time. This type of data could help detect a faulty sensor/sensor drift or even a dying motor.

In case of faulty sensors, an appropriate action (alert, control action, etc.) can be taken to compensate for inaccurate sensors so that the system performance is minimally affected. Examples include removing a faulty sensor from control system architecture, and changing the temperature set point if the humidity or temperature sensor is offset by a known value. Other applications include checking thermostat settings/parameters, data reporting, and verifying the sequence of operations and control functionalities. The requirements and potential advancements are similar to the ones discussed in Section 3.1.

3.2.2 Refrigerant Level

This application is similar to the “refrigerant charge” application described in Section 3.1. The refrigerant level is a key factor in HVAC performance and energy efficiency. This includes overcharging, undercharging, and leakage over time.

There are currently no permanently installed, internet-connected refrigerant sensors or chargers, with an open API available on the market. The benefit of having permanently installed refrigerant temperature and pressure sensors is that faults could be detected quickly. If those sensors are internet-connected, they could also immediately notify a contractor or homeowner that a fault is about to hinder a system from functioning efficiently, or functioning at all. ComfortGuard is a proprietary package of sensors that must be installed by a certified HVAC technician. This is the only product on the market that might contain internet-connected refrigerant sensors, but this is not information that is shared publically. If products like this were available with an open API, they could connect with endless third-party apps, thermostats and even large data collection software for research purposes.

A refrigerant canister/charger could also provide automatic re-charging of refrigerant systems to minimize or eliminate the effect of refrigerant leaks on equipment performance.

Table 6. Remaining Opportunities to Reduce Time and Cost Associated with Checking and Changing the Refrigerant Level

	Description	Inputs	Output
Current State-of-the-Art	Temporarily installed sensors with data storage in cloud (e.g., iManifold)	Refrigerant temperature and pressure	Digital reading and cloud storage of measurements
	Permanently installed sensors (e.g., Comfortguard)	Refrigerant temperature and pressure	Notification to user
Potential Technology	Permanent and internet-connected refrigerant sensors and chargers with open API	Refrigerant temperature and pressure	Wireless notification to users. Automatically adjust variable speed fan if applicable.
Remaining Opportunity	Permanent, internet-connected refrigerant sensors for remote access. Open API to save time and reduce cost.		

3.2.3 Air Filter Replacement

Air filter replacement is an important maintenance task that is usually recommended once every two or three months. Homeowners are typically responsible for filter replacement, and it is common for people to forget about it. The DOE (DOE 2016a) describes how replacing a dirty, clogged filter with a clean one can lower your air conditioner's energy consumption by 5% to 15%. In addition, the EPA (EPA 2016) mentions that incorrect air flow could waste up to 3% of HVAC energy use. Most smart thermostats will provide a time based notification to replace filters. A product like FilterScan could help detect dirty filters, but also might be used for general airflow maintenance if the sensor data was available through an open API. This product detects change in differential pressure to detect whether the filter needs replacement. Then, a notification (text, email, etc.) is sent to the user to replace the filter. An improvement on this technology would be if it were integrated into the air handler upon installation. If an open API were available, these types of sensors could potentially communicate with a variable speed motor, which could always be adjusting to the airflow available and run the fan as efficiently as possible. This application is summarized in Table 7.

Table 7. Remaining Opportunities to Reduce Time and Cost Associated with Air Flow Issues in HVAC Systems

	Description	Inputs	Output
Current State-of-the-Art	Detection in the change in pressure difference across air handler (e.g., FilterScan)	Pressure differential	Notification to homeowner
Potential Technology	Detecting dirty filters (also their location) and changing the air flow rate to compensate for dirty filters	Pressure differential	Notification to homeowner. Alter variable speed fan for optimum performance.
Remaining Opportunity	Permanent and internet-connected air pressure sensors that are integrated into all air handlers and automatic adjustment of variable speed motor through an open API		

3.2.4 Less Common Faults

This section includes all other faults that were not included in previous applications such as dirty coils, condenser drain, worn out parts, lubrication, faulty sensor reporting, communication delays, etc. Some of the state-of-the art products that are available on the market today are discussed here. There are many sensors that HVAC technicians can use once they are on site. The drawbacks of temporary sensors are the time required to install them and the potential for human error. The products listed in this section are permanently installed to help ensure accurate diagnostics and quick response times.

Some connected thermostat products (e.g., Nexia Diagnostics, Ecofactor) are able to determine some faults (incorrect/swapped wire installation, tripped breakers, etc.) of the HVAC system, simply through the thermostat signals. A full discussion of the use cases for connected thermostats is available in a recently published report (DOE 2016b).

ComfortGuard uses 10 sensors and monitors the system performance in real time. It also predicts system performance and provides diagnostic alerts (to homeowner or contractor) regarding dirty filters, heating/cooling efficiency, and component-level performance such as flame sensors, hot surface igniters, capacitors, pressure switches, thermal limits, coil effectiveness, expansion devices, refrigerant charging levels, reversing valves, defrost boards, fan motors, compressors, and contactors.

All of these applications of sensors and controls are helpful in FDD for residential HVAC systems. However, they are all relatively expensive and require homeowners to purchase the whole set of sensors from one manufacturer. It would be ideal if these products were available separately, integrated into the air handler and/or outdoor unit during manufacturing, and connected to the internet for data collection and communication.

3.3 Improved Operation

An HVAC system is operational if it is correctly responding to a thermostat and delivering air within manufacturer specifications. Basic HVAC performance can be improved upon in three ways: (1) comfort, (2) energy savings, and (3) grid power management.

The sub-topics below are divided into these three improvement categories, although, many of the sub-topics could apply to multiple improvement areas. For example, applications in the energy savings group are primarily focused on reducing energy consumption although they may also lead to improved comfort.

An overview of major improved operation applications, including the current state-of-the-art, the benefit of improving that current technology, and the major gaps associated with each application is shown in Figure 6. The detailed analysis of each major application is described in more detail in the subsections below.

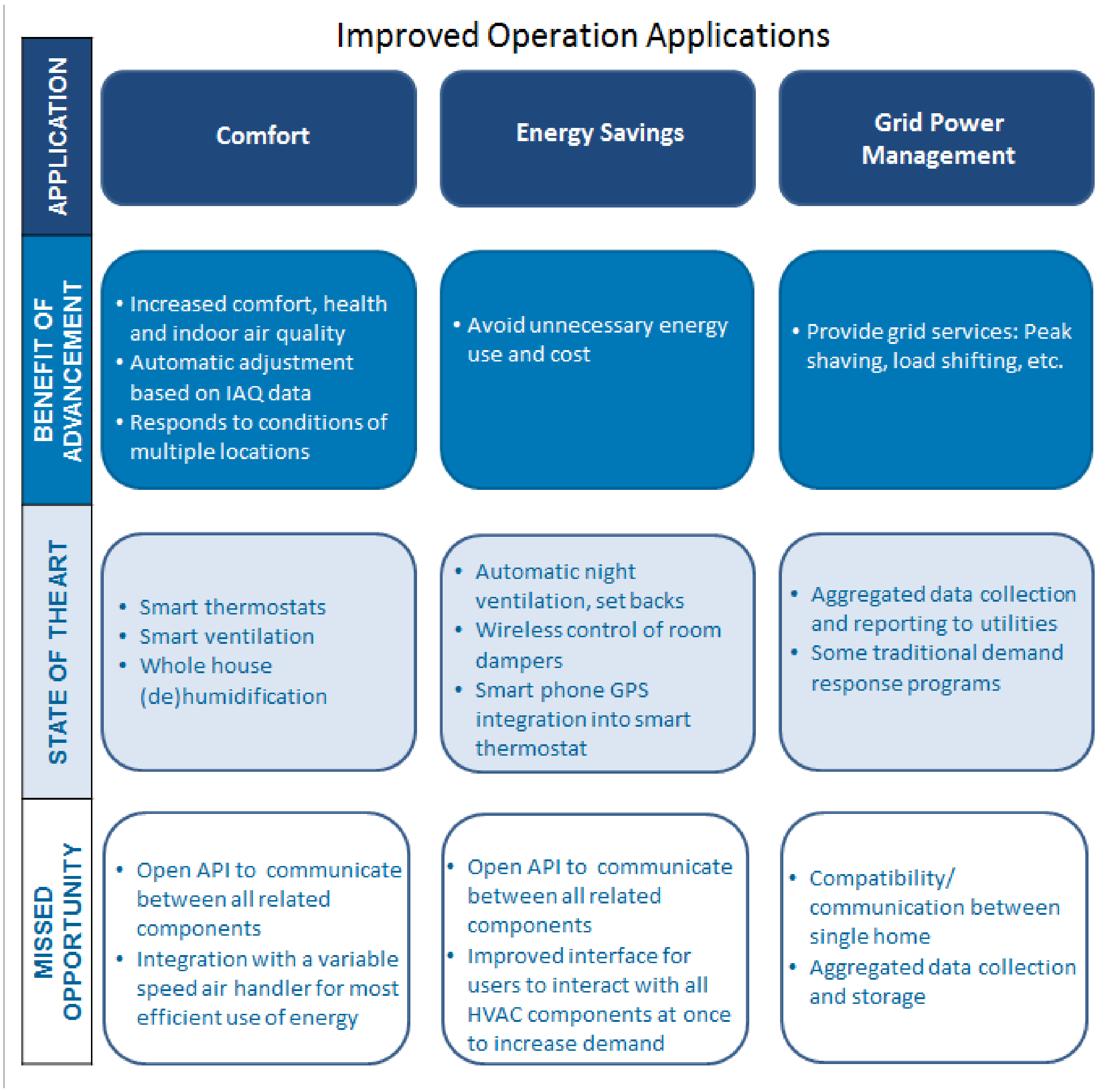


Figure 6. Summary of Improved Operation Applications

3.3.1 Operation Applications Focused on Comfort

3.3.1.1 Temperature Set Point

Thermostats provide temperature set point control. Basic thermostats measure temperature and use a manually input set point (analog or digital) to send a "turn on" or "turn off" command to the HVAC system. Programmable thermostats have the ability to change temperature set point based on a pre-defined user-input schedule. Connected thermostats offer enhanced communication, improved interface, and simplified schedule setting (DOE 2016b). Smart thermostats are a type of connected thermostat that contain computation features, and thus are capable of supporting advanced software tools to monitor system performance, detect faults, and ensure correct installation and operation.

Smart thermostats offer the most advanced way of controlling the indoor temperature. With smart thermostats, the temperature set point can be optimally controlled based on occupant behavior, outside temperature, historical set points, energy cost, or utility signals. The optimal set point can be calculated over the cloud or using the computational power available on the device. Depending on control algorithms, measurements from several sensors and data from users may be needed. The combination of two-way communication, data collection, and modeling human behavior has made these devices a platform for vendors to offer demand-response services to utilities (Baechler and Hao 2016).

Smart thermostats (e.g., NEST, Ecobee, etc.) are currently the state-of-the-art application of temperature set point control. EnergyStar has added a smart thermostat category[1], which can help identify a certain level of energy savings that can be expected from some thermostats. However, other than this Energy Star distinction, the amount of comfort gained and energy saved across the spectrum of smart thermostats available is different and currently cannot be easily compared.

3.3.1.2 Ventilation, Filtration and Indoor Air Quality

Ventilation provides fresh outdoor air to the spaces inside buildings. The primary function of ventilation control is to adjust the airflow (determined by standards like ASHRAE 62.2) entering or exiting a building. Inputs into this control task can be as simple as the time of day, or can be based on factors such as CO_2 measurements, outdoor temperature/humidity, and occupancy. Filtration can occur with or without ventilation and typically uses physical barriers to minimize particulates in the air that is circulated throughout a home. Both of these mechanisms can be associated with better IAQ (Singer et al., 2017). Table 8 focuses on how ventilation and filtration can be used to optimize IAQ and energy use.

Table 8. Missed Opportunities to Improve IAQ while Minimizing Energy Use

	Description	Inputs	Output
Current State-of-the-Art	ERV/HRV[(a)] Whole house air purification	Time of day, manual NA, Ultraviolet (UV) light always on	On/off state of motor UV light
	IAQ sensors that have open API and can control a thermostat (e.g., Foobot)	CO_2, VOCs, PM, CO, temperature, humidity	Air handler on/off state, and user notification
Potential Technology	Smart ventilation: optimizing input from IAQ sensors to control	Formaldehyde, PM, CO_2, CO, VOCs, outdoor conditions, number of	Automatically changes ventilation rate and turn on/off filtration system;

[1] https://www.energystar.gov/productfinder/product/certified-connected-thermostats/results

	Description	Inputs	Output
	ventilation and filtration system (perhaps at variable rates)	occupants	user notifications
Remaining Opportunity	Smart ventilation integrated with filtration system. Integration with a variable speed air handler through an open API would provide opportunities for energy savings by matching air flow rate to pollutant level.		

(a) ERV and HRV are energy recovery ventilation and heat recovery ventilation, respectively.

Smart ventilation is gaining momentum in research and in industry. The goal of some smart ventilation systems is to save up to 40% of ventilation related energy use (Walker, 2014). However, a major gap is the ability to control ventilation rates in all types of ventilation systems, using some of the same sensors that are used for other applications (but that may use proprietary communication protocols).

3.3.1.3 Humidity

As homes continue to have a lower and lower HVAC load, humidity becomes a more and more important factor to address directly (Brown et al., 2013). State-of-the-art humidity control devices can be integrated into the main air handler unit in a home. These humidifiers and dehumidifiers provide the ability to meet a certain humidity set point that is set by the user at the thermostat (or in a thermostat app).

Humidification and dehumidification are energy intensive processes due to the phase change of the liquid to vapor or vice versa. Therefore, any opportunity to save energy during this process should be capitalized on. Table 9 describes the missed opportunities to save energy when humidifying or dehumidifying a home.

Table 9. Missed Opportunities to Save Energy Associated with (De)Humidification

	Description	Inputs	Output
Current State-of-the-Art	Whole house (de)humidification	Temperature and humidity	Opens/closes water valve, or turns on the compressor and dehumidification blower set point to meet humidity set point
Potential Technology	Variable rate (de)humidification with open API	Indoor and outdoor humidity and occupancy sensors that detect number of people or activity level	Changes valve position, compressor and blower speeds to meet humidity set point
Remaining Opportunity	Variable rate (de)humidification could react to indoor and outdoor conditions and deliver ideal humidity levels with the least amount of energy use. Open API would enable connection to existing or third-party occupancy sensors or other measurements.		

3.3.2 Operation Applications Focused on Energy Savings

3.3.2.1 Natural Heating and Cooling

This application uses natural heating and cooling if outdoor weather conditions are favorable. Night ventilation and operation of windows are two ways to accomplish natural heating and cooling in residential buildings. To implement this application automatically, however, there are two major requirements:

- actual outdoor weather measurements and forecasts, which can be obtained using weather website APIs or local weather stations/sensors that send data to the cloud
- the ability of an HVAC system to allow natural heating or cooling, (e.g., supply/exhaust fan control, outside damper control, automatic window control), which is not common in currently available systems.

Table 10 shows the current state-of-the-art application and how it might be improved upon for the best possible control of natural heating and cooling.

Table 10. Missed Opportunities to Save Energy with Natural Heating and Cooling

	Description	Inputs	Output
Current State-of-the-Art	Automatic ventilation based on favorable outdoor air conditions (e.g., NightBreeze)	Outdoor temperature and humidity	Opens/closes damper or and turns fan on
Potential Technology	Fully integrated and automated natural ventilation with high control options	Indoor and outdoor temperature and humidity	Changes damper position and fan (exhaust, supply) speed Opens/closes windows
Remaining Opportunity	Automatic natural ventilation during favorable outdoor and indoor conditions using an open API to connect to the main HVAC system.		

3.3.2.2 Multi-Zone Temperature Distribution

In this application, different HVAC zones can be created and controlled independently by using additional actuation sensors and hardware at multiple locations. More than 70% of residential buildings use one thermostat (RECS 2009)[1] and are not capable of controlling the environment in individual rooms independently. Although most OEMs offer a multiple zone system, they are very expensive and typically only practical in new construction. A less expensive implementation of a zoned system at a large scale requires the following:

- low-cost temperature/humidity sensors that can be easily integrated into existing HVAC system. Some sensors that are available today can be connected to a thermostat through open API interfaces like IFTTT, but the full integration with the thermostat to create a zoned home based on sensor feedback has yet to be tested. These sensors currently cost $25-60 per sensor.
- inexpensive diffusers or dampers to control the amount of air flow rate entering different rooms. Although several commercial products (Ecovent, Keen Home Vent, etc.) are available for retrofitting the exiting diffusers, the products are relatively new and only being deployed primarily to enhance comfort.
- development and implementation of control algorithms. Currently, smart diffusers control the damper positions based on temperature set points, which can be set through occupant's smart phone apps. These apps have limited control commands based on mostly temperature settings in a home. More advanced controls with multiple sensor inputs (e.g., occupancy *and* temperature) have not been tested.

To capitalize on the energy savings benefit related to multiple zones in a house, the air flow should be dynamically adjusted according to the registers available. Reducing the fan speed lowers both the fan

[1] Although more detailed questions about HVAC equipment have been added to the RECS database since 2009, the question regarding the number of thermostats in a home was not reported on after 2009.

energy and heating/cooling energy consumption. Although there are commercially available products with more than one fan speed (e.g., INFINITY 18VS heat pump 25VNA8, Goodman 3 Ton 16 SEER AC Model DSXC160361 with Goodman Multi-Position Air Handler with Variable Speed Fan Model AVPTC48D14), they are not prevalent in existing buildings. Therefore, in this application, air handler or air handler motor replacement would be recommended (to enable variable speed) along with the multi-zone control.

Improved comfort is also a benefit of this application. If a home experiences high temperature differences between certain parts of the home, or has multiple stories, more uniform temperature distribution may be possible with variable air flow rate supplied to each room.

Table 11 describes the current state-of-the-art multi-zone systems and what kind of product might be an improvement on the state-of-the-art system.

Table 11. Remaining Opportunities to Save Time and Cost When Installing Multi-Zone Systems

	Description	Inputs	Output
Current State-of-the-Art	Wireless control of room dampers based on varied set points (e.g., KEEN), retrofit solution	Temperature and pressure	Varies damper position for each grill
	Wired control of zone dampers based on varied set points (e.g., Honeywell Wireless TrueZone), hard-wired solution	Temperature	Varies damper position for each zone
Potential Technology	Automated control of dampers and air flow rate using other sensors (e.g., occupancy)	Temperature, air flow rate and occupancy	Adjusts damper and fan speed
Remaining Opportunity	Integration of multi-zone systems with other sensors and variable speed equipment with open API.		

3.3.2.3 Complete Smart HVAC Optimization for Energy Reduction, Health and Comfort

This application uses predictive and optimization control approaches to reduce energy consumption, while maintaining IAQ and comfort in a specified range. Implementing this application requires much higher computational power than other applications. Therefore, it is likely that all of the computation would be performed on the cloud and the control actions can be sent through the internet. Depending on the type of control approach, the application may need weather forecast, occupancy behavior, and other models for predicting the system behavior and taking an appropriate action accordingly. This type of system would include control over the entire environment of the home, including temperature, humidity, multi-zoning, automatic shading, and mechanical and natural ventilation. Table 12 describes the current components that exist for this type of system, as well as the remaining opportunities in this fully integrated application.

Table 12. Remaining Opportunities for Complete HVAC Optimization for Energy Reduction, Health, and Comfort

	Description	Inputs	Output
Current State-of-the-Art	Complete system from one	CO_2, VOCs, PM, CO,	Controls temperature, humidity,

	Description	Inputs	Output
	company (e.g., Honeywell Whole Home, Lennox Complete iHarmony etc.)	occupancy, temperature and humidity	ventilation in a sort-of independent fashion with limited data exchange
	Disjointed retrofit products (e.g., Foobot, Ecovent, smart phone, occupancy sensors, smart thermostat, Keen) that provide input to different computation platforms	CO_2, VOCs, PM, CO, occupancy, temperature and humidity	Separate control of HVAC system components including set back, multi-zoning, automatic shading, mechanical and natural ventilation.
Potential Technology	Integrated sensor products that easily connect to a central hub which can optimize a complete HVAC system	CO_2, VOCs, PM, CO, air flow, occupancy and indoor/outdoor temperature and humidity	Optimized control HVAC system including set back, multi-zoning, mechanical and natural ventilation.
Remaining Opportunity	Energy savings and comfort associated with a complete smart system. Ease of connectivity and optimization between components and an improved user interface would enable more people to use such a product.		

3.3.3 Operation Applications Focused on Grid Services Integration

HVAC systems can be used to provide grid services, which may not necessarily result in reduced energy consumption. There are several applications in this area: (1) integration and coordination of multiple HVAC systems and other components at the community level, (2) enabling automated demand response through individual HVAC system control, (3) using residential buildings as a micro-grid and coordinating among the generation resources and loads inside residential buildings, (4) precooling to shift or shave the peak load, (5) duty cycling the HVAC unit, and (6) deciding the time interval between on and off times can be used for reducing peak load. All of these services can be provided through smart thermostats and are available with the technology on the market today. Discussion of the use cases for smart thermostats is available in a recently published report (DOE 2016b).

4.0 Summary of State-of-the-Art Product Features

This section provides examples of the connected residential HVAC products currently available. State-of-the-art component features are listed in tables, which help provide a picture of what advanced applications might be achievable using just the products on the market today. Automating each application listed in Section 3 would require each of the physical component technologies (sensors, data storage, human-in-the-loop, and controls) to be connected. This exercise has revealed that besides thermostats, most of the products on the market today focus on one end of the spectrum (sensors) or the other (controls), but not both – therefore connectivity *between products* is a key component that cannot be ignored.

The tables do not contain *all* of the products on the market, only examples of products that have many desirable features. The products are organized by application type, then by major product category (e.g., refrigerant-related products). These tables do not include manufacturers who just provide software because the software itself does not sense or control anything. The term "open API" that is used in the tables below refers to the ability for the product mentioned to connect to at least one other product via an API. To get an "x" in this category, the product does not need to have an API that is open to the public.

Table 17 shows the products in the thermostat category. The features captured here include all features that are possible with that thermostat and potentially some thermostat add-ons (like humidity relay switches), but does not include any capabilities that would be purchased from a separate company and added to the base product.

Table 13. Examples of Commissioning and Maintenance Refrigerant-Related Product Capabilities

Product Name	iManifold	Testo Smart Probes	ManTooth Dual Pressure Wireless Digital P/T Gauge	Smart Service Tool Kit Sporlan	Comfort Guard (Connected Fault Detection and Diagnostics – No public information is available)
Features					
Do-It-Yourself Install					
Sensors					
Air Temperature	x				
Humidity	x				
Air Pressure	x				
Refrigerant Temperature	x	x	x	x	
Refrigerant Pressure	x	x	x	x	
Data Storage and External Signals					
Able to receive external signal from utility					

Product Name	iManifold	Testo Smart Probes	ManTooth Dual Pressure Wireless Digital P/T Gauge	Smart Service Tool Kit Sporlan	Comfort Guard (Connected Fault Detection and Diagnostics – No public information is available)
On-board data storage				x	
Cloud data storage	x				
Human-in-the-loop					
User Programming					
Automated Programming					
Scheduled alerts					
Automated alerts	x				x
Communication Between Components					
Wi-Fi					
Bluetooth		x	x	x	
Open API					
ZigBee	x				
Controls					
Heating/cooling on/off					
Humidity level					
Ventilation					
Fan on/off					
Damper position					
Fan speed					
Zone control					

Table 14. Examples of Air-Side Commissioning and Maintenance Product Capabilities

Product Name	FilterScan	Honeywell Ventilation Systems
Features		
Do-It-Yourself Install	x	
Sensors		
Air Temperature		x
Humidity		x
Occupancy		
CO_2		
Air Pressure	x	x
Data Storage and External Signals		
On-board data storage		
Cloud data storage		
Local server		
Human-in-the-loop		
User Programming		
Automated Programming		
Scheduled alerts		
Automated alerts	x	
Communication Between Components		
Wi-Fi	x	
Bluetooth		
API to Connect with Thermostats		
ZigBee		
Controls		
Heating/cooling on/off		
Humidity level		

Product Name	FilterScan	Honeywell Ventilation Systems
Ventilation		
Fan on/off		
Damper position		x
Fan speed		x
Zone control		

Table 15. Examples of Advanced Thermostat (Operation) Product Capabilities

	Examples of Aftermarket Thermostats							Examples of Original Equipment Manufacturer Thermostats			
Product Name	NEST Thermostat E	Ecobee 4	WiserAir	Sensi	Lux Kono PRO	Honeywell Lyric Thermostat (2nd Gen)	Caleo (baseboard heat)	Carrier Infinity Touch	Lennox iComfort Wi-Fi	Trane ComfortLink II XL1050 (Nexia)	Rheem EcoNet Control Center
Features											
ENERGY STAR	x	x									
Do-It-Yourself Install	x	x	x	x	x	x	x				
Sensors											
Temperature	x	x	x	x	x	x	x	x	x	x	x
Humidity	x	x	x	x	x	x	x	x	x	x	
Occupancy	x	x									
Light	x		x								
Data Storage and External Signals											
Able to receive external signal from utility	x	x	x				x	x			
On-board data storage								x			
Cloud data storage	x	x									

	Examples of Aftermarket Thermostats							Examples of Original Equipment Manufacturer Thermostats			
Product Name	NEST Thermostat E	Ecobee 4	WiserAir	Sensi	Lux Kono PRO	Honeywell Lyric Thermostat (2nd Gen)	Caleo (baseboard heat)	Carrier Infinity Touch	Lennox iComfort Wi-Fi	Trane ComfortLink II XL1050 (Nexia)	Rheem EcoNet Control Center
Geofencing	x	x	x		x	x		x			
Human-in-the-loop											
User programming	x	x	x	x	x	x	x	x	x	x	x
Scheduled alerts								x	x		
Automated alerts	x	x	x	x		x			x		x
Energy reporting			x		x						
Integrated voice control		x									
Communication Between Components											
Wi-Fi	x	x	x		x	x	x	x	x	x	x
Bluetooth	x										
Open API	x	x		x	x	x	x				
Zigbee			x								
Controls and Actuators											
Heating/cooling on/off	x	x	x		x	x	x	x	x	x	x
Humidity level	x	x	x					x	x		x
Ventilation		x						x			
Fan on/off	x	x	x		x	x		x	x	x	x
Fan timing	x	x			x						
Multi-zone (control more than one thermostat)	x							x			
Dual fuel capable		x							x		
2 or more stage equipment	x	x	x		x				x	x	
Variable capacity equipment									x		
Heat pump with auxiliary heat	x	x	x		x						

Table 16. Examples of Indoor Air Quality (Operation) Product Capabilities

Product Name	Foobot	NetAtMo	Awair	Breezometer	FilterScan	AirAdvice	Honeywell Ventilation Systems	NightBreeze	Aprilaire Dehumidifier
Features									
Do-It-Yourself Install	x	x	x	x	x	x			
Sensors									
Air Temperature	x	x	x			x	x	x	
Humidity	x	x	x			x	x	x	
Occupancy									
CO_2	x	x	x	x		x			
Air Pressure					x		x		
Data Storage and External Signals									
Able to receive external signal from utility									
On-board data storage						x			
Cloud data storage	x		x	x					
Local server						x			
Human-in-the-loop									
User Programming								x	x
Automated Programming									
Scheduled alerts									
Automated alerts				x	x	x			
Communication Between Components									
Wi-Fi	x	x	x		x				
Bluetooth									
API to Connect with Thermostats	x		x	x					
ZigBee									
Controls									
Heating/cooling on/off									

Product Name	Foobot	NetAtMo	Awair	Breezometer	FilterScan	AirAdvice	Honeywell Ventilation Systems	NightBreeze	Aprilaire Dehumidifier
Humidity level									x
Ventilation								x	
Fan on/off								x	
Damper position							x	x	
Fan speed							x	x	
Zone control									

Table 17. Examples of Other Advanced Operation Products and Product Capabilities

Product Name	EcoVent	KEEN Home Vent	Honeywell Complete (Integrated HVAC System)	NetAtMo Weather Station	Lennox iHarmony	Symaro Sensors
Features						
Do-It-Yourself Install	x	x		x		x
Sensors						
Air Temperature	x	x	x	x		x
Humidity			x	x		x
Occupancy						
Air Pressure	x	x		x		x
Indoor Air Quality						x
Sound				x		
Data Storage and External Signals						
Able to receive external signal from utility						

Product Name	EcoVent	KEEN Home Vent	Honeywell Complete (Integrated HVAC System)	NetAtMo Weather Station	Lennox iHarmony	Symaro Sensors
On-board data storage						
Cloud data storage						
Local server	x				x	
Human-in-the-loop						
User Programming	x	x				
Automated Programming	x	x				
Scheduled alerts						
Automated alerts						
Communication Between Components						
Wi-FI					x	
Bluetooth						
ZigBee		x				
Open API	x	x	x	x		
Controls						
Heating/cooling on/off			x			
Humidity level			x			
Ventilation			x			
Fan on/off			x		x	
Damper position	x	x	x		x	
Fan speed			x		x	
Zone control					x	

5.0 Remaining Opportunities and Barriers

This section summarizes the remaining opportunities that could help decrease time, cost, energy use, and human error associated with various advanced HVAC applications. The technical aspects of this section are organized based on the components described in Section 2: sensors, data storage and external signals, human-in-the-loop, communication between components, and finally, computation, control, and actuation. Market barriers round out this section to capture the reoccurring non-technical themes that appear throughout the paper.

The studies mentioned in this section of the paper use different baseline controllers, buildings, and systems. Therefore, these studies cannot be compared in a unified manner to conclude anything. Confounding variables from each study ensure that the findings from individual studies cannot be added up to find a meaningful comprehensive result. The studies are merely presented to show that advanced sensing and control *can* result in significant energy savings and improved comfort.

5.1 Sensors

Occupancy sensors have the potential to save a lot of energy in homes (Piper et al., 2017). From setting back a thermostat, to lowering the ventilation rate, there are a number of applications that could benefit from accurate and inexpensive occupancy sensors. There are a few mechanisms by which occupancy is currently measured in homes. Motion sensors, GPS/geofencing locators, and PIR sensors can be inexpensive ways to measure occupancy; however, these methods have some limitations. Advanced occupancy sensors have the potential to measure the number of people and their activity level in homes. This type of advanced sensor research is currently being done by the Department of Energy's ARPA-E Program[1] and therefore will not be discussed further.

Other sensors have recently become much more accessible. Motion, temperature, and humidity sensors are now internet-connected, are relatively inexpensive ($30-$60 each), and can connect to other devices through open API apps such as IFTTT (e.g., D-Link Motion, ThermoPeanut, MESH, etc.). No known research has been done with the latest products to determine the level of accuracy or the potential calibration offset over time. If these sensors have reasonable accuracy over time, they could be used as conduits for other measurements. For example, with more research a temperature sensor could potentially be attached to the outside of a refrigerant line to help monitor the refrigerant temperature over time to determine if there is a sudden change in the temperature of the refrigerant, which often is associated with certain faults. More research related to the use of low-cost sensors in a home could be helpful to determine possible applications for commissioning, maintenance, and operation.

5.2 Data Storage and External Signals

Storage and accessibility of equipment meta data could help reduce errors, time on site, and ultimately make maintenance of HVAC systems less expensive. For example, every time a technician visits a site, system information (e.g., refrigerant type, stages, equipment type) could be entered for diagnosis and maintenance purposes. Automatic availability of such information to contractors who connect to the system (through Wi-Fi for example) could reduce errors, decrease time spent on the site, and expedite the overall process. Availability of such data (including equipment characteristics) can be quite helpful in detecting an outlier/fault or optimizing the system performance during operations in automated fashion.

[1] https://arpa-e.energy.gov/sites/default/files/documents/files/SENSOR_ProgramOverview_FINAL.pdf

Moreover, advanced controls could also achieve a significant amount of energy and cost saving when responding to a grid dispatch signal for demand response purpose. For example, by responding to a real-time price signal from the grid, the average electricity energy saving due to peak load shaving is about 5% (OPOWR 2014; Yoon et al. 2014; Consumers Energy 2014).

5.3 Human-in-the-Loop

Consumer interaction plays a significant role in the efficient operation of an HVAC system. Several field deployments have shown that consumer feedback devices can lead to 12-15% energy savings (GridTalk (2013) and Parker et al (2006).

The *inability* to easily incorporate the end user (actively or passively) in the control loop can have the reverse effect. A recent study by Callaway et al. (2014) indicates that programmable thermostats of the time were particularly difficult for users to understand, which led to ineffective usage or even abandonment. Programmable thermostats capture over 58% of the market, yet 45% of households with thermostats still set one temperature and leave it most of the time (EIA 2015).

Recent smart thermostat products seem to address this issue by creating an interactive and flexible user interface. These products seem to be gaining popularity in the market, although as of 2015, the market share was still only 4% (EIA 2015). At this point, although the number of smart thermostat users is relatively low, one study shows that those users are in fact energy conscious and are using the thermostats to their full potential. A study by Apex Analytics (2017), using NEST thermostats, showed that about 80% of the people who use them were interested in saving energy/money[1]. As these thermostats become more mainstream, it will be important to continue to conduct research about if users are allowing the technology to reach its full potential.

Another area for user interface improvement is related to the ease of use of combined components. Ideally, one interface would exist that would control and optimize all HVAC-related components. This software/hardware could use a home’s Wi-Fi connection to automatically detect and connect *all* of the components to a simple user interface. Potential areas of interest are summarized below:

- development of an interface and learning algorithms that maximize sensor input and simplify direct user interaction to decrease the occupant burden during setup and use.
- an inexpensive and user-friendly hardware and software platform that is compatible with all components.
- an interface that consumers can use to set acceptable utility control parameters for demand response programs.

5.4 Communication Between Components

Easy implementation of advanced control applications on a large scale would require a high level of compatibility between equipment from different manufacturers, especially when multiple systems, such as heating, cooling, humidification, dehumidification, and ventilation systems are involved. The use of open standards for residential controls would allow for more ready integration of controls. Currently, most OEM solutions utilize proprietary communications with the exception of the wiring standard to connect thermostats.

[1] Users were asked to opt-in to an energy saving program and about 80% of users accepted. Attrition was minimal and was less than 5% at the conclusion of the study.

Smart or connected thermostats play a crucial role in connecting and interacting with HVAC related equipment and systems. These thermostats provide hardware to gather user inputs, compute control actions, and send actuation commands to HVAC equipment. Other state-of-the-art computation platforms are also entering the market. With multiple manufacturers responsible for the HVAC equipment, user interfaces, sensors, and actuators, there is a growing market for open API communication protocols that enable interoperability among these technologies.

Most manufacturers do not provide the capability to extract data from the system. However, they will allow a connection to certain other products in order to improve the flexibility and functionality of their product. For example, some manufacturers are working with each other directly (e.g., Ecobee and Amazon Alexa). Even more manufacturers are signing up for a more open integration platform, like IFTTT, which can use hundreds of devices to sense and control various products in a home. It would be beneficial to have all sensors, thermostats, actuators, and HVAC equipment with the following capabilities:

- ability to incorporate additional sensors into the system seamlessly, including “plug and play” and auto-configuration functionality.
- availability of component-level information (including sensor data), which may require establishing two-way communication between devices.
- cyber security to prevent unauthorized access of connected equipment.

In general, there are a few product categories that do not currently have any compatibility or communication capabilities. For example, most refrigerant-side monitoring equipment does not connect to Wi-Fi, nor does it connect to other devices in the home. Although this equipment is currently used as a one-time commissioning or retro-commissioning product, with enhanced communication capabilities, it could be used for maintenance as well. Other product categories with little to no compatibility with other vendors include (de)humidification equipment and ventilation equipment.

5.4.1 Opportunities for Refrigerant Sensor Communication

A glaring missed opportunity related to communication between components appears in Table 15 (Section 4.0). This table shows how most of the products on the market today that could help detect and communicate faults from the refrigerant side of heat pump and air-conditioning systems are not permanently placed, nor are they connected to the internet.

Goetzler et al. (2012), show that central AC and heat pump FDD algorithms could save 0.40 quads of energy. In particular, improper refrigerant charge is the most important fault to be addressed. Proctor (2004) reported that about 62% of residential air conditioners had incorrect refrigerant charge, and 35-45% of residential HVAC systems suffer from insufficient refrigerant charges; this decreases the system efficiency by 12-20%. Detecting low charge faults in the residential AC units and correcting them would reduce the cooling energy consumption by 5-10%, which is equivalent to 0.1-0.2 quads of energy savings (Roth et al. 2006).

FDD provides several other significant benefits that also amortize over the life of an HVAC system. These benefits, beyond reduced electricity use, include more efficient preventative maintenance services, increased system lifetime, reduced number of repair parts, and reduced labor (Roth et al. 2006; Wiggins et al. 2012).

Clearly, permanently placed, internet-connected refrigerant sensors with an open API could be used to help save a substantial amount of energy.

5.4.2 Automated System Zoning

Another example of interconnectivity that could provide a substantial amount of energy savings is automated system zoning. This would require sensors (e.g., temperature, occupancy, and potentially air pressure) to be connected to controllers (e.g., air dampers) through a central hub that could perform computations and interaction with the user. Brown et al. (2007) used an occupancy schedule to dictate the set points for individual zones during the heating season. The report shows 26% energy reduction with register controls. A multi-zone setback strategy implemented by Oppenheim et al. (1992) results in 12% energy savings as compared to a single-zone strategy with an 8-hour 12°F setback. Automating this type of control could help ensure that occupant comfort was not sacrificed for energy savings.

5.4.3 Opportunities for Ductless Mini-split Communication with Central Systems

For the last 5 years or so, many utilities have provided incentives for residential ductless mini-splits, with most homeowners adding one indoor unit in a central living area. Controls for these systems have been disjointed and not suitable for pairing ductless mini-splits with pre-existing systems such as forced-air furnaces, zonal electric resistance, or boilers with radiant heaters. One study has shown that the interaction between ductless mini-splits and central systems is not trival (Sutherland et al., 2016). Additionally, anecdotal post-installation reviews[1] of these homes have shown that these units are not reaching their full potential because the previous existing heating system continues to operate in parallel with the mini-split. Controllers that communicate between both systems, especially with analytical capabilities, could help this equipment reach its full potential.

5.5 Computation, Controllers and Actuators

There are many ways that computation, controllers and actuators can be improved. One example is variable actuation. Although 2-stage equipment and variable speed fans in air handlers are currently uncommon in residential buildings, these features have the potential to save a lot of energy if used correctly in conjunction with many of the applications discussed in Section 3.0. For example, the DOE test procedure and ASHRAE test procedure in 2006 show that 2-stage furnace control can improve energy efficiency by 3% as compared to single-stage furnaces. One report also showed that even replacement fans with variable speed capacities could save over 150 kWh/year (Aldrich and Williamson, 2014). Being able to control these variable actuators could provide substantial savings opportunities for the U.S.

There are other opportunities besides the central HVAC system where the use of this technology could save energy. For example, the control technologies used in most of the humidity and ventilation (ERV/HRV) systems offer binary control, e.g., on/off, open/closed. Similarly, most of the existing whole-home air purification systems are continuously on, offering no control flexibility. Increasing the control flexibility of these systems could provide more precise control of outputs, reduce oscillations, and increase overall equipment life. Therefore, it is important to develop or integrate technologies that increase the actuation flexibility of all motorized technology, not just the primary air handler.

[1]Including homes from Efficiency Maine and the Bonneville Power Administration

Moreover, increasing control flexibility will also provide an opportunity to correct faults automatically in certain situations, and avoid or delay a technician visit while retaining the system performance.

5.6 Market Barriers

A number of market barriers could be addressed to accelerate the uptake of advanced HVAC controls, smart sensors, and their associated firmware/software in the residential market. Consumers consider first cost as the primary obstacle holding them back from purchasing smart HVAC devices that are capable of implementing advanced controls (Danova 2014). While prices for some control devices have declined, prices for high end, effective models are still high (Callaway et al. 2014). The next most common market barrier for consumers is the lack of awareness and education on how devices operate. We have already discussed how this applies to programmable thermostats. Another barrier for consumers is the issue of cyber security and privacy. Consumers might view smart HVAC controls as introducing risk to a device that formerly had none. A report from the California Energy Commission (Ghansah 2012) highlights a few cyber security and privacy issues that may arise from using current programmable communication thermostats and advanced metering infrastructure.

Lastly, for smart HVAC controls to reap additional monetary savings for consumers, they should also have grid interoperability functionality that can take advantage of real-time utility rates or utility incentives. This calls for the proliferation of utility programs and business models that incentivize load-shifting behavior.

6.0 References

Aldrich, R and J. Williamson. 2014. “Evaluation of Retrofit Variable-Speed Furnace Fan Motors. DOE-102014-4306. National Renewable Energy Laboratory, Golden, CO. https://www.nrel.gov/docs/fy14osti/60760.pdf

Apex Analytics. 2017. “Energy Trust of Oregon Nest Thermostat Seasonal Savings Pilot Evaluation.” November 22, 2017. Prepared by Apex Analytics, LLC and Demand Side Analytics.

Baechler M and H Hao. 2016. “Business Case for Nonintrusive Load Monitoring.” PNNL-25425, prepared for the Bonneville Power Administration by Pacific Northwest National Laboratory, Richland, Washington.

Brown CA. 2007. “Multizone register controlled residential heating: Optimized for energy use and comfort.” MS Thesis, U. C. Berkeley.

Brown SA, BA Thornton, SH Widder and MC Baechler. 2013. “Review of Residential Low-Load HVAC Systems.” PNNL-23017, Pacific Northwest National Laboratory, Richland, Washington. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23017.pdf

Callaway L and N Strother. 2014. “Executive Summary: Smart Thermostats – Communicating Thermostats, Smart Thermostats, and Associated Software and Services: Global Market Analysis and Forecasts.” Navigant Research. Washington, D.C. Accessed on November 12, 2015 at https://www.navigantresearch.com/research/smart-thermostats

Danova T. 2014. The Connected Home Report: Forecasts and Growth Trends FOR THE Leading ‘Internet of Things’ Market. Business Insider Intelligence. Accessed on November 12, 2015 at http://www.businessinsider.com/connected-home-forecasts-and-growth-2014-9

DOE (U.S. Department of Energy). 2016a. “Maintaining Your Air Conditioner.” Accessed on December 30, 2016. https://www.energy.gov/energysaver/maintaining-your-air-conditioner

DOE (U.S. Department of Energy). 2016b. “Overview of Existing and Future Residential Use Cases for Connected Thermostats.” Accessed on December 29, 2016 at https://energy.gov/eere/buildings/downloads/overview-existing-and-future-residential-use-cases-connected-thermostats

DOE (U.S. Department of Energy). 2016d. “The National Opportunity for Interoperability and its Benefits for a Reliable, Robust, and Future Grid Realized Through Buildings.” DOE/EE-1341

Domanski PA, HI Henderson, and WV Payne. 2014. “Sensitivity Analysis of Installation Faults on Heat Pump Performance,” *NIST Technical Note* 1848:9-16.

EERE (Office of Energy Efficiency and Renewable Energy). 2011. *Final Rule Technical Support Document: Energy Conservation Standards for Residential Central Air Conditioners, Heat Pumps, and Furnaces*. EERE-2011-BT-STD-0011, U.S. Department of Energy, Washington, DC. Accessed on November 12, 2015 at http://www.regulations.gov/#!documentDetail;D=EERE-2011-BT-STD-0011-0012

EIA (Energy Information Administration). 2015. “Residential Energy Consumption Survey (RECS).” U.S. Department of Energy, Washington, D.C.

EIA (Energy Information Administration). 2015 “Monthly Energy Review Oct 2015.” U.S. Department of Energy, Washington, D.C. Accessed on November 12, 2015 at http://www.eia.gov/totalenergy/data/monthly/pdf/sec2.pdf

EIA (Energy Information Administration. 2013. How much electricity does an American home use. Accessed November 12, 2015 at http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3

EIA (Energy Information Administration). 2009. “Residential Energy Consumption Survey (RECS).” U.S. Department of Energy, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 2016. “ENERGY STAR HVAC Quality Installation Program.” Accessed on December 30, 2016. https://www.energystar.gov/ia/home_improvement/downloads/ESQI_factsheet.pdf?8fd5-1967

Gao G and K Whitehouse. 2009. “The Self-Programming Thermostat: Optimizing Setback Schedules based on Home Occupancy Patterns.” In *First ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, New York, NY.

Ghansah I. 2012. Smart grid cyber security potential threats, vulnerabilities, and risks. California Energy Commission. Accessed on December 22, 2015 at http://www.energy.ca.gov/2012publications/CEC-500-2012-047/CEC-500-2012-047.pdf

Goetzler W, R Zogg, J Young, and J Schmidt. 2012. “Energy Savings Potential and RD&D Opportunities for Residential Building HVAC Systems.” U.S Department of Energy. http://www1.eere.energy.gov/buildings/pdfs/residential_hvac_research_opportunities.pdf

Goyal, S., H. Ingley, and P. Barooah. 2013. “Energy-efficient control of an air handling unit for a single-zone VAV system.” In Proceedings of IEEE 52nd Annual Conference on Decision and Control (CDC), pp. 4796–801. Florence, Italy.

Goyal, S., and P. Barooah. 2015. "Experimental study of occupancy-based control of HVAC zones", Applied Energy, vol. 140, p75-84.

GridTalk. 2013. Shaving Peak Residential Electricity Demand with Grid-Based Technology. Accessed on Nov 12, 2015 at http://www.sandc.com/blogs/index.php/2013/03/shaving-peak-residential-electricity-demand-with-grid-based-technology/

Lstiburek JW and B Pettit. 2010. “Final Report on the Expert Meeting for Diagnostic and Performance Feedback for Residential Space Conditioning System Equipment.” DE-FC26-08NT00601, Building Science Corporation, Westford, Massachusetts.

Maasoumy, M. 2016. “Smart Connected Buildings Design Automation Foundations and Trends.” *Foundations and Trends® in Electric Design Automation*, Vol 10, No 1-2, pp1-143. http://dx.doi.org/10.1561/1000000043

Oppenheim, P. 1992. “Energy-Saving Potential of a Zoned Forced-Air Heating System.” *ASHRAE Transactions.*

Parker, D., D. Hoak, et al. 2006. “How Much Energy Are We Using? Potential of Residential Energy Demand Feedback Devices.” 2006 ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA.

Piper, B., I. Metzger, N. Ricciardi, and Z. Gao, 2017. "Home Energy Management Pilot System Savings Validation Pilot." *New York State Energy Research and Development Authority*. Report Number 17-16. Albany, NY.

Proctor J. 2004. "Residential and Small Commercial Air Conditioning – Rated Efficiency Isn't Automatic." In *Proceedings of the ASHRAE Winter Meeting*, Anaheim, California.

Roth K, D Westphalen, and J Brodrick. 2006. "Residential central AC fault detection and diagnostics." *ASHRAE Journal* 48.5, pp. 96–97.

Siemann M. 2010. "Performance of Residential Heating and Cooling Control Strategies using Distributed Wireless Sensor Networks." MS Thesis. University of Maryland, College Park.

Singer BC, WW Delp, DR Black, and IS Walker. July 2017. "Measured performance of filtration and ventilation systems for fine and ultrafine particles and ozone in an occupied modern California house." *Indoor Air* 27.4, pp.780-790.

Somasundaram S, S Katipamula, RG Pratt, ET Mayhorn, BA Akyol, A Somani, N Fernandez, A Steckley, N Foster, and ZT Taylor. 2014. "Transaction-Based Building Controls Framework, Volume 1: Reference Guide." PNNL-23302, Pacific Northwest National Laboratory, Richland, Washington. http://bgintegration.pnnl.gov/pdf/PNNL_23302.pdf

Sutherland, K, Parker D, Martin, E. 2016. "Evaluation of Mini-Split Heat Pumps as Supplemental and Full System Retrofits in a Hot Humid Climate. FSEC-RR-646-16. Presented at 2016 ACEEE Summer Study on Energy Efficiency in Buildings. http://www.fsec.ucf.edu/en/publications/pdf/fsec-rr-646-16.pdf

Wang N, and JD Goins. 2015. Buildings of the Future Scoping Study: A Framework for Vision Development. PNNL-24126, Pacific Northwest National Laboratory, Richland, WA.

Walker IS. 2014. "Smart Ventilation (RIVEC) – 2014 BTO Peer Review. Slide 3. https://energy.gov/sites/prod/files/2014/05/f16/rbi09_Singer_042414.pdf

Wiggins, M., and J. Brodrick. 2012. "HVAC fault detection," *ASHRAE Journal*, 54(2):78-80.

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