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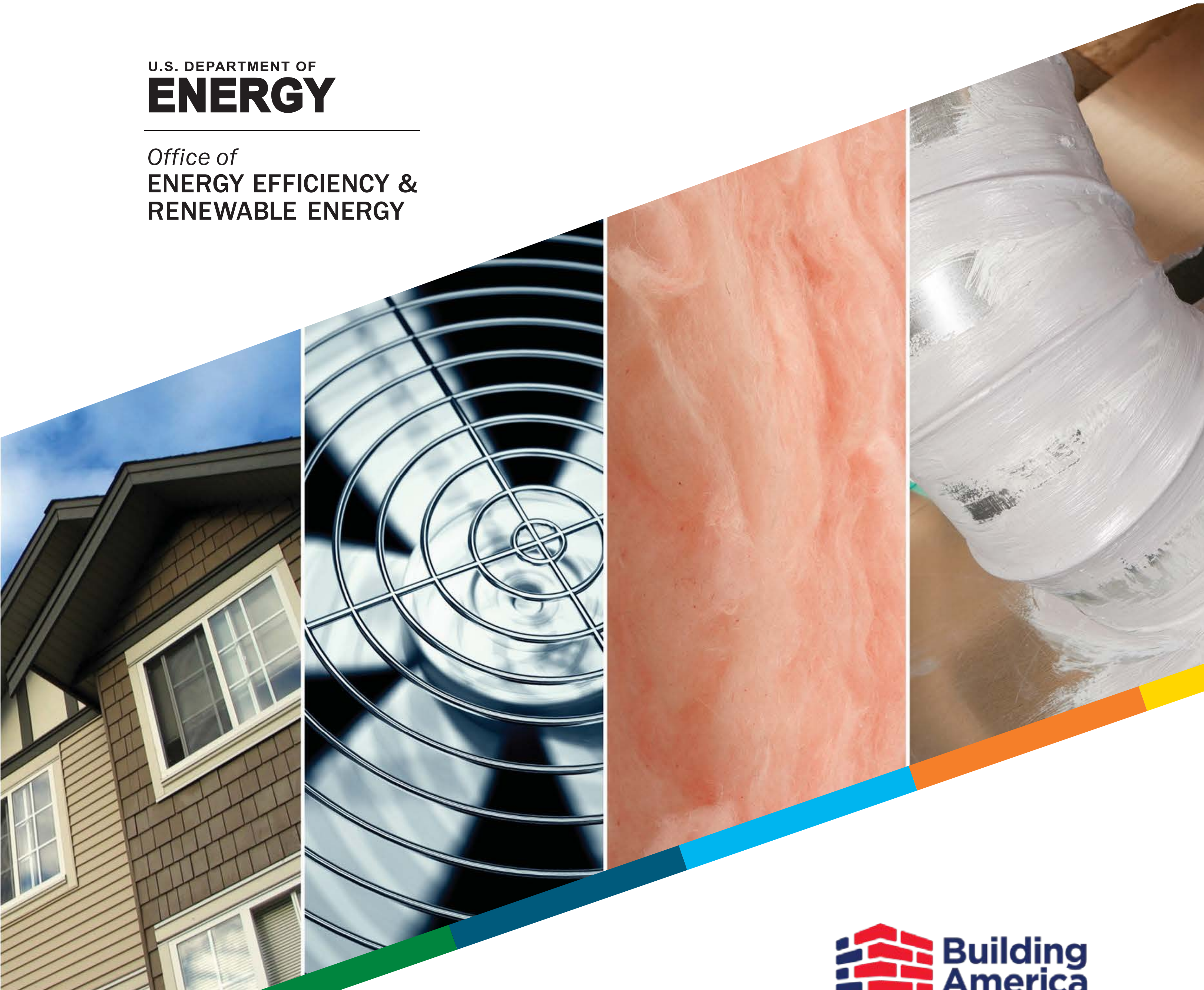

Building America
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Connected Thermostat Alternatives for Room Air Conditioners and Minisplit Heat Pumps

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Disclaimer

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Table of Contents

Executive Summary

Over the past decade or so, there has been a market explosion in the availability of smart, connected thermostats that can optimize climate control, encourage energy efficiency, provide remote control, and enable households to enroll in utility demand response programs that incentivize peak load reduction through energy bill credits. However, the most advanced thermostats are all designed for central heating, ventilation, and air-conditioning (HVAC) systems—analogous technology to address point-source heating and cooling systems such as window air conditioners (window ACs) and minisplit heat pumps (MSHPs) is not as advanced or prevalent in the market. There is a critical need to fill this gap because these types of single-zone HVAC equipment will remain a significant player for the foreseeable future. Window ACs, particularly legacy (old) units that are notoriously inefficient, are very common in multifamily housing and can be a significant source of summertime energy use for the occupants as well as peak load for the electric grid. Homes that use MSHPs are also an audience primed for a connected thermostat solution. MSHPs have long been common in parts of Europe and Asia, but more recently their combination of energy efficiency, modularity, and ability to both heat and cool have increased their popularity in the United States, especially in electrification retrofit applications.

There are a handful of startup companies offering third-party connected thermostats for room ACs and MSHPs that allow for remote temperature control and scheduling through mobile apps. These infrared-based (IR-based) thermostats work by taking the place of the HVAC unit’s original IR remote so that it is placed within line-of-sight of the HVAC unit. These devices are relatively new and untested, and there has not been a comprehensive study to examine how well they work. To help address this need, we selected a handful of commercially available IR-based thermostats and ran each through a series of actions in our laboratory for a basic technology assessment.

At a high level, we found that most of these products work reasonably well, but none are truly seamless, and the reliability of basic functionalities is the dominant factor in whether a product is effective at promoting convenient energy and comfort management. Several features seem especially promising, such as incorporation of indoor air quality (IAQ) metrics and the capability to alert users when their time-of-use rates change (although the latter is currently not available in the United States). Possible barriers to broad user acceptance include non-seamless initial setup processes, product cost, practical challenges around ideal thermostat placement, and lack of clear differentiation between different product tiers. Importantly, we would like to see more research and development toward controls that would enable MSHPs and primary/central thermostats to explicitly interact and coordinate. This would lead to increased energy savings and improved comfort for MSHPs in retrofit applications.

Background

The state of the art of thermostats has advanced significantly over the past decade or so. Beginning with the launch of the first-generation Nest Learning Thermostat in 2011,[1] there has been a market explosion in the availability of smart, connected thermostats that are designed to be user friendly, unlike their programmable thermostat predecessors (Carlsen 2022, Levy 2011). Nest included novel features then not yet standard in conventional thermostats such as remote connectivity, do-it-yourself installation, and a learning algorithm, but the crux of the innovation was its fundamental approach to design: For the first time, a thermostat was invented with the express objective of improving the end user experience. This marked shift in target audience to the end user (rather than the contractor) catalyzed a profound change not only in the thermostat technology space, but it also elevated the stature of home energy management systems (HEMS) more broadly as a practical and even desirable tool to enhance the energy use experience in homes.

The popularity of the Nest thermostat and its concept prompted accelerated market uptake of a new class of connected thermostats, and competitors such as ecobee and Honeywell soon followed. In 2017 connected thermostats earned a place in the ENERGY STAR® labeling program with the release of Version 1.0 of the Connected Thermostat Product Specification (U.S. Environmental Protection Agency and U.S. Department of Energy 2017). As of April 2024, there are 79 connected thermostats on the ENERGY STAR qualified products list. In addition to optimizing climate control, connected thermostats enable households to enroll in utility demand response programs that are designed to incentivize peak load reduction through energy bill credits, making them a valuable asset for utility efficiency programs. More broadly, flexible demand capacity from residential HVAC systems is projected to be a crucial distributed energy resource, underscoring the vital role of connected thermostats in virtual power plants moving forward (U.S. Department of Energy 2023).

While homes with central heating, ventilation, and air-conditioning (HVAC) systems today have many sophisticated thermostat options from which to choose, analogous technology to address single-zone heating and cooling systems such as room air conditioners (room ACs) and minisplit heat pumps (MSHPs) is not as advanced or prevalent in the market. Creative hacks abound to couple modern connected thermostats with room ACs and MSHPs, but the solutions are far from elegant. Such “off-label” use prevents the most advanced thermostats from providing the kind of elevated user experience that is their raison d’être. It is no wonder that utility efficiency programs have been largely limited to central systems in single-family homes, but there is a critical need to fill this gap. According to the most recent Residential Energy Consumption Survey results, 22% of U.S. households in 2020 had one or more single-zone AC systems, including wall, window, and portable ACs (which we will collectively

[1] Specific commercial products mentioned in this report are for discussion purposes only—NREL does not endorse or support any particular brand, product, service, or manufacturer.

refer to as room ACs in this report) and MSHPs (U.S. Energy Information Administration 2023). Together these units represent a largely untapped potential for both energy bill savings and load shifting.

To highlight one problem, window ACs are notoriously energy intensive. Although newer, inverter-driven models demonstrate vastly improved energy and comfort performance, and some are beginning to incorporate connectivity and HEMS integration, the majority of units in the field today are inefficient, legacy devices that operate using rudimentary control schemes. The most basic systems have an onboard thermostat and a setpoint that is adjustable via an infrared (IR) remote. These units do not have WiFi capabilities, and so “remote” control refers to control from the couch rather than from anywhere outside the home. Window ACs are particularly common in multifamily housing and can be a significant source of summertime energy use for the occupants as well as peak load for the electric grid. A connected thermostat designed to work with conventional window ACs would go a long way toward reducing energy bills and peak demand.

Homes that use MSHPs are also an audience primed for a connected thermostat solution. MSHPs have long been common in parts of Europe and Asia, but more recently their combination of energy efficiency, modularity, and ability to both heat and cool have increased their popularity in the United States, especially in electrification retrofit applications. The U.S. market share for ductless heat pumps has been growing at 10%–30% each year (Bhandari and Fumo 2022). Their retrofit use case presents interesting design challenges because in many scenarios, the MSHPs are installed to provide supplemental heating and cooling in homes that already have ducted, central systems in place. To achieve optimal comfort and save energy the two systems should coordinate with one another for best results, but currently there is no easy, off-the-shelf technology solution to provide this type of coordinated control. As a result, many retrofit installations of MSHPs fail to achieve their theoretical energy savings potential (Metzger et al. 2020).

Efforts to introduce connected capabilities to conventional single-zone HVAC systems for the purpose of utility demand response has met some limited success. For example, in 2013 Con Edison partnered with ThinkEco to launch the coolNYC program, which was aimed at providing demand response opportunities for the many room ACs (and some MSHPs) in New York City’s residences. The program was novel because participation was not limited to room ACs with built-in WiFi capabilities. The smartAC kit developed by ThinkEco provided an aftermarket solution for converting legacy room ACs into connected devices by pairing a demand response-capable smart plug (dubbed “modlet” for “modern outlet”) with a mobile app-enabled remote thermostat. Such programs are few and far between; today, existing demand response programs designed for single-zone HVAC rely almost exclusively on newer, WiFi-enabled ACs and MSHPs, which comprise only a small fraction of the installed base.

As noted above, there are many factors ensuring that these point-source HVAC systems will remain a significant player for the foreseeable future, and it is clear that we do not yet have the ideal tool(s) that simultaneously address the needs for remote connectivity, user-centric design, utility demand response capabilities, and integration with whole-home systems. Considering all the complexities and opportunities at play, it seems timely to take a broad look at the present state of connected thermostat technology for room ACs and MSHPs. To this end, we conducted a survey study of current devices on the market. In this report we outline the key features and functionalities that are most relevant for delivering the kind of coordinated control that we have learned to expect from room ACs' central system counterparts, and discuss what improvements are needed for this class of solutions to scale.

Connected Thermostats for Room ACs and MSHPs

The Basics of an IR Thermostat

There are a handful of startup companies offering third-party connected thermostats for room ACs and MSHPs that allow for remote temperature control and scheduling through mobile apps. These products all fundamentally operate in the same way: They replace the room AC's native IR remote with a separate thermostat that is WiFi enabled. During the initial setup, the user "pairs" the thermostat with the original IR remote that controls the room AC or MSHP. This pairing is usually accomplished by pointing the IR remote at the thermostat and pushing the power button on the remote. Once paired, the thermostat is placed within line-of-sight of the room AC or MSHP unit, typically on an opposing wall, and takes the place of the IR remote. The thermostat is connected to the home's WiFi network so that the user can access its controls remotely via a mobile app or a website.

These third-party thermostats are fairly rudimentary in their operation. Their most common features and limitations are listed in Table 1; there are some variations among brands and products, but the basic functionalities are standard. Most products are designed to work with both room ACs and MSHPs, and some advertise they can participate in utility demand response programs.

Table 1. Common Features and Limitations of Third-Party Thermostats for Room ACs and MSHPs

Features	Limitations
• Set up schedules via iPhone/Android app • Preferred temperature presets through modes such as “Home,” “Away,” and “Sleep” • Geofencing (actions can be triggered based on the geographical proximity of users’ mobile phones) • Alerts and reminders • Integration with voice assistants such as Amazon Alexa, Apple Siri, and Google Assistant • Historical data (e.g., usage logs, temperature vs. time) for estimating energy use patterns	• Uses IR signal (much like a remote controller), so the thermostat needs to be placed in line-of-sight of HVAC unit • One-way communication (any adjustments made directly on the AC or MSHP unit will typically result in offset with thermostat) • Most thermostat models need to be plugged into a 120V outlet, which can make optimal placement challenging • Not always compatible with some legacy HVAC units • Most lack the capability to facilitate participation in utility demand response

A Survey Study to Assess the State of Technology

These devices are relatively new and untested, and there has not been a comprehensive study to examine how well they work. To help address this gap, we selected a handful of commercially mature products and ran each through a series of actions in the lab for a basic technology assessment. Our goal was not to develop a comprehensive test protocol or to conduct a product review, but rather to survey and understand what products are available, what their basic capabilities and limitations are, whether they work as advertised, and what, if any, gaps in the technology exist that more research and development are needed to address. We created a list of tasks to perform and corresponding qualitative metrics (see Table 2), then tried using each product to control three different point-source HVAC units and recorded our observations.

Table 2. List of Tasks and Qualitative Metrics Used to Evaluate Each Thermostat

Task	Qualitative Metrics/Key Questions
Device pairing	Ease of initial pairing with remote
	Reliability of connection once paired
App interface	Notable differences between iOS and Android user interface
	Ability to accommodate multiple users (i.e., controllable from multiple mobile devices)
	Customizability of settings
	Any other general usability notes
Basic functions	Ease and reliability of setpoint changes
	Ease of setting up schedules
	Are there modes (e.g., “home” or “away”) that simplify control actions?
	Beyond scheduling and simple modes, are there any advanced (“smart”) features that facilitate energy saving and/or better comfort? For example, if geofencing is offered does it work well?

Task	Qualitative Metrics/Key Questions
Operational characteristics	Where is the setpoint temperature referenced? (At the HVAC unit or at the thermostat?)
	What happens when you raise/lower the setpoint temperature directly on the HVAC unit? Is the setpoint shown on the app always consistent with what is shown on the HVAC unit?
	What happens when you raise/lower the setpoint temperature *using the remote*? Is the setpoint on the app always consistent with what is shown on the HVAC unit?
	Sensitivity to line-of-sight—how far out to the periphery can the thermostat be placed and maintain a reliable connection?
Application programming interface (API) support and integration with home energy management systems	Compatibility with smart home hubs such as Amazon Alexa, Apple HomeKit, and Google Home
	Compatibility with voice assistants such as Amazon Alexa, Apple Siri, and Google Assistant
	Is the API open?

The three HVAC units used for testing were a Frigidaire window AC, a Toshiba window AC, and a Mitsubishi MSHP, each shown together with their original IR remote controls in Figure 1. These were placed in the open high bay in the laboratory and not in thermal chambers because the goal was to examine the control and communication functionalities of the thermostats rather than the air-conditioning performance of the HVAC systems.

Frigidaire Window AC Model FFRE0633S1 6000 BTU; EER 12.1 Manufactured 2017	**Toshiba Window AC** Model RAC-WK0612CRRU 6000 BTU; EER 11 Manufactured 2022	**Mitsubishi Electric MSHP** Model MSZ-FH18NA 18,000 BTU; SEER 21 Manufactured 2015
 	 	 

Figure 1. HVAC units and their remote controls used for thermostat testing

All report photos by the authors, unless noted otherwise

Product Selection

One of the first tasks was to sort through the options and select which products to procure. We looked at ten different thermostats from seven manufacturers; these are shown in Figure 2. These brands and products were selected entirely based on practical factors: how readily they were available for purchase (which can be one indication of level of commercial maturity) and compatibility with U.S. systems. We believe we captured most, if not all, of the major players in this space at the time of this work in 2023. Retail prices ranged from US$57 to US$125 at the time of purchase, but we have chosen not to include the individual product prices in this report because prices frequently change with special promotions and retailer discounts. All of these products were purchased online, in most cases directly from the manufacturer's website.

Figure 2. Third-party connected thermostats for room ACs and MSHPs

All of these thermostats are IR based and so they operate on the same basic principles, but the manufacturers and target markets vary slightly. Some of the thermostats appear to be designed primarily as a tool for MSHPs, but the ones we purchased all claim to work with both window ACs and MSHPs. While our intent was not an exhaustive product review, it was important to obtain a comprehensive understanding of the product landscape—who the manufacturers are, which devices are most broadly used (although "broad" is a relative term in this niche market), and what the distinguishing characteristics of each offering are. What we quickly learned was that product differentiation—and how to know whether a few extra features are worth the incremental cost of US$10, $20, or in some cases $40—can be challenging to a new user.

One aspect of navigating products that we found more confusing than we anticipated was that some manufacturers offer different tiers of their thermostat product with only slight variations in capabilities. These variations can include physical attributes, such as device form factor and whether it has an onboard display and controls, as well as operational characteristics, such as the ability to pair with a supplemental temperature/humidity/occupancy sensor that can wirelessly trigger thermostat control functions. While it is common practice for consumer electronics makers to repackage different feature sets to create a variety of products that are well-matched to different user segments, a relatively new technology that is still trying to gain traction may be better served by ensuring that the introductory step of product selection does not frustrate (and thereby alienate) would-be adopters. Manufacturers' reasonable desires to offer multiple price points notwithstanding, the substantial overlap in capabilities across product levels could be confusing to prospective users if the functional differences between product tiers are not clearly laid out without the need to read in-depth descriptions on the product websites.

Initial Setup and Connection Reliability

To begin using these thermostats, we first needed to connect each device to the WiFi network and pair it to the window ACs and MSHPs in our laboratory. The ease or difficulty of this commissioning step can make or break a user's willingness to embrace the technology. Our experience (summarized in Table 3) was mixed; we found that some devices were seamless to set up, while others required more patience.

Table 3. Summary of Pairing and Connectivity Statistics

Out of the 10 models we looked at….	
6	Paired easily with all three HVAC units and connected to the WiFi without problems.
1	Paired with all three HVAC units after some effort (initially slow to respond).
9	Paired successfully with the Mitsubishi MSHP.
9	Paired successfully with the Toshiba AC.
7	Paired successfully with the Frigidaire AC.
9	Maintained reliable connection once established.

Our Frigidaire AC is an older, more basic model than the Toshiba AC and is discontinued, and so it was not surprising that three of the thermostats failed to connect to it. Out of the three brands that failed to connect to the Frigidaire AC, only one has a disclaimer on its website indicating that Frigidaire models are not supported.

Most of the thermostats we tested are described on their product websites as being compatible with both room ACs and MSHPs. Indeed, six out of the ten products we tested were straightforward to commission, and pairing went smoothly with all three of our HVAC units. A useful feature during the pairing exercise that we encountered in one of the products was the ability to select the correct MSHP model from a drop-down menu in the app.

The connection, once established, was reliable for most, although we did find that when the AC or MSHP is power cycled, it can take a few moments for the connection with the thermostat to be restored. This is not a problem as long as the user knows to be patient. One thermostat demonstrated frustratingly poor connection reliability throughout our testing. The controls worked some but not all of the time, and it was sometimes difficult to tell from the app whether the HVAC unit was on or off.

While all of the products offer apps for both iOS and Android platforms, and for the most part they performed equally well, we encountered minor issues with the Android user interface on a couple of devices. In one case we were prevented from downloading the companion app from Google Play, with an error message that it "won't work on this device." We suspect, however, that this may be because the Android tablet we used is more than five years old. While mobile devices of this vintage may be uncommon, in general backward compatibility is a relevant factor for this class of products. One of the targeted use cases is the legacy window AC, and people who rely on old, inexpensive room ACs may be also likely to have older models of smartphones.

One-Way Communication

One artifact of these and other IR-based thermostats that users should note is that communication with the HVAC unit is inherently one-way, i.e., the HVAC receives commands from the thermostat (via app inputs) but cannot send signals back to the thermostat. This means that changing the setpoint temperature using the buttons on the HVAC unit itself (or by using the original remote control) can result in a mismatch between the setpoint and temperature shown on the app and those shown on the HVAC unit. This issue should not negatively impact the usability of these thermostats as long as users are aware of this limitation, which is handled slightly differently by each product. For one of the thermostats we tested, adjusting the temperature directly on the Toshiba window AC display seemed to override the app completely and disable the ability of thermostat to control the AC. One product offers a manual control mode that, once set up, blocks all input from the original remote. While not elegant, these approaches do effectively mitigate the mismatch problem by disabling the tempting option to use both the app and the original remote interchangeably.

Notably, one product has a sync feature that reliably syncs the temperature and operational status of the AC with what is reported on the app.

Scheduling and Other Basic Functions

With the initial commissioning completed, we familiarized ourselves with the basic operational characteristics of each thermostat.

Overall, most of the products performed their basic functions well and we found their mobile apps to be easy to use. From the app, users can typically control the mode, fan speed, and temperature, as well as set up a schedule. Several apps offer multiple default schedules that a user could choose if they did not want to create one on their own. One app features a scheduling “wizard,” which quizzes the user on their occupancy pattern, e.g., wakeup time, work hours, etc., and then autogenerates a scheduled based on the information provided. One app even features a run-time-based filter cleaner reminder.

Geofencing capability is available in all but one of the brands we tested, but our experience using it was not always reliable or predictable. The minimum radius required ranges from 200 meters to 1 mile (some products use metric units, others imperial). For a few thermostats the HVAC turned off/on promptly when we exited/entered the geofencing range, but for several others the functionality was either flawed or puzzling at best. Some products simply failed to trigger any action when we crossed the geofence radius. In one case, we could see from the app how many users were inside versus outside our geofence (hardly useful information), but traveling outside the geofence disabled our ability to control the AC from the app, which effectively defeats the purpose of having a WiFi-connected thermostat.

One area where a product can differentiate itself from competitors is in how well it can accommodate multiple users and how the syncing works between different users. Some apps allow the user to invite additional users by triggering an email directly from the app. For one of the products, we had an iPhone and an Android user simultaneously logged into their apps, and when the setpoint was adjusted from the Android app, the iPhone user received a notification about the change. While all of the products we tested claim to support multiple users, several of the apps could not allow multiple users to be logged in simultaneously; when a second user logs in from a different device, the first user is automatically logged out. A related—and potentially confusing—limitation we encountered in one app was that logging into the same account from another device does not automatically populate the app with information from the first device.

An option offered by one of the thermostats that may be particularly useful for MSHPs is the ability to rely on temperature sensing at the thermostat rather than the AC unit itself. Since MSHPs are typically installed near the ceiling, when there is significant temperature stratification, this setting change can help ensure thermal comfort by maintaining the setpoint near the thermostat, which is likely to be closer (than the heat pump head) to where occupants are.

One thermostat has an interesting mode called “comfort,” which is essentially a smart thermostat feature. The user gives feedback to the app on whether they are hot, too warm, a little cold, etc. and the AI algorithm manages the heating and cooling needs accordingly while continuously learning the occupant’s preferences over time. When multiple users are present, the “comfort” mode can average the desired temperatures of those present.

Overall, although we did not conduct any formal usability testing, we encountered numerous design aspects that we found to be lacking in sophistication. Following are examples (in no particular order):

- Response time: The lag between command (user input on the app) and execution (setpoint or other change at the HVAC unit) was irritatingly long (more than several seconds) for some thermostats.
- Visual/graphics challenge: In one app, the text and background are similar colors, making it difficult for the user to see what they are doing. One app uses a clock graphic that is so sensitive that the scheduling function is difficult to use.
- Cumbersome user interface: When making changes to the setpoint, etc., the user must click “send” before changes are actually implemented, which seems redundant.
- App navigation: The scheduling feature in the app is a little hidden and not easy to find (several clicks away from the “Home” screen).
- Less than full compatibility: One of the apps does not allow temperature or fan speed changes when the Frigidaire AC is in “econ” mode.

- Issues related to being in/out of WiFi range: In one instance, the “away” mode was activated automatically when the smartphone left the WiFi range, but once the app was not connected to the same WiFi network as the thermostat, we were unable to activate the “away” mode.
- Thermostat placement: One of the thermostats does not work well at distances over 10 feet, even though the product website recommends placing the thermostat 6–13 feet away from the MSHP.
- Smartphone always required: Some thermostats do not have any controls on the devices themselves, and all inputs must be made from the app, which could be perceived as cumbersome.

While each of the above would not be a dealbreaker on its own, they collectively add to the general impression that the technology is somewhat stuck in beta-testing phase.

Additional Features, Subscriptions, and Advanced Capabilities

In addition to the basic functionalities, several products offer additional capabilities worth noting.

- One product with a built-in IAQ sensor offers an **optional subscription model to unlock additional features** such as diagnostics for monitoring AC unit efficiency, an anti-mold function (which runs AC fan after shutting off AC to remove residual moisture in vents), machine learning algorithms to detect system anomalies and optimize for weather, and airflow regulation based on location and indoor/outdoor air quality. We did not test these subscription-based capabilities.
- Another thermostat with a built-in IAQ sensor has an **open window detection feature** in its app, which can trigger push notifications to the user to alert them that a window was likely left open. The app pulls outdoor air quality data from an unspecified external source and provides information on air quality and humidity inside the home and recommendations for ventilation. There is an additional subscription service to automate actions in response to air quality or open window concerns, but the subscription appears available only to European users.
- One product offers a creative workaround for situations where there is not a convenient location with an outlet that is also within line-of-sight of the HVAC unit. **Multiple thermostat devices can be connected as a system**, and only the one assigned to act as the “gateway” device needs to be connected to AC power. Additional devices can be powered via AAA batteries and connected via WiFi to the gateway device. While our study was aimed at looking at the simple case of a single HVAC unit, this feature could be very useful if there are multiple room ACs or MSHPs but not all are ideally positioned across from a wall outlet.

- One European manufacturer has an app with an **opt-in feature for electricity price notifications** that is apparently currently available only to EU customers. The app displays hourly electricity prices for both today and tomorrow and allows the user to set the minimum/maximum threshold price in €/kWh to receive alerts. Another product advertises a subscription feature incorporating time-of-use electric pricing (also only available in Europe). We hope that these features can expand to include U.S. utilities soon. (To be fair, this limitation is likely because standardization of utility data format is still a work in progress in the United States, so the lack of this feature is not the fault of device manufacturers.)

Smart Homes Integration

Manufacturers can differ on what precisely they mean when they advertise "smart homes integration," but for this class for technology, most of the focus is centered on voice commands: All ten thermostats are compatible with Google Assistant and Amazon Alexa, and eight of them work with Apple Siri. As for more comprehensive HEMS integration, three models offer Apple HomeKit integration, while three other models offer Samsung SmartThings integration. In addition, five devices can use IFTTT.[2]

More broadly, some manufacturers are singly dedicated to room AC thermostats, while others offer this technology as a product within a broader suite of energy management devices. There are several companies that offer connected thermostats for both room ACs and central systems, but based on the technical specifications, these offer no better coordination between the different HVAC systems within a home than the simple ability to control two otherwise independent systems from a single app.

Discussion

The goal of this survey was to obtain a snapshot of the technological maturity of IR-based thermostats and to investigate the utility of this class of products in addressing a current need. We were intentional in our plan to not rate the products relative to one another, but rather to describe their features and our experiences using them in a qualitative manner with the objective of making broad conclusions about the practicality of this type of thermostat solution, potential limitations, and what research could improve their functionalities overall. At a high level, we found that *most* of these products do work reasonably well but that none are truly seamless, and that the reliability of basic functionalities is the dominant factor in whether a product is effective at promoting convenient energy and comfort management.

The initial setup process to pair these thermostats required patience, and in some cases too much of it to be practical. The issues were two-fold: At times the technology seemed

[2] If-this-then-that (IFTTT) is a software platform for users to link a variety of services by using conditional statements to trigger actions.

buggy and connections were difficult to establish, but other times poor user interface could be blamed. If the initial setup process is not sufficiently intuitive and the process feels too onerous, we fear that many would-be users could be turned away for good. Several thermostats required firmware updates during the commissioning step; this is largely unavoidable these days because firmware could go through several version updates between the time the product comes off the assembly line and when it is purchased by the end user. Nonetheless it is another required step that impacts a user's perception of overall ease of setup.

An important part of the initial setup is determining the optimal location (in many cases the wall-mounting spot) for the thermostat so that it is within sufficient proximity to the HVAC unit, has direct line-of-sight to its IR receiver, and can be plugged into a 120V outlet. This is less challenging in a laboratory environment because we are not constrained to finding a convenient spot on an opposing wall. However, we did notice that some products are more sensitive to placement, and signals to the HVAC unit became less reliable at wide angles and/or long distances, while other products were able to accommodate more flexible placement.

Products that are primarily marketed outside the United States feature some capabilities that would also be useful here in the United States. Many utilities have begun to implement time-of-use pricing for residential customers, and the ability to modulate one's heating and cooling use to respond to periods of high energy costs and to do so automatically could help justify the initial investment for many families. Another feature worth noting is the possibility of using this type of thermostat without home WiFi. Interestingly, one of the European makers offers a product that claims to be designed for remote cabin applications and uses GSM network rather than WiFi. Recognizing that HEMS devices are largely out of reach for low- and moderate-income or rural households that do not have access to high-speed internet service, the ability to purchase a SIM card to run the thermostat seems like it could be very useful. We would like to understand better how this works and what the data requirements are, but the concept seems promising.

For the legacy room AC application, these third-party thermostats are likely more economical than replacing the AC units with newer, WiFi-enabled models. Its applicability to rental units is an interesting consideration because central thermostats typically belong to the building owner (along with HVAC equipment), but many renters purchase their own room ACs.

Whether these products are truly *smart* or simply *connected* is a fair debate and the answer lies just as much in semantics as it does in the level of built-in technical sophistication. In fact, the terms "smart thermostat" and "connected thermostat" are used interchangeably in much of the HEMS space, and even the ENERGY STAR label does not distinguish between the two. Given this trend, we do not attempt to draw this distinction, and simply call out the features and functionalities (either in the app or in the hardware) that help to promote easy management of energy and comfort, regardless of whether those capabilities rely on advanced algorithms.

Technical merit and user acceptance are equally crucial for any HEMS device to deliver results. While our expertise is not in marketing, there are a few issues we can point out that we feel could improve public perception of these devices.

For example, in several cases the lack of differentiation between different tiers within a product line made it very confusing for us to figure out which models to buy. Creating a whole new line of hardware to add two soft features seems counterproductive to the goal of simplifying energy management for prospective users.

We see great potential for integrating IAQ metrics into these thermostats. In addition to the thermostat that has a built-in IAQ sensor, another manufacturer offers an upgraded product that can trigger the AC fan to turn on when high a concentration of carbon dioxide or total volatile organic compounds is detected. In recent years the combined threat from wildfires, pollution, and the novel coronavirus have heightened the need for, and thus the public's awareness of and appreciation for, monitoring the quality of air we breathe. Bundling this feature together with an energy/bill-saving tool seems a win-win. Furthermore, it would allow utility efficiency programs to address IAQ as a "piggyback" benefit to their existing thermostat programs.

For the most part there was no discernable difference in thermostat performance across different models of HVAC equipment we used, although there were several thermostats that had difficulty connecting with our Frigidaire window AC. The Frigidaire unit is closest in practice to what we would consider a "legacy" device in the field, with only the most basic control capabilities built in. As described in the Background section of this report, the ability to support such legacy window ACs is a very important and potentially impactful use case in the United States. Not surprisingly, we noticed that the products that are more heavily marketed outside the United States tend to be more focused on the MSHP use case.

Finally, we would like to see more research and development toward controls that would enable MSHPs and primary/central thermostats to explicitly interact and coordinate. This would lead to increased energy savings for MSHPs in retrofit applications.

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