# Thermporal: An Easy-to-Deploy Temporal Thermographic Sensor System to Support Residential Energy Audits

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## ABSTRACT

Underperforming, degraded, and missing insulation in US residential buildings is common. Detecting these issues, however, can be difficult. Using thermal cameras during energy audits can aid in locating potential insulation issues, but prior work indicates it is challenging to determine their severity using thermal imagery alone. In this work, we present an easy-to-deploy, temporal thermographic sensor system designed to support residential energy audits through quantitative analysis of building envelope performance. We then offer an evaluation of the system through two studies: (i) a one-week, in-home field study in five homes and (ii) a semi-structured interview study with five professional energy auditors. Our results show our system helps raise awareness, improves homeowners' ability to gauge the severity of issues, and provides opportunities for new interactions between homeowners, building data, and professional auditors.

## CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; *Ubiquitous and mobile computing systems and tools*; • **Social and professional topics** → Sustainability.

## KEYWORDS

Sustainable HCI; Ubiquitous computing; Building energy audits; Temporal thermography; Quantitative thermography

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## 1 INTRODUCTION

Underperforming, degraded, and missing insulation is common in US residential buildings [39]. Detecting these issues, however, can be difficult. There is typically no visible indication of a problem on the finished surfaces of a building's *envelope*—the physical separator (*i.e.*, composed of exterior walls, windows, etc.) between the conditioned interior of a building and the unconditioned environment outside it. While professional energy audits are effective at locating insulation issues, these services are not widely used due to their cost and a lack of awareness about their need or availability [40,47]. Additionally, tools and techniques such as *thermography* that help reveal insulation issues have previously been inaccessible to homeowners. However, recent improvements to and falling costs of infrared sensing technologies are beginning to fundamentally change who has access to thermal cameras and has led to their increased use in energy audits by both professional and novice energy auditors [2,6,13,27,33].

Thermal cameras are used during energy audits to rapidly scan for and document anomalous heat signatures that may highlight the locations of potential insulation issues [6,27]. However, using a thermal camera and determining if a heat signature indicates a problem typically requires training and experience [34]. Moreover, energy audits generally rely on single, *in-situ* thermal images taken during walkthrough inspections, which may not capture enough information for accurate assessments [17,49]. Prior work also suggests that inexperienced users struggle to determine the severity of issues and lack confidence in their findings [34,35].

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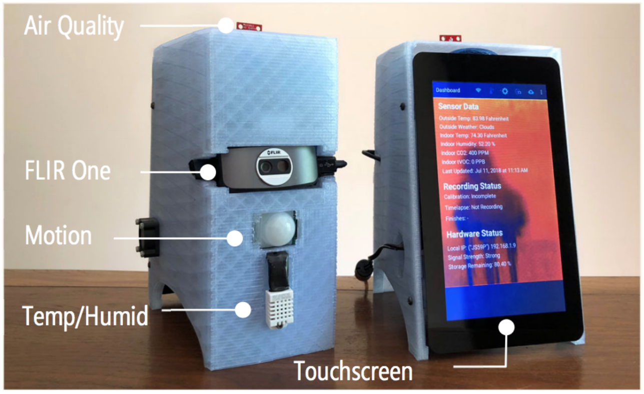


**Figure 1: Our temporal thermographic sensor system, *Thermporal*, is designed to collect and store all the data necessary for performing quantitative analysis of insulation performance and includes: a FLIR One thermal camera, environmental sensors, and a Wi-Fi connection for accessing weather data; users primarily interact with the system using a touchscreen display.**

To address these challenges, we present an easy-to-deploy, temporal thermographic sensor system (Figure 1) designed to support residential energy audits through a quantitative analysis of imagery from multiple time-series captures of a building's envelope. Our custom-built system, called *Thermporal*, combines low-cost, off-the-shelf hardware with a novel software suite to semi-automatically collect, analyze, and report on *temporal* thermographic data from nightly scans. Prior work in temporal thermography has focused on algorithmic performance and evaluations in controlled, unoccupied spaces (*e.g.,* [10,18]). In contrast, our primary research questions are human-centered: *What might users learn from temporal thermographic assessments of building envelope performance? How does using our temporal thermography system influence user behaviors or perspectives? What do professional auditors think of temporal thermography systems and how do their views differ from homeowners? And, finally, what design implications are there for future thermographic systems?*

To begin answering these questions, we report on two studies: (i) a one-week, in-home field study with five homeowners in five households and (ii) a semi-structured interview study with five professional energy auditors soliciting reactions to *Thermporal*. Our Study 1 findings show *Thermporal* helps to (i) raise awareness, (ii) detect, confirm, and disprove suspected insulation issues, and (iii) improve homeowners' confidence in their findings compared to using a smartphone-based thermal camera alone while Study 2 findings suggest auditors see *Thermporal*'s potential to provide beneficial data and utility during energy audits.

In sum, this paper contributes: (i) the design and evaluation of a novel semi-automatic, temporal thermographic sensor system that supports residential energy auditing, (ii) a summary of benefits and challenges associated with such systems, and (iii) design recommendations for future temporal thermographic systems intended for in-home use.

## 2 RELATED WORK

Here, we survey related work on (i) thermographic energy auditing and (ii) temporal thermography.

### Thermographic Energy Auditing

Energy audits identify sources of building inefficiencies and other issues through walk-through inspections, on-site measurements, health and safety checks, blower door tests, visual inspections, and computer simulations [44]. Though laborious, the US Department of Energy (DOE) recommends residential energy audits because of their impacts on reducing energy use (*e.g.,* 5-30% reductions in monthly utility bills) and improving housing stock (*e.g.,* improving insulation quality) [47]. And, as noted in the introduction, thermographic-based assessments are becoming increasingly common during audits due to the availability of low-cost thermal cameras marketed to professional and novice users.

Thermal cameras work by detecting the electromagnetic radiation emitted by all objects above absolute zero [19]. The thermal data is automatically combined with images from a conventional camera to produce a contextualized thermal image or thermogram. Energy auditors use thermal cameras to survey surface temperatures in walls, roofs, ceilings, and other parts of a building's envelope while looking for inconsistent patterns, discontinuities, and other anomalous heat signatures that may indicate the presence of an efficiency issue [6,27]. While thermographic scanning can be beneficial during energy audits (*e.g.,* to locate missing insulation), there are limitations to the technique that impact data accuracy such as wind, rain, and the intensity of sunlight. Additionally, according to ISO standards thermal scans should be conducted only when a minimum temperature differential of 14°C between a building's interior and exterior can be established [21,26]. However, even given proper environmental conditions (which can be difficult to achieve [34]) criticism of building thermography practices include that they are subjective [34], inaccurate [49], and that inexperienced users struggle to determine the severity of issues and/or lack confidence in their findings [34,35].

### Temporal Thermography

Rather than relying on visual assessments of surface temperature anomalies in thermal images, another approach is to quantitatively assess the rate of heat transfer through a building's envelope, also known as its thermal transmittance or R-Value in the US, and compare it to a known or optimal value (*e.g.,* a building code) [28]. While this approach is more explicit, it is nonetheless limited by a sensitivity to environmental conditions and needs to be performed when weather conditions have been stable (*e.g.,* no precipitation, strong consistent temperature differentials) for extended periods of time. This also makes results hard to replicate. Additionally, the setup and data collection requirements are prohibitive as camera calibration (*e.g.,* background thermal reflectivity, wall material emissivity) and environmental data (*e.g.,* interior/exterior temperature) are necessary.

To address the first two issues, temporal thermography methods have been proposed [1,9,16,28,36-38]. These methods (i) use similar data and procedures, (ii) are less sensitive to changing environmental conditions as they average multiple measurements over a longer period, and (iii) provide accurate and repeatable estimates of thermal transmittance. Notably, Nardi *et al.* [37] compared these methods and found that those proposed by Albatici *et al.* [1] were most accurate. However, while these studies suggest that temporal thermography can be used broadly as a general measurement technique for energy auditing they have not been evaluated by professional or novice auditors.

In our work, we explore how an easy-to-deploy, temporal thermographic sensor system called Thermporal can aid energy auditors in the field. We use off-the-shelf sensors (housed in a custom enclosure, Figure 1) to collect environmental data and computational methods (*i.e.,* [3]) to semi-automatically infer thermal camera calibration data from captured images which simplifies setup procedures and reduces the potential for user error. The system then uses the collected data from nightly time-series captures to achieve favorable environmental conditions and avoid the impact of sunlight to quantitatively analyze envelope performance. Results are then compared to regional building codes in an automated report that complements residential audits and helps users gauge the performance of wall insulation.

## 3 SYSTEM OVERVIEW

Informed by our previous user-centered work with professional and novice energy auditors [14,23,30,31], we iteratively designed *Thermporal* to be mobile, easy-to-use, and contain all the components necessary for temporal thermographic data collection, analysis, and reporting. The system is composed of a physical data collection unit (iterated from [30]) and a remote web server that address previous system limitations by adding computational support and reporting. Here, we describe these components and their use.

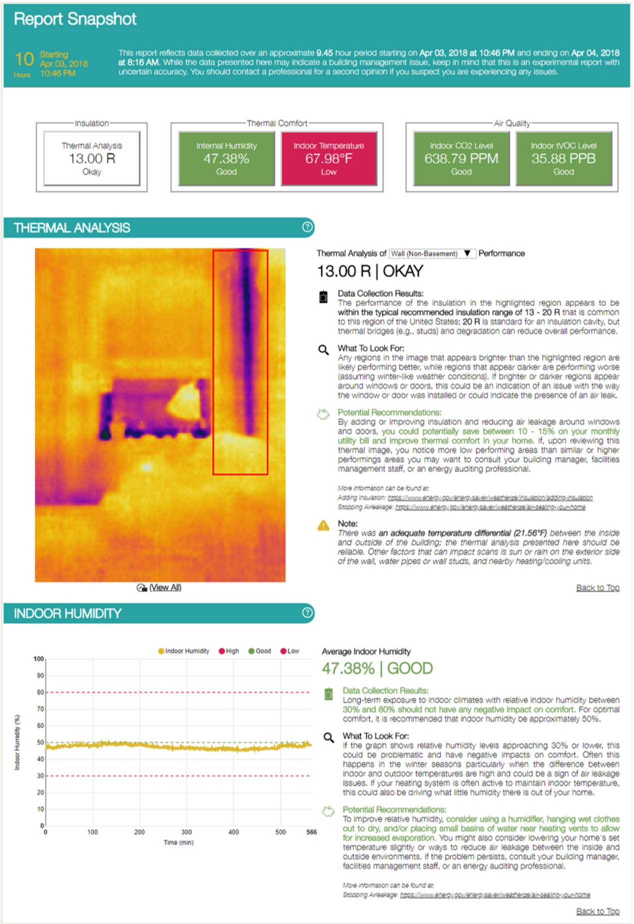
*Sensor Unit.* The sensor unit consists of: (i) a custom-built 3D-printed enclosure, (ii) a set of environmental sensors, (iii) a Raspberry Pi running the Android Things [20] operating system (v6.0) for local computing, power distribution, and Internet connectivity, and (iv) a touchscreen display. The enclosure is free standing, allowing it to sit stably atop a table, shelf, or other flat furniture (Figure 1). The on-board sensors include: temperature, humidity, air quality, GPS, and motion. These sensors are commonly used in building sensing applications (*e.g.,* [14,23]) and most are required for envelope performance calculations. Additionally, the indoor temperature/humidity sensor helps correct thermal image measurements and supplies comfort metrics while the GPS sensor improves the location accuracy of external weather information (compared to IP-based lookups). To protect user privacy, a concern described in [34,35], a motion sensor enables *Thermporal* to filter out data when people or pets are present. Finally, an air quality sensor (*i.e.,* CO2 and tVOC) echoes the health and safety side of residential audits [44].

*Application & User Interface.* We developed an Android application to control the sensor unit and communicate with the backend web server. Users interact with this application via the touchscreen to: connect the sensor unit to their Wi-Fi network, calibrate the thermal camera, schedule data collections, and generate reports. When idle or recording, the touchscreen acts as an ambient display of real-time sensor data and status messages (Figure 1, right).

*Backend Server. Thermporal's* backend server processes images and data from sensor units deployed in the field via an API. The API can: recognize a calibration target placed in the scene to determine distance to the building envelope and background thermal reflectivity, run a computer vision module to create an emissivity map of the image based on inferred material classes [3], calculate thermal transmittance of a user-specified Regions-of-Interest (ROI), and generate a report from data stored on a sensor unit. As a privacy measure, data is only temporarily stored on the backend server while responding to requests.

*Opertaion.* To use *Thermporal*, the user first places the sensor unit in an interior room perpendicular to an exterior wall's surface, as far back as possible. Before beginning a temporal scan, users calibrate the sensor unit—a standard step for any thermographic system—by affixing a calibration marker to the wall's surface. Our custom-made calibration marker consists of an 11x9 sheet of paper with: (i) a QR code that allows the marker to be located and (ii) a high-emissivity sheet of tinfoil—crumpled and smoothed—that creates an area for *Thermporal* to periodically check surrounding reflectivity (see [42] for calibration requirements). Users then press the application's calibration button and an automated parameter estimation process begins by sending an image to the

backend server. The server estimates the location and distance of the calibration target which is used to extract accurate temperature information from thermal images. The backend server then generates a map of emissivity values



This report reflects data collected over an approximate **9.45** hour period starting on **Apr 03, 2018 at 10:46 PM** and ending on **Apr 04, 2018 at 8:16 AM.** While the data presented here may indicate a building management issue, keep in mind that this is an experimental report with uncertain accuracy. You should contact a professional for a second opinion if you suspect you are experiencing any issues.

Thermal Analysis of Wall (Non-Basement) ▼ Performance

13.00 R | OKAY

Data Collection Results:
The performance of the insulation in the highlighted region appears to be **within the typical recommended insulation range of 13 - 20 R** that is common to this region of the United States; **20 R** is standard for an insulation cavity, but thermal bridges (e.g., studs) and degradation can reduce overall performance.

What To Look For:
Any regions in the image that appears brighter than the highlighted region are likely performing better, while regions that appear darker are performing worse (assuming winter-like weather conditions). If brighter or darker regions appear around windows or doors, this could be an indication of an issue with the way the window or door was installed or could indicate the presence of an air leak.

Potential Recommendations:
By adding or improving insulation and reducing air leakage around windows and doors, you could potentially save between 10 - 15% on your monthly utility bill and improve thermal comfort in your home. If, upon reviewing this thermal image, you notice more low performing areas than similar or higher performings areas you may want to consult your building manager, facilities management staff, or an energy auditing professional.

*More information can be found at:*
*Adding Insulation:* https://www.energy.gov/energysaver/weatherize/insulation/adding-insulation
*Stopping Airleakage:* https://www.energy.gov/energysaver/weatherize/air-sealing-your-home

Note:
*There was* ***an adequate temperature differential (21.56°F)*** *between the inside and outside of the building; the thermal analysis presented here should be reliable. Other factors that can impact scans is sun or rain on the exterior side of the wall, water pipes or wall studs, and nearby heating/cooling units.*

Average Indoor Humidity

47.38% | GOOD

Data Collection Results:
Long-term exposure to indoor climates with relative indoor humidity between 30% and 80% should not have any negative impact on comfort. For optimal comfort, it is recommended that indoor humidity be approximately 50%.

What To Look For:
If the graph shows relative humidity levels approaching 30% or lower, this could be problematic and have negative impacts on comfort. Often this happens in the winter seasons particularly when the difference between indoor and outdoor temperatures are high and could be a sign of air leakage issues. If your heating system is often active to maintain indoor temperature, this could also be driving what little humidity there is out of your home.

Potential Recommendations:
To improve relative humidity, consider using a humidifier, hanging wet clothes out to dry, and/or placing small basins of water near heating vents to allow for increased evaporation. You might also consider lowering your home's set temperature slightly or ways to reduce air leakage between the inside and outside environments. If the problem persists, consult your building manager, facilities management staff, or an energy auditing professional.

*More information can be found at:*
*Stopping Airleakage:* https://www.energy.gov/energysaver/weatherize/air-sealing-your-home

**Figure 2: Partial example of *Thermporal's* infographic-style report from our homeowner deployment study (H2) with two of five metrics shown. We have included a full sample report in the Supplementary Materials.**

in the image based on inferred materials in the scene and sends this information to the sensor unit. Once the sensor unit stores these data the user can specify a ROI (*e.g.*, a thermographic anomaly, wall surface) by placing a bounding box around it and scheduling a 12-hour, overnight temporal scan. See Supplementary Materials for more detail.

*Online Report.* After a scan completes, users can upload their data to the backend server to generate a report (one per scan) that is temporarily available via a web portal. Reports are styled as lightly-interactive infographics (Figure 2), pairing simple visualizations (*e.g.*, graphed humidity data, a thermogram) with automatically generated analysis, recommendations, and tips based on the collected data and guidelines from national health organizations (*e.g.*, CDC [7]), building operations societies (*e.g.*, ASHRAE [22]), and local building codes (*e.g.*, Maryland Energy Admin. [29]).

The report is color coded to quickly indicate whether issues exist (*i.e.*, red) or not and uses non-threatening language (*e.g.*, "high" vs. "danger"). The top of the report offers an at-a-glance overview of building performance, thermal comfort, and air quality metrics. Each metric is clickable and navigates to explanatory sections below. These sections describe the metrics with: (i, left) an interactive data visualization (*e.g.*, line graph) that displays recommended ranges for the data and exact measurements for every minute of the scan on mouse-over and (ii, right) a textbox that describes the results, offers interpretations, and recommends actions. Recommendations ranged from Do-It-Yourself (DIY) solutions (*e.g.*, hang wet clothes indoors to address low humidity) to advising professional assistance (*e.g.*, for poor insulation). For the thermal data, the average thermal transmittance (converted to an R-value) is compared to regional building codes [29]; users specify the type of ROI being analyzed (*e.g.*, basement wall) which updates the building code comparison.

## 4 HOMEOWNER FIELD STUDY (STUDY 1)

To investigate homeowner usage and perceptions of *Thermporal*, we conducted a one- week, in-home field study (modeled after previous studies of thermography tools [32,35]) with five participants during the early spring of 2018. Each participant was provided with a FLIR One$^{TM}$ thermal camera attachment for their personal smartphone, a temporal thermography sensor unit, calibration targets, painter's tape, and a tripod. To guide their auditing activities, participants were asked to complete two thermographic "missions" (based on the prompting methods in [41]): the first to investigate their home with the smartphone attachment (baseline), the second to deploy the temporal system. After each mission participants completed an online questionnaire about their experience and perceptions of the activity. At the end of the week participants were debriefed via a semi-structured interview and compensated $60. Roughly 45 days later, participants completed a final online questionnaire to investigate any lasting impacts of participation on attitudes or behaviors and whether any actions were taken to address issues in the home. The lead researcher, a professionally certified thermographer, reviewed captured data and system logs from the field deployments to ensure compliance with current standards and, thus, reasonably accurate reports before analyzing participants' reactions to and interpretations of results.

### Method

*Participants.* We recruited five participants (3 male, 1 female, 1 non-disclosed) from the Washington DC metropolitan area using mailing lists, university list-servs, and social media (Table 1). Potential participants completed an eligibility questionnaire where we screened for home-owning adults (age

| ID | Age | Gender | State | Site | Education | Profession |
|---|---|---|---|---|---|---|
| H1 | 30 | Male | MD | Single-family | Bachelors | Music Licensing |
| H2 | 41 | Female | MD | Single-family | PhD | University Professor |
| H3 | 53 | Male | MD | Single-family | Bachelors | IT Manager |
| H4 | 60 | Male | DC | Single-family | Masters | Attorney |
| H5 | 40 | * | VA | Low-rise condo. | PhD | Data Scientist |

**Table 1: Participant demographics for the field study.**

18+) with compatible smartphones. We enrolled participants on a first-come, first-served basis.

We collected demographic information and assessed initial attitudes toward energy efficiency in a short, pre-study questionnaire. All participants were formally educated, working professionals (Table 1). Our participants self-rated *being concerned about climate change* on a 7-point Likert scale ordered *very unconcerned* (1) to *very concerned* (7), with *M*=6.4 (*SD*=0.8). Three had never conducted an energy audit, one performed DIY energy audits bi-annually, and the last reviewed their utility bills monthly. The two participants that performed auditing activities also reported making seasonal weatherization improvements (*e.g.,* sealing air leaks), the others cited uncertainty of how to begin auditing activities or cost barriers. One participant had previously had a professional energy audit of their home. Finally, two participants had previously used a thermal camera, though not in connection to energy auditing.

*Deployment Sites.* The participants' homes were typical of those constructed in the Washington DC metropolitan area. Four were single-family, wood and timber-framed with cavity insulation and finished drywall interiors. The other was a low-rise condominium similar in construction to the single-family homes, but steel framed with some areas of brick facing on the exterior. With respect to evaluating insulation performance, regional building codes and recommendations are similar (*e.g.,* wall insulation should be between R-13 and R-20 [29]). Participants' homes were 54.2 years old on average (*SD*=21.6) and participants had owned their homes for an average of 11 years (*SD*=8.6).

*Procedure.* We began deployments during weeks with weather conducive to thermography (*e.g.,* low predicted precipitation, cold). Upon arrival at a participant's home, a researcher discussed the study plan, obtained consent, provided the participant with study materials, and reviewed training documents for both the thermal camera and the temporal sensor system. These documents, included in our Supplementary Materials, were created by a research team member with a professional thermography certification and were further informed by tutorials and documentation found in thermographic smartphone applications [15], how-to guides from manufacturers [53], and DOE materials [46,47].

Participants were asked to acquaint themselves with their smartphone thermal cameras before beginning the two study missions (which structured and motivated data collection):

- **Mission One (Baseline):** Investigate your home with the thermal camera attachment for signs of energy inefficiencies and collect at least 25 photos.
- **Mission Two (*Thermporal*):** Use the temporal sensor system and collect information overnight about at least two areas that you are curious about and review this data online.

Participants received missions via email and completed each at their convenience. After each mission they filled out an online survey about their experience. The surveys used open and closed questions to ask how participants performed their audits and why, if they found issues, and their perceptions of the activities. The survey took 8 minutes to complete.

After completing the two missions, participants completed an in-person, semi-structured debrief interview. We asked participants to describe their prior experience with home maintenance and energy auditing, review collected study data, and discuss perceptions of thermographic sensing including opportunities for and barriers to making home improvements based on their findings. Sessions were audio recorded, lasted an average of 54 minutes (*SD*=8.3), and were led by the first author, a certified thermographer.

Forty-five days after completing the debrief interviews, we invited participants to participate in a follow-up survey. The follow-up survey asked participants if they had taken any actions on uncovered issues, if any, as a result of their auditing activities and explored any lasting impacts the study may have had on their attitudes or behaviors. The survey took ~5 minutes to complete.

*Data and Analysis.* We calculated descriptive statistics for the survey data and transcribed the debrief interviews. We analyzed the transcripts using an iterative coding method with both inductive and deductive codes [5,24]. The initial codebook was based on [35] and contained 12 codes under three categories: *experiential, design ideas & challenges, and broader impact.* To gather feedback about our sensor system that may not have been captured by the previous codebook, we added codes for *likes* and *dislikes* (14 total codes). To begin our analysis, two researchers independently coded a randomly selected transcript. Cohen's Kappa ($\kappa$) was used to measure inter-rater reliability (IRR); our unit of analysis was the response to a single question. IRR on the transcript was $\kappa$=0.85 (*SD*=0.11) with codes ranging from *strong* to *near perfect* agreement [50]. Having achieved IRR, a single researcher

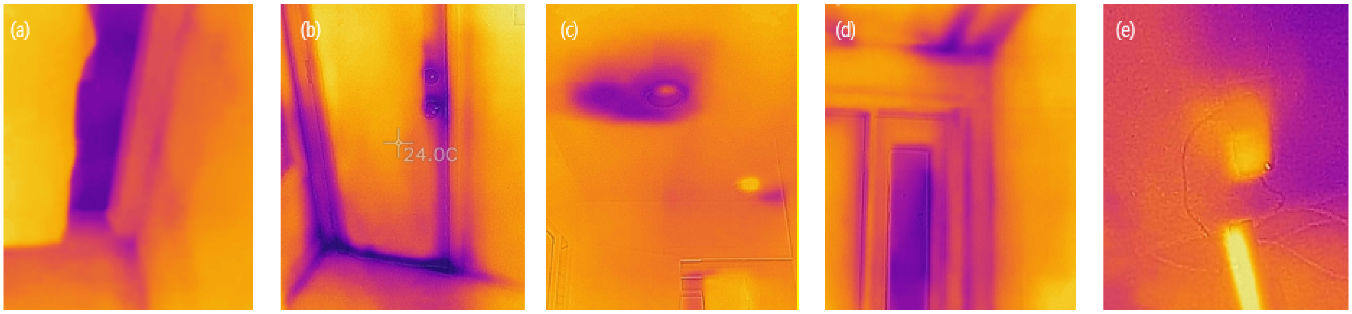


**Figure 3: Homes in Study 1 exhibited a variety of potential issues (based on participant's self-report): (a) break in an the exterior walls between an original living space and a potentially uninsulated renovation of a non-living space, (b) air leakage around a door, (c) potential missing insulation around a light fixture, (d) thermal bridging in a ceiling, (e) "phantom energy" issue caused by leaving electronics plugged in with no immediate plans for future use.**

coded the remaining transcripts. The final codebook is included in the Supplementary Materials. Participant quotes are attributed using: 'H' for homeowner, 'S' for a survey response or 'I' for an interview response, followed by their identification number (*e.g.,* HS1).

## Mission One: Smartphone Thermography Results

In mission one participants used smartphone thermal camera attachments to inspect their homes. We report on participant activities, findings, self-reported confidence in their assessments, and reactions to smartphone thermography.

### Mission Overview

Participants spent an average of 23 minutes (*SD*=5.7) completing mission one. They generally looked for thermal anomalies such as air leakage around windows and doors, insulation problems, and moisture damage. *"I was looking for anything out of the ordinary - places where cold might be getting in other than windows, like surrounding the windows, or irregularities in insulation pattern"* (HS4). In the debrief interviews, participants emphasized using the cameras to investigate previously identified areas of concern (like [35]):

> *"I found problems in the office, which is where I did the scans with the sensor device. I knew it would be bad as it was formerly a sunporch that the previous owners had poorly refinished"* (HI2).

*Participant Findings.* All five participants found evidence of air leakage and/or insulation issues (Figure 3). *"Doors leak cold at the bottom more than other areas, some outlets appear to not be insulated, possible variation in insulation in the bathroomâĂİ"* (HS5). Two survey participants described phantom energy issues (*i.e.,* unused devices consuming power). Most participants (4) suggested DIY fixes for the issues they uncovered, such as two participants who suggested resealing areas where they observed air leakages. In contrast, solutions for insulation issues were non-specific. Two participants described generally trying to *"find a way"* (HS3) to deal with these issues while one mentioned wanting to review their data with a professional.

*Self-Confidence.* Despite finding issues and suggesting repairs, participants reported being only somewhat confident in making assessments (*M*=5.0, *SD*=0.9, on a 7-pt Likert scale rated very unconfident to very confident). Most (4) somewhat agreed that their thermal imagery was easy to interpret (*M*=5.6, *SD*=1.0) and could be used to evaluate the need for improvements (*M*=5.8, *SD*=1.2). Participants reported only being somewhat likely (*M*=5.4, *SD*=0.5) to act on their recommendations. The 3 participants who were more confident used thermal imagery for confirmatory purposes, such as HS3: *"I have the thermal readings to support my assertions."* As with previous studies [35], less confident participants found it challenging to determine if a photo revealed an actual issue and what the impact of fixing it might be: *"There are some very cold spots in the office, but it's hard to tell if it's just because it's unheated or that there's some big gaps in the insulation"* (HS2).

Two participants reiterated their difficulties during this mission with interpreting thermograms, such as HI5:

> *"I don't think they were interpretable on their own. The reticle with the temperature reading was particularly difficult to make sense of…Although, [the experience] did give me some questions to ask if I was consulting with an exper"* (HI5).

*Reactions to Smartphone Thermography.* Participants found the thermal camera to be *easy* to use (*M*=6.2, *SD*=1.2). Two participants reported minor issues with connecting the camera to their phones and another found it challenging to find a period of suitable weather for thermographic scans. All participants *agreed* or *strongly agreed* that the thermal camera was useful toward learning about their home (*M*=6.4, *SD*=0.8) and *agreed* that the thermal camera was helpful in determining whether problems exist (*M*=5.8, *SD*=0.8). Most (4) *agreed* that using the thermal camera had increased their interest in energy auditing (*M*=6.4, *SD*=0.8).

### Mission Two: Temporal System Results

In mission two participants used *Thermporal* to further investigate their homes and any previously located issues. We report on participants activities, findings, self-reported confidence in their assessments, and their reactions to our temporal sensor system including the automated report.

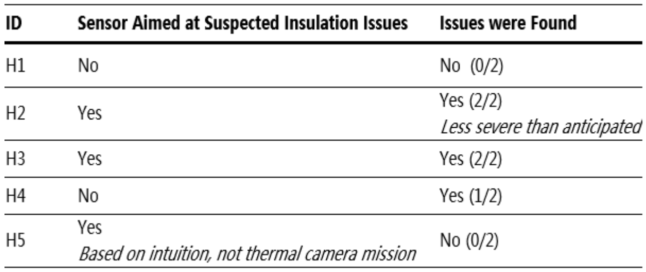
*Mission Overview.* Participants each completed two 12-hour deployments of the system and spent an additional 16 minutes (*SD*=1.9) reviewing their data via the automatically generated online reports. All participants reported that the sensor system helped them learn about and assess insulation performance and environmental conditions in the home. The three participants that found insulation issues in mission one reexamined them using our system. Other deployments measured exterior wall performance in primary living areas (*e.g.,* dining room, office). In the interviews, all participants were positive about the system, particularly the holistic view of their household provided by the summative reports:

> *"It kind of gave me a why. It's real cold here and this is below code. Here's some further information you can look at. That was super helpful. I can be like, I agree that this is a problem and now it's telling me something I can do"* (HI2).

As a direct result of the temporal data collection and analysis, all participants obtained new insights not revealed by their smartphone-based thermal camera use in mission one. During the interviews, four participants described a sense of engagement through the process of collecting and analyzing the temporal data while one was neutral due to the setup time. When asked about how our system could be improved, all participants wanted increased coverage of their household (*e.g.,* all walls to be analyzed).

*Participant Findings.* While the smartphone-based thermal camera attachment was preferred for the rapid discovery of ROIs, the sensor system was considered more useful in determining whether ROIs were actual problems as it directly compared insulation performance to regional building codes (Table 2). Additionally, participants liked that the sensor system presented this information alongside other household environmental metrics:

> *"It was interesting that it tells you the wall insulation and the humidity, because we thought our humidity was on the lower side because we both get dry, so we installed a whole house humidifier and it was good to know that it was good"* (HI1).



| ID | Sensor Aimed at Suspected Insulation Issues | Issues were Found |
|---|---|---|
| H1 | No | No (0/2) |
| H2 | Yes | Yes (2/2)<br>*Less severe than anticipated* |
| H3 | Yes | Yes (2/2) |
| H4 | No | Yes (1/2) |
| H5 | Yes<br>*Based on intuition, not thermal camera mission* | No (0/2) |

**Table 2: Participants' use of *Thermporal* to analyze and uncover issues in their capture sessions. Results for three participants conflicted with expectations.**

Three participants chose to aim the sensor unit at suspected issues during their deployments-two who identified ROIs with their thermal cameras, one who was investigating the insulation performance claims of their homeowners' association. Of these participants, one confirmed the issues were problematic, one discovered the issues were less severe than anticipated, and the last was surprised to learn no issues were present where they were expected. Two participants performed general insulation inspections in their deployments (*i.e.,* no previously identified ROIs), and one confirmed their home was performing efficiently. However, HS4 uncovered an unforeseen insulation issue-not discernable with the thermal camera attachment aloneâĂŤwriting in their survey that, *"I didn't realize this area was so poor."* In sum, temporal thermographic analysis was able to confirm participant findings and correct participants' expectations about insulation performance.

*Interactive Report.* Four participants were positive about the automatically generated report. All participants noted that the report helped them learn about relevant building codes, thermal comfort, and air quality standards. HI1 described how they *"learned what good levels for these [metrics] were, so that was helpful."* Additionally, most participants (4) liked the added depth of the temporal data and report in comparison to the thermograms collected in mission one:

> *"I like the idea of having a report that I can refer to again afterward. You get that with pictures too, but the reporting aspect gives you more detail, [...] the environmental and air quality readings gave you something more to look at."* (HI3)

In contrast, HS5 thought the report lacked depth and utility, perhaps partially because they did not find issues: *"My reports were negative, I am not sure what else to glean from them."* They expanded in their debrief interview, saying:

> *"The time series weren't all that informative and it was unclear how to interpret them, the text summaries were more helpful, but I'd prefer it if I had a specific part list... and a better way to tag and compare things spatially"* (HI5).

In the interviews, three participants envisioned using this data to communicate with professionals to highlight problems and as an auxiliary source to confirm professional recommendations. HI2, for example, stated: *"If there's a big problem, that's the thing I want to fix, but I don't trust that some guy is coming in and not trying to sell me."* However, participants desired a report with more capabilities and customization options. All participants mentioned that evaluating temperature and humidity data was more nuanced than the system allowed. The system focused on thermal comfort (*e.g.,* measurements staying within a certain range), but participants deliberately lowered temperatures at night to save on energy costs causing their overnight scans to suggest low thermal comfort in the home. Three participants wanted to customize the report to hide sensitive or personal data (*e.g.,* before sharing with professionals, to remove photographs the motion sensor may not have detected).

*Data Privacy.* Data Privacy. Four participants raised concerns when asked about data privacy. These participants were comfortable deploying the sensor system in their households as long as they had control over the collected data and it was not sent to external entities without consent. As HI2 summarized:

> *"If it were not an internet connected device and just on the local network in my house, that would be fine. If information is going out, then I have a big problem with technology like that"* (HI2).

While participants indicated that the motion sensor data filtering helped address these concerns, they did not trust the approach to be foolproof. In contrast to these perspectives, HI4 wanted to share data, compare their home to their neighborhood, and provide data access to local policy makers so it could be used to more accurately appraise home values and motivate more improvement programs.

*Self-Confidence.* Most participants (4) indicated that using the temporal thermographic sensor system lent additional confidence to the earlier assessments. One participant, HI3, was not surprised by their results because they felt the issue was clear from the earlier thermal photos, but on reviewing the report wrote, *"the R value is lower than I would've thought, especially in the living room which was upgraded 10 years ago."* Most (4) somewhat agreed that their collected data was easy to understand ($M$=5.8, $SD$=0.7) and could be used to evaluate the need for improvements ($M$=5.8, $SD$=1.1). Most participants (4), however, remained only somewhat confident ($M$=5.0, $SD$=0.6) that they would implement their recommendations. Participants with reports indicating an issue (3) tended to be slightly more confident, like HS3 who wrote: *"We have good information now, it will be a matter of cost/benefit/comfort analysis."* Conversely, participants with reports indicating no issues (2) became more neutral. HS1 explained: *"I had no recommendations."*

*Reactions to Thermporal.* While positive about the temporal sensor system overall, most (4) participants nevertheless noted a software or hardware issue during the mission in their interviews. Participants found the sensor system was only somewhat easy ($M$=5.0, $SD$=1.4) to use as setup was *"a bit tricky"* (P3) and waiting for the camera to connect took too long. Lack of control over the 12-hour collection time was another frustration: the long data collection time was viewed as problematic by two participants, whereas one participant wanted to record data for longer consecutive periods of time (though this is a limitation of the study procedure and not the system itself). Two participants also noted that the strength of their home's Wi-Fi network prevented them from deploying where they wanted (*e.g.,* in basements).

### Follow-up Survey Results

Forty-five days after the debrief interviews, participants completed a brief survey to ascertain whether they had taken actions to address issues, if found, and if there were any lasting impacts of participation in the study.

*Actions Taken.* Two participants reported acting on their recommendations for adding additional air sealing to window and door areas. One participant, who had not implemented recommendations, reported needing to wait for funds to be available to address the issues they found. The remaining two participants reported that issues were a low priority, as HS2 explained *"It didn't seem super critical."*

*Attitudes and Behaviors.* All participants reported thinking more about energy efficiency issues in their home since their participation in the study had ended. As HS3, summarized *"It has made me generally more aware of where there might be issues and why."* Additionally, all participants reported thinking more often about insulation performance and air leakage issues, most (4) reported thinking more often about thermal comfort issues, and two reported thinking more often about air quality issues. Finally, one participant reported an increased interest in looking into professional services.

### Study 1 Summary

Study 1 comprised of a week-long field study including two thermographic data collection missions, a debrief interview, and a follow up survey with homeowners. Participants analyzed anomalies discovered with their thermal cameras, confirmed conclusions, and even made new discoveries that challenged pre-existing assumptions about envelope performance by using *Thermporal* which, for some, led to improved confidence in their assessments, but not action.

| ID | Age | Gender | Sector | Auditing Experience (yrs.) | w/ Thermography (yrs.) |
|---|---|---|---|---|---|
| P1 | 35 | Male | Private | 6 | 2 |
| P2 | 29 | Male | Private | 7 | 3 |
| P3 | 28 | Male | Private | 5 | 5 |
| P4 | 32 | Male | Private | 7 | 5 |
| P5 | 49 | Male | Private | 6 | 6 |

**Table 3: Demographic information for professional energy auditor participants.**

## 5 ENERGY AUDITOR INTERVIEWS (STUDY 2)

To investigate how the professional energy auditing community might view *Thermporal*, and systems like it, we conducted a two-part semi-structured interview study with five professional energy auditors. Part one reviewed their thermography experiences and discussed modern initiatives (*e.g.*, novice's DIY audits, automated collection). In part two we used design probes (modeled after a previous study [34] which centered more on Unmanned Aerial Vehicle scenarios) to solicit feedback on our sensor system. Participants were compensated $40 for their participation.

### Design Probes

The three design probes consisted of two text scenarios (~250 words) and a demonstration of our sensor system. Each scenario built on the previous and emphasized diverse ways energy auditors could interact with clients, described new data collection and analysis methods, and asked participants to consider how future integration of such systems may impact energy auditing. With Study 1 participant permission, the demonstration included a review of their collected data. While the text-based design probes used 2$^{\text{nd}}$-person narration, we provide an abbreviated summary below. The full scenarios are included in our Supplementary Materials.

*Scenario 1 (Text): Residential-scale Audit.* The first text probe described a residential audit where a sensor network similar to *Thermporal* had been installed in a home prior to the auditor's arrival. The probe also incorporated the desires of Study 1 participants by including increased coverage area and capabilities while positioning the client as being knowledgeable of the data and prospects for improvements.

*Scenario 2 (Demonstration): Multiple-Residential Audits.* The second design probe demonstrated setting up and interacting with the sensor system. The probe also reviewed reports and homeowner experiences from Study 1.

*Scenario 3 (Text): Urban-scale Audits.* The second text probe described an urban-scale audit where thermographic sensor networks were common in the built environment. The probe described how sensor systems like ours were being installed at the neighborhood level and asked participants to consider how auditing practices might change as a result.

### Method

*Participants.* We recruited five professional energy auditors (all male) in the Washington DC metropolitan area through email lists, word-of-mouth, and social media. Our participants ranged in age (*M*=34.6 years; *SD*=8.5), audit experience (*M*=6.2 years; *SD*=0.8), and thermography experience (*M*=4.2 years, *SD*=1.6) (Table 3). While no participants held a professional thermography certification, all had received on-the-job training to perform thermography through corporate training programs or workshops.

*Procedure.* Sessions lasted an average of 103 minutes (*SD*=26.3). Our semi-structured approach allowed us to pursue topics we had not identified *a priori*, which emerged in accordance with a participant's personal background, skills, and experience. The design probes followed the interviews. Participants were asked to "think aloud" and evaluate each scenario or presentation. Our objectives were to identify participant interests, concerns, and thoughts about how such systems might impact professional practices.

*Data and Analysis.* The sessions were audio recorded, transcribed, and coded for themes. As with Study 1, we iteratively analyzed the data using a mixture of inductive and deductive codes [5,24]. We created two codebooks—one for each part of the study—which were derived from codebooks used in previous work [34]. The final codebooks are included in the Supplementary Materials. Participant quotes attributed using a 'P' for professional energy auditor and their identification number (*e.g.,* P1).

For the semi-structured interviews, our codebook contained ten codes under three categories: views on thermography, impact of thermography and benefits and challenges. Two researchers independently coded a randomly selected transcript. The unit of analysis was the response to a single question. IRR on the transcript was $\kappa$=0.85 (*SD*=0.13) with codes ranging from *strong* to *near perfect* agreement [50]. Having achieved IRR, a single researcher coded the remaining transcripts.

For the design probes, our codebook contained ten codes under three categories: interests, concerns, and reactions to scenarios. IRR on a single randomly selected transcript was $\kappa$=0.89 ($SD = 0.13$) with codes ranging from strong to *near perfect* agreement [50]. Having achieved IRR, a single researcher coded the remaining transcripts.

### Interview Findings

Many of our findings reaffirm those in [34], which pre-dated readily available, commodity smartphone-based thermal cameras and increased activity in novice DIY building thermography. Here, we focus on new findings regarding additional barriers to utilizing thermography during inspections, perceptions of potential new data sources (*i.e.,* automated thermography and smart home data), and perceptions of novices or homeowners performing DIY thermographic energy audits in residential buildings.

*Barriers to Utilizing Thermography.* With respect to barriers not described in prior work [34] (*e.g.,* weather and knowledge of construction practices), three participants stated that limited time onsite prevented them from using thermography as much as they would like or should. Two participants also described challenges with interpreting thermographic data in detecting moisture issues—starkly contrasting their confidence in using thermography to detect air leakage or insulation issues. Both participants described scenarios where they had thought they found moisture issues within a home but weren't confident enough to report it. They felt they needed more training before making such an assertion to clients. As P1 described: *"If it's really obvious what it is then maybe, but if it's a questionable moisture issue, personally, I am not comfortable diagnosing that."*

*New Data Sources.* All five participants thought having smart home data about household environmental conditions, operational schedules, and performance would be valuable. As P3 described,

> *"Temperature, how often your unit is turning on and off, what it's being set to... you can't trust how accurate a homeowner's going to know their own behavior...I'd like to have that data to analyze and see what's really affecting things"* (P3).

Even so, one participant offered a caution: *"[these are] data points and it comes down to the creativity of how you can use and apply the data to achieve a goal"* (P5) and was not confident that more data would provide new insights.

*Perceptions of Homeowner Thermography.* All participants were receptive to questions and prompts about homeowners performing DIY energy audits with thermal cameras, generating their own reports, and approaching auditors with these artifacts. Most (4) thought a report from the homeowner could address two challenges. First, scheduling audits is often difficult as preparations are time-consuming, and having up-front information would help prioritize ROIs. Second, the increased, easy access to thermography data may help calibrate energy models. Despite this potential, two participants were simultaneously concerned that this practice may lead homeowners to focus on the wrong things (*e.g.,* replacing windows, which may not impact energy use). As summarized by P5:

> *"In the sense that thermography raises awareness, I think it's good. A key hurdle to all energy efficiency programs is people being aware. But, people may misinterpret their images and be led down the wrong path if their home is better off than it appears or if there is a better solution to problems."* (P5)

This participant also reflected that building owners who are interested in sustainability or energy efficiency are often discouraged when they learn more about the work and preparation involved in executing upgrades or renovations.

### Design Probe Findings

Overall, the first two design probes elicited positive reactions while the third, on urban-scale deployments, was viewed less favorably, primarily due to data overload concerns (similar to [34]). Across all three design probes, participants were positive about new client interactions and major concerns included appropriately placing the sensor system in residential buildings and validating the measurements.

*Design Probe 1 Findings.* Most participants (4) reacted positively to this scenario, which depicted a built-in, multi-room, continuous, home-sensing system. They described how the system would enable new services and practices, such as remote auditing, quality assurance of retrofits, pre-screening locations, and making it easier to plan daily service routes ahead of time. All thought it would encourage building owners to reach out about services to energy auditors or directly to contractors. Two participants described how clients commonly exaggerate their home maintenance practices (*e.g.,* claiming they change HVAC air filters regularly) and therefore such a system may offer more reliable data. Finally, one participant suggested that such systems may be useful in insurance claims.

All participants described concerns over the coverage areas and sensor placement. While Study 1 homeowners desired more room coverage, professionals added crawl spaces and other uncommonly accessed areas that are part of standard energy audits. Assuming good coverage, participants (3) remained concerned about system installation (*e.g.,* proximity to a combustion source could result in inaccurate air quality measurements). Finally, two participants expressed concern about the volume of data being collected and how to make it useful.

*Design Probe 2 Findings.* All participants (5) were positive about *Thermporal* and its automatically generated report. Participants were not surprised that homeowner in Study 1 were interested in indoor air quality measurements. In their experience, many clients are interested in viewing these data despite the weak ties to energy efficiency program goals. Two participants, in fact, suggested adding more sensing (*e.g.,* a carbon monoxide sensor). Additionally, participants appreciated that a thermographic scan could determine the

R-value of an exterior wall, as—again—this could help calibrate their energy models. One participant particularly liked being able to get an R-value without needing to know the wall assembly explicitly as accurate information is not always available and few homeowners are comfortable with destructive testing (*e.g.,* drilling or cutting holes). Despite the potential value of the sensor system's data, all participants also voiced concerns over data privacy and how to prevent unauthorized access to homeowners' data.

Regarding the homeowner reports, all (5) believed they them to be useful for raising awareness of issues and the impact of environmental factors (*e.g.,* humidity issues). Two participants asked about the language used to rate sensor readings (*e.g.,* low/high vs. safe/unsafe), describing how they face similar challenges in their own reporting with regard to how to avoid scaring or misleading clients. One participant discussed how the report related to a broader issue in the field: reports do not lead to action; the participant did not believe this system would resolve this issue.

Participants offered suggestions to improve and expand the system toward the goals of obtaining more accurate data and improving usability. After reviewing the example reports, two participants suggested the report should feature an "auditor view" with direct access to raw data and options to export this data. One participant suggested the system implement more automation to scaffold homeowners on how to select ROIs. The regions were too broad, and tighter selection of effected areas would improve the report's accuracy. Another participant wanted to set building codes for older buildings (*e.g.,* historical buildings) which would likely not meet current standards (the participant noted this is an issue in current, commercial software as well).

*Design Probe 3 Findings.* Three participants were negative about the third design probe, which described sensor systems like ours being deployed at an urban scale. Their primary considerations were data overload and that such an initiative would not fit into current practice. As P1 described:

> *"This is operating at a different level than I'm used to dealing with, but its more or less replicating what the system does on an individual level, so I would say you might have some of the similar challenges only magnified."* (P1)

However, two of these participants proposed that this could be helpful for policy makers. The remaining two participants were neutral, equating the probe to an eventuality of buildings having this kind of built-in sensing by default. Still, they thought new practices and procedures would be necessary to integrate such technology into their audits.

## 6 DISCUSSION

In this work we presented *Thermporal*, a temporal thermography system designed to support residential energy audits, and we evaluated it through two small, but complementary, studies with both homeowners and professional energy auditors. Our results, though early, suggest *Thermporal* aids homeowners in assessing insulation issues and could be helpful in both professional auditing and other in-home sensing applications. Here, we synthesize our findings related to the benefits and challenges of temporal thermography as well as its capacity for motivating change and improving homeowner agency. Finally, we provide design recommendations for future thermographic systems for in-home use and describe the limitations of this work.

*Benefits and Challenges.* Temporal thermography provided participants with an new means of collecting data, testing assumptions, and exploring findings related to home performance. Whereas previous studies showed novices focused mainly on problems or issues they found [35], our participants' use of temporal thermography allowed them to (i) consider and describe both negative and positive results, (ii) draw, walk back, and even reject previous conclusions or assumptions, and (iii) more clearly describe the importance of their findings. We also observed that homeowners whose reports supported their findings/assumptions or revealed a previously undetected issue increased their confidence in their ability to make assessments while those with negative or conflicting results reported decreased confidence. These actions and findings suggest that, in the case of thermography, the additional scaffolding provided by our system may have eased some of the typical issues associated with novice sensing (*e.g.,* confirmation biased) [8,45].

Auditors' views on *Thermporal* were positive and consistent with homeowners'—mostly offering suggestions for improvements and mechanisms to help integrate the system into their current activities. Temporal thermography may also begin to address their concerns about homeowners incorrectly performing DIY thermographic energy audits: a potential check on being misled by thermal imagery. Thus, with further iteration and testing thermographic systems like ours may offer less experienced or less confident practitioners (*e.g.,* [34,35]) a chance to further investigate and confirm building efficiency issues, albeit at the cost of increased setup time, data, and collection periods.

*Motivating Change.* While not all homeowners in our study found issues in their residences, those that did were reluctant to act due to the overhead involved (*e.g.,* cost, time, hassle [40]) which was unsurprising to our professional auditors. While improving awareness is a goal of both professional auditors and most energy programs [11,43,48,51], we are left questioning how to further motivate improvements. While this question is common with technological interventions within both Sustainable HCI and energy efficiency literature [4,25,40,52], it still very much an open challenge though future systems could go further in scaffolding users through the entire renovation process. Additionally, homeowners and professional auditors suggested getting data to policy makers who may be able to improve incentives programs. However, initiatives may meet reluctance given privacy concerns.

*Homeowner Agency.* Homeowners also discussed ways in which *Thermporal* improved their agency within their home. Because self-collected data tends to be more meaningful and trusted than data presented by others [12], and because they were more confident in the temporal data than individual thermograms, homeowners perceived an increased capacity to investigate and act—be it on their own or using their results to facilitate conversations with professionals. Professional energy auditors offered support for empowering homeowners to collect their own data and generate reports that could be used to initiate conversations, viewing this as supplementing to their practice rather than replacing it.

*Design Recommendations.* Several design recommendations came out of conversations with participants. All participants suggested modifications that would enable *increased coverage* to make comprehensive scans easier to conduct. Homeowners also desired *tighter integration into homes* with permanently installed sensor units continually performing analysis coupled with *alerts, notifications, and seasonal updates* about performance changes in the home. Both participant groups suggested changes to the report, such as: allowing for *spatial and temporal comparisons*, providing more *direct access to raw data*, allowing for *filtering and customization* to address privacy concerns around sharing data, and encouraging *professional-client* interactions. Finally, our professional auditors were interested in support for managing *data overload* issues and *aiding the selection of ROIs* to improve accuracy using computational methods.

*Limitations.* We acknowledge several limitations in addition to those described within the findings and discussion. *Thermporal* was calibrated for the environmental conditions expected during our deployments and more testing is required to validate the system across building conditions as poor calibration results could lead to inaccurate estimations and poor results for users. We should also note that, in addition to the limitations related to our sample sizes, all participants had a high degree of formal education. This combined with the gender skew in Study 2, which included exclusively male energy auditors (consistent with the field demographics and previous research [34]), suggests larger studies with more diverse population are warranted. Similar to [35], the mission structure may have influenced the way participants perceived their experiences and therefore unstructured use of *Thermporal* should be explored. Finally, following up with participants after 45 days may not have allowed enough time for them to act on their findings considering the costs.

## 7 CONCLUSION

In this work we presented an easy-to-deploy, temporal thermographic sensor system designed to support residential energy audits. We evaluated it through in-home, user deployments and semi-structured interviews with professional energy auditors. Our findings suggest that temporal thermography may assist homeowners with gauging the severity of issues, provide new auditor-client interactions, and improve homeowner agency. While we observed long-term benefits such as increased awareness, motivating change and maintaining user privacy require further work. Finally, we offer design recommendations to researchers and designers of future thermographic systems, tools, and applications.

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