# Understanding the Role of Thermography in Energy Auditing: Current Practices and the Potential for Automated Solutions

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**ABSTRACT**
The building sector accounts for 41% of primary energy consumption in the US, contributing an increasing portion of the country's carbon dioxide emissions. With recent sensor improvements and falling costs, auditors are increasingly using thermography—infrared (IR) cameras—to detect thermal defects and analyze building efficiency. Research in *automated* thermography has grown commensurately, aimed at reducing manual labor and improving thermal models. Though promising, we could find no prior work exploring the professional auditor's perspectives of thermography or reactions to emerging automation. To address this gap, we present results from two studies: a semi-structured interview with 10 professional energy auditors, which includes design probes of five automated thermography scenarios, and an observational case study of a residential audit. We report on common perspectives, concerns, and benefits related to thermography and summarize reactions to our automated scenarios. Our findings have implications for thermography tool designers as well as researchers working on automated solutions in robotics, computer science, and engineering.

**Author Keywords**
Energy audits; thermography; robotics; formative inquiry; design probes; Sustainable HCI; human-robotic interaction

**ACM Classification Keywords**
H.5.m. Information interfaces and presentation (*e.g.*, HCI)

## INTRODUCTION
The building sector accounts for 41% of primary energy consumption in the US, far more than any other sector, and contributes an increasing portion of total carbon dioxide emissions—40% in 2009 compared to 33% in 1980 [46]. One reason for these high emissions is building age. Residential buildings, for example, constitute 95% of all buildings in the US and are on average over 50 years old [51]. Most were constructed using energy inefficient designs and their materials have degraded over time. To address these issues, renovations and retrofits of existing building stock has become a pressing need. The US Department of Energy (DOE), for example, has set a goal of reducing housing energy use by up to 70% [37]


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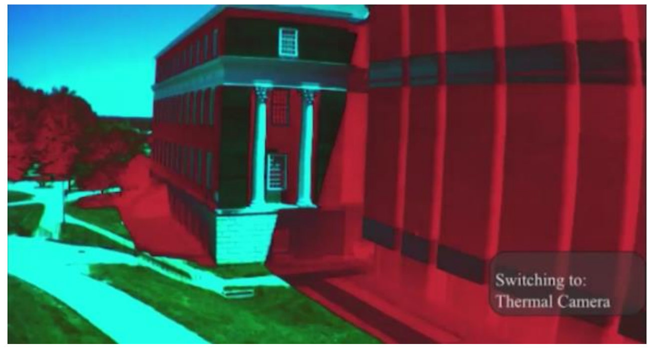


**Figure 1:** We developed five automated thermography scenarios inspired by the research literature (*e.g.*, [6,10,35,41]) to help elicit reactions to envisioned automated solutions. Above, a screen capture from our unmanned aerial vehicle (UAV) design probe. See supplementary video.

As a response, professional energy auditing has seen a resurgence of interest [25,39]. Audits help identify building inefficiencies through walk-through inspections, on-site measurements, and computer simulations [45]. The DOE recommends home energy audits because of their impact on reducing energy usage (*e.g.*, 5-30% reductions in monthly utility bills) and increasing structural safety [49]. With recent improvements in handheld sensor technology and falling costs, auditors are increasingly using thermography—infrared (IR) scanning with thermal cameras—to detect thermal defects and air leakage [2,8,28,47].

Work in *automated* thermography has also grown markedly in the past three years, encompassing disciplines from computer science and robotics to environmental and civil engineering. Researchers have primarily explored technical approaches for automatically transforming thermal images into higher fidelity 3D representations of buildings [17,20,29,31,38] and employing robots for data collection [6,10,13,30,35,41]. However, user studies of these tools have not been performed. And while some work exists on examining client reactions to thermography in general (*e.g.*, [18,25]), perceptions of thermography use from the *auditor's* perspective has received little attention. As the primary users of thermography, this perspective is important both to the design of current thermal scanners

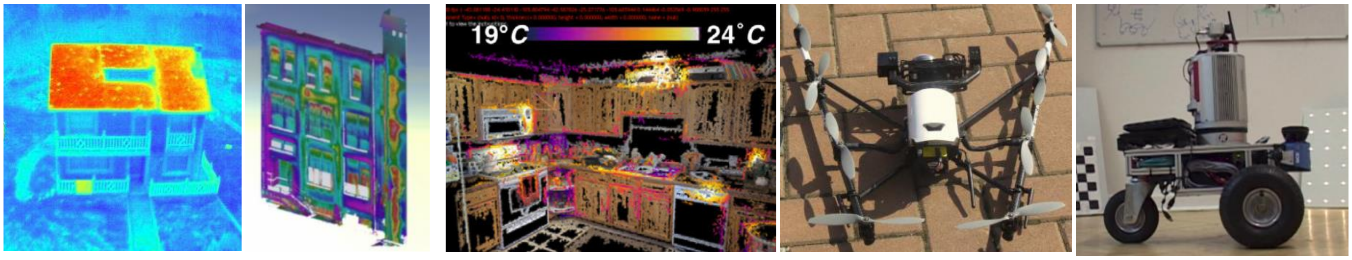

**Figure 2:** Example automated thermography from the literature: (a) UAV-based thermography [30]; (b) a textured 3D façade model [41] (c) 3D thermographic reconstruction of a kitchen [20] (d) a UAV equipped with a thermal camera [41]; (e) the Irma3D indoor thermal mapper robot [6]

and analysis software as well as to this growing area of automated thermography.

In this paper, we investigate current energy auditing practices and the role of thermography therein. We also critically assess the potential for automated thermographic methods. Our research questions include: How is thermography currently being used by auditors? What benefits and drawback do auditors identify when envisioning the use of robotics for thermographic data collection? What are the implications for the design of these automated thermography tools?

To address these questions, we conducted two studies: a semi-structured interview study with 10 professional energy auditors that included five design probes, and an observational case study of one on-site residential audit. For the design probes, we developed five scenarios of automated thermography based on the research literature—*e.g.*, indoor robotic thermography [6,10] and large-scale urban thermography using unmanned aerial vehicles (UAVs) [13,30,35,41]. The scenarios were designed to provoke and ground discussion and critically assess how automated thermography may be used in the future. The interviews provide insight into current auditing procedures, the benefits and challenges of thermography, and reactions to our design probes, while the observation helps contextualize our findings and further emphasizes the complexities of energy auditing.

Inspired by the recent call to action from within HCI [43] to better understand practical efforts towards sustainability and to question the (over)promise of purely technological solutions, this paper contributes the first human-centered investigation of thermographic automation. Our contributions include: (i) an assessment of energy auditing and thermography's role therein through semi-structured interviews and a complementary observational study; (ii) a critical examination of the potential for emerging automated thermographic solutions through the use of five custom a design probes; and (iii) a set of reflections and guidelines to help inform the design of future energy auditing and thermographic tools. As interdisciplinary work, our findings have implications not just for the design of emerging thermographic tools but also those research communities focused specifically on automated methods and human robotic interaction, which span computer science, building science, and civil engineering.

## BACKGROUND AND RELATED WORK

We describe background related to energy auditing and thermography as well as research in automated methods and links to Sustainable HCI.

### Building Energy Audits

As noted in the introduction, energy audits are becoming increasingly common. For example, recent legislation mandates building audits every 5-10 years in some cities [1]. Most energy audit programs extend from a physical-technical-economic model (PTEM) of energy consumption [23]; the dynamics of human behavior are not typically incorporated [24]. Residential audits are administered by utilities or government contractors and involve a range of evaluations from blower door tests[1] [48] to thermography [47]. This data is entered into software tools and processed by computational models to predict the effects of potential retrofits. Finally, client-facing reports are produced with efficiency recommendations.

Studies of energy auditing focus largely on potential environmental benefits [3] and/or on the building owner perspective [23,24]. For example, in a large-scale study of homeowner experiences, Ingle *et al.* [25] found that physical face-to-face discussion with auditors was critically important *("the most informative part of the whole process"*, p. 13) and that the use of infrared thermography was "particularly compelling" because it made invisible energy flows and leakage problems more tangible (p. 16). This latter point seems crucial. In an experimental study of 87 homes, Goodhew *et al.* [18] found that those households who saw thermal imagery from their audits were nearly five times more likely to install retrofits. Thus, thermography is not just a measurement approach but a way of communicating findings to clients.

Studies of the auditors themselves are much rarer. One exception is a recent study by Palmer *et al.* [39], who surveyed 459 auditors and explored common audit practices, shared challenges, and the degree to which homeowners took action on efficiency recommendations. Though thermography was not their primary focus, they found that 63% of auditors surveyed used infrared imaging "fairly often" or "always" (the primary impediment was equipment cost). Our studies offer a complementary

[1] A blower door is a powerful fan mounted on an exterior door that lowers indoor air pressure causing outside air to flow through unsealed cracks and openings; these air leaks appear as salient streaks with the infrared camera [48]

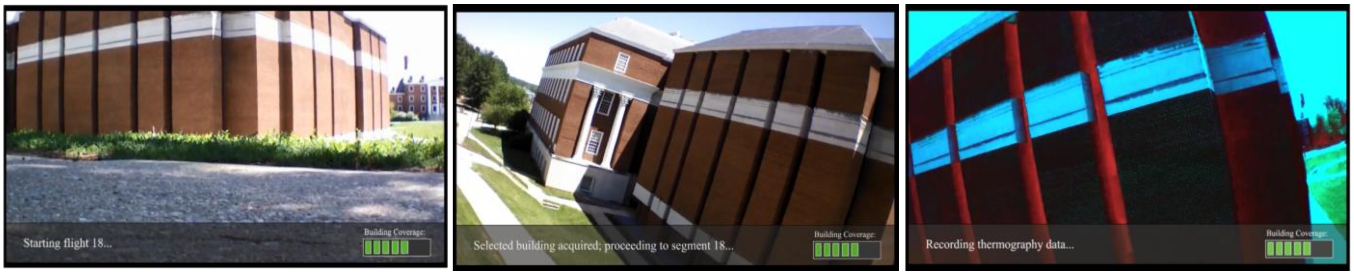


**Figure 3:** Screen captures from the UAV-based thermography video design probe (Scenario 4). See supplementary materials for full video.

*qualitative* perspective along with a specific emphasis on thermography and emerging automated solutions.

### Thermography Use
Energy auditors use thermography to measure surface temperatures of walls, roofs, ceilings, floors, and other parts of a building's envelope to detect heat loss, air leakage, moisture buildup, and to locate hidden infrastructure (*e.g.*, water pipes) [8,28]. Before surveying, the thermographer must assess environmental conditions such as weather, wind, HVAC operations, and direction/intensity of the sun—all of which can affect or prevent proper scans. For example, the ISO standard requires a minimum temperature differential of 10° C between the interior and exterior to properly detect thermal irregularities [26,50]. In addition, to increase air flow between the building envelope and the outdoors, blower door tests are commonly used in conjunction with thermography [47,48]. While the DOE recommends thermographic-based energy audits [47], criticisms include that it remains a qualitative method subject to the expertise of the auditor and lacks special software tools, algorithms, and audit guidelines [50].

### Automating Thermography
Recent automated thermography efforts have focused on two areas (Figure 2): transforming thermal images into 3D-reconstructions of buildings (*e.g.*, [17,20,29,31,38]) and employing robots and vehicles to scale up data collection (*e.g.*, [6,10,13,30,34,35,41]). Researchers argue that traditional 2D thermal images: (i) do not include geometry and spatial relationships, which are important for interpreting thermography [20,29]; (ii) are unordered, messy, and difficult to organize [17,20]; (iii) and require time-consuming and labor intensive post-hoc analysis [17,20,38]. Thermographic 3D reconstruction is cast as a solution to these problems and as a means of enabling better modeling that should reduce auditor error and subjectivity [17,29].

Typically, the 3D-models are built either by computational photography methods—*e.g.*, structure-from-motion (SFM) [17,20,35]—or through the use of precise range scanners such as LiDAR, which are texture-mapped with thermal images [31,36,38]. Both require large amounts of data. Thus, researchers are increasingly using robots for data collection, including ground-based rovers for indoor thermography (*e.g.*, [6,10]) and UAVs for outdoor thermography (*e.g.*,[13,30,35,41]). The robots are equipped with a suite of sensors such as thermal and optical cameras, laser scanners, and GPS. These "massive data acquisition" systems [30] are described as advantageous because they reduce manual labor, can survey otherwise inaccessible areas of buildings (*e.g.*, high floors, rooftops), and collect more precise data. They can also enable or facilitate new types of analyses (*e.g.*, surveying and comparing thermal performance from large numbers of buildings [34]).

Given the technical complexity of this work, most research thus far focused on technology evaluations (*e.g.*, accuracy of geometric models [20]) rather than user studies. Indeed, we could find no prior work that explored the auditor perspective of these emergent methods, that attempted to elicit user feedback to early models/designs, or that tried to demonstrate that 3D reconstructions enabled auditors to better detect building defects or energy inefficiencies compared with their 2D counterparts. In this paper, we begin to address these gaps.

### Sustainable HCI
Since its emergence at CHI in 2007 [5], sustainability HCI research has matured and evolved. Although much of the early work focused on persuasive technology aimed at promoting environmentally sustainable behaviors (*e.g.*, see reviews [14,16]), more recent work has called for and explored a broadened scope including politics [15], socioeconomics [11,12], energy infrastructure [42], and sociological perspectives [9,44]. Researchers have also reflected on the tension between HCI—typically a design- and innovation-oriented discipline—and research where findings may imply non-technology solutions (*e.g.*, the implication is *not* to design [4,40]). As formative work, our research shares similar aims to other qualitative Sustainable HCI studies (*e.g.*, [12,19,52]), that is, to understand current practices in an area and identify what role HCI may play.

Finally, we take inspiration from two recent "call to action" articles [33,43] that outline limitations of Sustainable HCI and articulate paths forward, such as the need to draw from and study work outside of HCI, to pursue practical as well as fanciful research, and to address broader topics. We provide the first HCI-based examination of the everyday practices and views of energy auditors and the potential disconnects between the technology-driven research in automated thermography and the complexities, nuances, and practical demands of performing audits in the field.

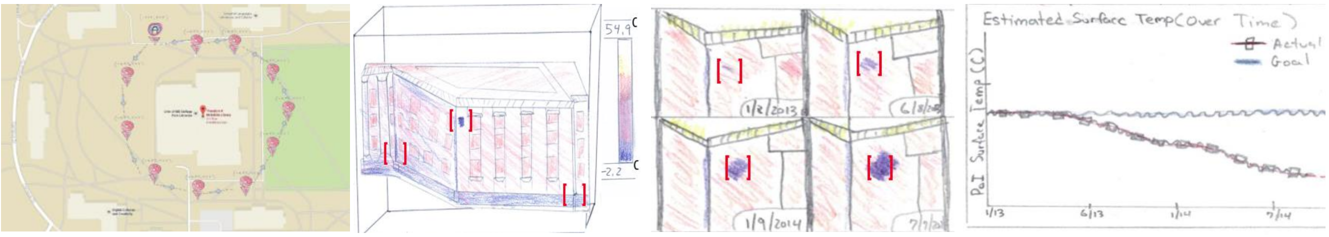


**Figure 4:** Screen excerpts from our interactive mid-fidelity prototype built in Axure. (a) Users input a rough thermography route for the UAV. (b) The analysis software automatically identifies anomalous thermal signatures (red brackets) on a 3D-reconstruction. (c) The auditor can zoom in and see how this area of the building has changed over time (every few months). (d) A co-located temporal graph of the estimated surface temperature is also provided.

## STUDY 1: INTERVIEW STUDY AND DESIGN PROBES

To investigate the role of thermography in energy auditing and to elicit feedback about emerging automated methods, we conducted a two-part study with 10 professional auditors: a semi-structured interview and design probes.

### Automated Thermography Design Probes

The design probes included five scenarios using three different mediums: (i) three written narrative scenarios (~150 words) of increasing complexity that described thermographic 3D reconstruction and robotic data collection, (ii) a short video mockup of a UAV performing a thermal audit, and (iii) an interactive medium-fidelity prototype demonstrating how automation control and analysis software of a thermographic UAV may work in the future. Each probe was inspired by recent work in automated thermography and was designed to provoke discussion, ground conversation, and elicit feedback. The probes used 2nd-person narration to help our participants envision the scenarios. The full probes are included in our supplementary materials and summarized below.

**Scenario 1 (Text): Residential Audit.** The first text probe described a residential audit using a UAV.

*As you arrive at a home, meet with the client, and assess the home's interior, a UAV collects exterior thermographic data and builds a 3D thermal model of the building in real-time. You investigate the 3D model (all building sides and the roof) via an interactive application on your tablet/smartphone. You can also browse anomalous thermal signatures, which can be shared with your client. The UAV automatically returns to a docking station on your vehicle after completing its scans.*

**Scenario 2 (Text): Automated Audit of a Large Campus.** The second probe positioned the participant as a facilities manager at a large campus site such as a university or government facility with many buildings.

*You are responsible for a small fleet of thermography UAVs. The UAVs fly around semi-autonomously collecting thermal data about each building on your campus. When abnormalities are detected, the UAVs are programmed to more closely examine these areas and provide high resolution reports of potential problems. The UAVs reduce labor costs compared with manual assessments, can investigate otherwise inaccessible areas of buildings (e.g., high exterior floors), and enable historical reports showing thermal performance over time.*

**Scenario 3 (Text): Large-scale Urban Audit.** The final text probe had the participant work as a government employee in charge of analyzing the energy efficiency of a large urban center with skyscrapers, office buildings, and other structures.

*You have real-time access to utility usage for each building as well as indoor and outdoor thermographic robots. The ground-based robots are permanently deployed at the larger buildings (e.g., skyscrapers) and communicate with the UAVs to provide interior/exterior thermal scans. As with Scenario 2, the UAVs function semi-autonomously and special software compares utility usage with thermal data over time.*

**Scenario 4 (Video): UAV-based Thermography.** The ~41 second video probe showed a semi-autonomous UAV collecting thermographic data of a campus building and performing real-time analysis. We created the video using a Parrot AR Drone 2.0 UAV, which is equipped with a 720p 30fps optical video camera. *Adobe After Effects* was used to create the robot's interface and to apply a "thermal filter" to the video stream (Figures 1 and 3).

**Scenario 5 (Medium-Fidelity Prototype): UAV Control and Analysis Interface.** For the final probe, we presented a medium-fidelity interactive software prototype that scaffolded the participant through the process of establishing a new survey project, including: scheduling a semi-autonomous UAV data collection flight and analyzing the collected data both spatially and temporally. This analysis procedure included: automated generation of a 3D model with a thermal overlay, an overview of interactive features, an automated point-of-interest analysis, and a comparison of historical data. The prototype was created in Axure using a combination of hand-drawn sketches and built-in widgets (Figure 4). For consistency, a research assistant operated the prototype for all participants.

In summary, the probes depicted a range of automated thermography scenarios, which varied in technological complexity, autonomy, and scope. Each scenario emphasized at least one new data collection approach along with some new analysis not currently possible with handheld IR cameras (*e.g.*, the ability to see thermal signatures change over long periods of time).

### Method

#### *Participants*

We recruited ten professional energy auditors (8 current, 2 former; 1 female) through email lists, word-of-mouth, and social media from across the US. Our recruitment materials

| ID | Employer | Audit Expr. (Yrs) | Age | Gender | Thermography Training |
|---|---|---|---|---|---|
| P1 | Former | 1 | 25 | Male | Training Course |
| P2 | Private | 20 | 61 | Male | Level 3 |
| P3 | Former | 6 | 30 | Male | College Course |
| P4 | Private | 11 | 57 | Male | Level 2 |
| P5 | Private | 6 | 41 | Male | Level 2 |
| P6 | Private | 7 | 51 | Male | Level 1 |
| P7 | Government | 2 | 36 | Female | None |
| P8 | Private | 4 | 64 | Male | Level 2 |
| P9 | Private | 3 | 30 | Male | None |
| P10 | Government | 7 | 53 | Male | Training Course |

**Table 1:** Study 1 participant (professional auditor) demographics.

specified that participants needed professional experience using thermal cameras for building energy audits. Our participants ranged in age ($M$=44.8 years old*;* $SD$=14.2*)*, audit experience ($M$=6.7 years; $SD$=5.5), and location—six states were represented in total (Table 1). All participants reported the same number of years performing energy audits as performing thermography with the exception of P6 (7 years energy auditing, 4 with thermography). For thermography training, five participants received certification training through professional organizations (*e.g.,* Infrared Training Center, The Snell Group, and similar organizations), two participants received on-the-job training through a company sponsored program, and one had taken a college course. Two reported no official training. To enable geographic diversity, half the interviews were conducted remotely via Skype with screen sharing to view the design probes. For the co-located interviews, participants read printouts of the text scenarios and used a researcher's laptop for the video and mid-fi prototype.

### *Procedure*

Each session lasted an average of 93 minutes ($SD$=19.47) and included a background questionnaire, semi-structured interview, and design probes. The semi-structured approach allowed us to dynamically pursue themes we had not identified *a priori*. All participants were asked a similar set of questions, but new topics emerged in accordance with a participant's background, skills, and experience. The design probes immediately followed the interviews. Participants were asked to "think aloud" and evaluate each scenario. The researcher provided guidance at the start of the video and throughout the mid-fi prototype. Our objective was to identify aspects of the probe that participants were interested in and uncover concerns. At the completion of the session, participants were compensated $20.

### *Data and Analysis*

The sessions were audio recorded, transcribed, and coded for themes of interest. As exploratory work, we pursued an iterative analysis approach using a mixture of inductive and deductive codes [7,22]. We created two codebooks—one for each part of the study—which initially derived from the research literature, our study protocol, and post-interview discussions amongst the research team. The unit of analysis was an answer (or stream of answers) for a specific topic in Part One and a full reaction to each probe in Part Two. Our iterative coding approach was similar for both.

*Part One Analysis.* Codes included: views on thermography (*e.g.,* misconceptions, procedures, automation), impact (*e.g.,* uses, benefits, findings), and challenges (*e.g.,* application, clients, interpretation). A random transcript was selected and coded by two researchers. To calculate inter-rater reliability (IRR), we used Krippendorff's alpha (*$\alpha$=0.64; SD=0.43; total disagreements=7* out of 120 decisions). Krippendorff's [27] suggests that scores below alpha < 0.667 be discarded or recoded. In our case, 4 of the 10 codes were < 0.667. The two researchers met, resolved all 7 disagreements, and updated the codebook accordingly. Both researchers then independently coded a second random interview, establishing IRR ($\alpha$=0.85, $SD$=0.24). Finally, the first researcher coded the remaining interviews.

*Part Two Analysis.* For Part Two, we started with 11 codes including: types of use (*e.g.,* traditional thermography, alternative applications), interests (*e.g.,* automation, data, features), concerns (*e.g.,* technical feasibility, data quality) and reactions to scenarios (*e.g.,* positive, neutral, and negative). IRR was established after two iterations (final *$\alpha$=0.80; SD=0.27*). However, the neutral reaction code was difficult to reach agreement on and was removed before the 2nd code pass. Again, disagreements were resolved through consensus. The remaining eight probe transcripts were coded by a single researcher.

## Findings

We present frequent patterns and emergent themes.

### *Part One: Existing Practices*

We summarize five themes related to the current practices, concerns, and desires of thermography practitioners. Though our interviews asked about general auditing practices, our focus here is on thermography.

**Required Knowledge.** Our participants highlighted the expertise needed to assess thermographic data, including: an understanding of building materials and construction (6 participants), an understanding of the physics of heat and airflow (5), applied training and experience (4), and an awareness of environmental conditions (3). As P2 states: *"the thing that is absolutely the most critical is to understand how heat behaves and interacts with different materials."* Participants emphasized that simply pointing a thermal camera at a structure was insufficient: *"you have to keep the environment in mind or else you're going to make a judgment call and it's going to be wrong" (P7).*

**Thermography Benefits.** Despite the admitted complexity, all participants (10) expressed that thermography provided at least some benefit to the audit process. Reaffirming prior work (*e.g.,* [18,25]), 7 participants thought that thermography was useful as a communication tool for interacting with clients: *e.g.,* P1 reflected, *"how do you explain convective heat flow? If you have an image you can go and look… sometimes it's tough in words."* In addition, as a form of non-destructive testing, thermal cameras allow auditors to assess areas that are hidden or difficult to access.

P10 gave a poignant example from an audit where he had trouble believing a client's complaint:

> *"But we gave her the camera, [and] she went right into the bedroom ...directly over her bed between the two ceiling joists was about a four foot strip with no insulation."*

Participants also found thermography useful as a diagnostic (6) or verification tool (5). For example, P6 said, "*I use [thermography] as a screening tool to then target the areas that you want to focus on.*" For verification, thermography was used to confirm a suspicion or to check that a retrofit (*e.g.*, new insulation) was completed correctly. P7 stated, *"…you can survey large areas very quickly and… it should help you target areas to further investigate.*"

**Client Interactions.** Participants emphasized that an energy audit is a social process as much as it is a technical one. Most participants felt that client interactions were crucial to a successful audit (9), including information gathering at the audit's onset, understanding client perceptions and motivations, and establishing trust. Some clients were wary that auditors were attempting to sell them retrofit materials. This attitude, P5 conjectured, *"...stems from people selling [thermography] as a silver bullet. You've got people that say it can do more than it does."* To overcome these issues, energy auditors strategically include the client in the audit process, asking residents to identify problems with them:

> *"...give the customer the thermal camera. And have them look around, and have them say 'oh my look at that', 'what's that', which is very engaging and opens them up to a discussion about the dynamic of what's happening in the house, or the wall, or the attic."* (P10).

In terms of client motivations for scheduling an audit, comfort was the most frequently mentioned. Cost savings and environmental concern were also mentioned, though less common (*e.g.*, P8 recalled only one household who was concerned with their "*carbon footprint*" over 4 years).

**Thermography Challenges.** All participants expressed concerns about thermography, including the difficulty of interpretation (8), untrained or undereducated practitioners (7), and equipment sensitivity (6). Interpretation was viewed as difficult because of the influence of confounding factors such as weather, shading, nearby buildings, and building materials. Given these complexities, thermography was characterized as a highly *subjective* process (similar to [50]), as captured by P2:

> *"The reality is that you can have three guys with the same camera, looking at the same thing, and have three totally different reports" (P2).*

Weather could also be frustrating because of the required interior-to-exterior temperature differential: *"unless there's a really big temperature swing you're not going to see much with the thermal camera" (P1).* However, high end equipment has the potential to mitigate some weather conditions, as stated by P5: *"if you've got the right camera the time of year [or day] really doesn't matter."* While having adequate equipment is important, participants emphasized that having a better camera only helps to a degree; it will not make practitioners better interpreters.

**Desire for Automation.** Before moving into the design probes (so as to limit bias), we asked our participants how they might automate an energy audit with or without thermography. Eight participants expressed interest in automation including: data collection (6), assessment (5), and report generation (2). For data collection, participants mentioned thermal cameras mounted to cars that survey neighborhoods quickly to identify locations with "*visual thermal patterns that may be indicative of energy issues*" (P4). Similarly, P10 suggested a thermographic overlay in Google Earth that would allow inspection of entire areas and identify "*building stock that is inefficient.*"

For automating assessment, three participants mentioned 3D reconstruction, two mentioned better energy models or simulations, and two mentioned reducing or eliminating subjectivity. For example, P9 thought a dream tool would be a thermography report that "*could interface with a 3D model of the [audited] home.*" P4 thought automation should eliminate subjectivity: *"make it independent of the auditor… my interpretation should not be different from yours."* For report automation, participants mentioned efficiency and reducing the tedium of manual preparation, P6 states: *"The biggest problem in dealing with the volume of work is creating reports."* Still, some participants expressed concerns with automation, such as P2, *"how do you get the software to understand what the [auditor] otherwise understands*."

**Part One Summary.** Our findings reaffirm and extend past explorations of energy audits (*e.g.*, [18,25,39]). Thermal tools should be designed both for expert users (the auditors) and for client interactions. In terms of automation, our participants were most interested in automating data collection and assessment followed by report generation. However, these automated solutions should remain visually oriented to facilitate client interactions and will need to address the same challenges that manual approaches have to overcome (*e.g.*, establishing temperature differentials).

### *Part Two: Design Probes*

We first summarize overall reactions to our probes before describing common themes, suggestions, and concerns.

**Overall Reactions.** Our design probes elicited mixed reactions. Though most (9) reacted positively to the mid-fi prototype (Scenario 5) and to the multi-building and urban scenarios (Scenarios 2 and 3), only 2 participants found value in the UAV-based residential audit (Scenario 1) and reactions were equally split to the video (Scenario 4). P5 reacted negatively to all scenarios, feeling that it would be hard to acquire *"actionable data"* and expressing concerns for data quality: *"doing an exterior flyby is not going to be a replacement for an actual audit of a building."* He was most positive about automating interior scans.

*Scenario 1.* Most participants (7) reacted negatively to the UAV-based residential audit, expressing doubt that meaningful data could be acquired from exterior scans without, for example, blower door tests as well as concerns for cost and data overload. For the two participants that reacted positively, they mentioned its ability to examine inaccessible places, save time, and generate 3D models.

*Scenario 2.* In contrast, 9 participants reacted positively to the UAV-based multi-building scenario, largely because of opportunities such as tracking degradation over time and examining inaccessible areas and equipment (*e.g.,* HVAC). Still, participants expressed concerns about cost and the need for the system to have more information on building materials and construction for proper analysis.

*Scenario 3.* Similar to Scenario 2, most participants (9) were positive about the large-scale urban monitoring system, including the connections between thermography and utility data, the automatic anomaly detection, and "push" notifications. Participants also mentioned that this system could be used to check on LEED certified buildings that are supposed to be performing efficiently. Primary concerns included handling reflective surfaces and the "heat island effect" (where built structures like pavement cause increased ambient temperatures).

*Scenario 4.* Half of the participants (5) reacted positively to the video probe of a UAV surveying a campus building. Identified benefits included the ability to reach inaccessible areas ("*terrific for large buildings,"* P6), and as a tool for performing rapid preliminary investigations. Concerns included feasibility, the need for more information than is available from an exterior thermal scan, and the autonomy of the UAV (how it was controlled).

*Scenario 5.* Finally, most participants (9) reacted positively to the mid-fi prototype, citing its ability to provide geometrical (3D) model data, historical analysis, and automation scheduling. Participants suggested that the software tool should incorporate energy analysis from metering, information about building construction, and combined interior/exterior views.

Below, we briefly describe the key benefits and concerns identified across the five scenarios.

**Automated Data Collection.** Most participants (9) agreed that there was the potential to save time and money with automated data collection "*You can get the UAV to film a whole side of the building at once and then you can zoom in on the sections you want to see."* (P8). However, there was general recognition that simply performing thermography was not sufficient—more data was necessary such as utility usage, weather, and information on building materials. Still, most participants thought UAV-based or other automated methods would be sufficient for preliminary analysis—though P5 thought it would create too many false positives.

**Historical Analysis.** Most participants (9) mentioned the benefits of historical analysis, which are really only feasible via automated data collection due to labor/time costs. As P7 highlights: *"…If you said, 'Hey, for four months, we've had this. Let's look and see how it could be fixed.' I like that idea."* Typically, thermal scans do not include temporality (*i.e.,* the ability to look back in time and observe changes).

**Model Generation.** A majority of participants (6) saw value in automatically generating 3D building models with accurate geometry because it increases the utility of the collected data, enables faster analysis, and the resulting geometry could be exported into other tools:

> *"You spend a lot of time building this model, just measuring the outside of the house, counting the windows and the doors, and looking around. Then, you take that data load it into your modeling program… this would streamline that" (P10).*

**Automatic Anomaly Detection.** While most participants (8) accepted the "anomaly detection" in our scenarios without comment, 2 provided critical feedback related to the complications of filtering out noise, removing false positives, and the difficulty of interpreting the data:

> *"How do you get rid of the noise and have actionable data so that you save labor? …I think you're going to expend a vast amount of labor in chasing down false positives" (P5).*

**Data Quality.** Half (5) of our participants raised concerns about data quality including the feasibility of using automated exterior scans to acquire useful thermal data across environmental conditions (*e.g.,* weather, sun direction). P8 questioned whether exterior scans could yield meaningful data at all:

> *"I don't see this as being very useful at this point primarily because the use that I've been able to make of [external] thermography is limited." (P8)*

**Data Overload.** Three participants expressed concerns about data overload: *"I don't see the value at this initial moment …there's some new generation tools but it's still just too much data*" (P6). Others thought the 3D reconstructions would allow for better organization of the data leading to better interpretations.

**Feasibility.** Feasibility concerns included technological viability, robustness, and cost. Robustness and maintenance costs were potential barriers to adoption: "*I don't know that many fiscal managers would be able to justify the system"* (*P3*). Additionally, some participants (4) raised concerns about the need to have control over the environment because, *"you have to set up a pressure difference to be able to identify air infiltration…a UAV can't do that" (P1)*.

**Fear and Privacy.** Though only mentioned by three participants, there was reasonable concern about how robotic thermography may frighten people or impinge on privacy: "*If [people are] in the building, they'd feel a little bit frightened"* (P3). P7 mentioned that UAVs may collect unintentional data: "*though you're focused on your clients' residence, you're going to get some of the neighbors"* (P7).

**Part Two Summary.** Our findings highlight important concerns with automated solutions described in the literature but which have previously not been discussed or acknowledged such as issues of data quality, data overload, technical feasibility, privacy, and problems of overreliance on automated exterior scans. Still, participants were positive with the general idea of automation especially 3D reconstruction, historical/temporal analysis, anomaly detection, and the potential for time savings.

## STUDY 2: OBSERVATIONAL CASE STUDY

To contextualize our Study 1 findings we conducted an observational case study of a residential energy audit.

### Method

We recruited a senior energy auditor from the Maryland Energy Administration's list of certified practitioners. The participant was male, age 50 and had 5 years of energy auditing experience Informal thermography training was provided by his employer. For the observation, the auditor selected an appointment he considered a *"typical audit"* and received client permission for our presence. The audit took place in a mid-sized home and lasted ~100 minutes. One researcher shadowed the auditor, taking field notes and photographs. Due to weather conditions, thermography was *not* used; however, the auditor spoke to the researcher about how/why he would ordinarily use thermography. Following the audit, the participant completed a 30-minute debrief and was compensated $20. We thematically analyzed field notes from the observation and debrief session [7] looking for patterns that confirmed, extended, or differed from Study 1.

### Findings

We present our observational findings around three areas: procedure, using thermography, and challenges.

**Audit Procedure.** The auditor said that he generally spends 2 hours in the field, plus 4-5 hours for report generation and follow-up confirming Study 1's finding that *report generation* is effortful and time consuming. The audit procedure included meeting the client, establishing rapport, and determining reasons for the audit. The client joined the auditor for an initial walkthrough, which the auditor later explained was critical to enhancing client understanding and buy-in. During the walkthrough, the auditor took pictures of areas of interest and performed both a combustion test (*e.g.*, checking appliances) and a blower door test. Here, the auditor indicated he would normally use his thermal camera. Finally, the auditor met with the client to explain findings and suggested changes explained in terms of cost savings. The next day, the auditor created and sent his report to the client using in-house software.

**Thermography.** Though thermography was not used, the auditor did not think thermography would have altered his overall efficiency recommendations to his client. He described using thermography for confirmation, client communication, and to help work crews perform retrofits. Again, the visual nature of thermography was key to "*help[ing] explain complex things*." He described a client base motivated by utility bills: "*Many people expect the bill to be wrong, not to have an issue in the home*." The thermographic images helped overcome that misconception.

**Primary Challenges.** The auditor described two technical challenges: establishing proper conditions for thermography and the effort required to generate a report.

## DISCUSSION

As the first qualitative, human-centered inquiry into both conventional and emerging thermographic processes and tools, our findings help reveal challenges, highlight energy audits as a social-technical process, and inform future work. Below, we reflect on our findings, provide design considerations, and discuss limitations and future work.

### Conventional Thermography

Auditors were generally positive about the role of thermography in energy auditing, particularly as a communication and diagnostic tool—but stressed that it required skill and expertise to use. Here, we focus on three aspects of conventional thermography that have implications for design and future research.

*Social Process*. As in [25], energy auditing was portrayed as a social process as much as a technical one. Auditors emphasized the importance of understanding their client's needs and reasons for a home assessment, gaining trust and credibility, and being able to explain identified problems and their implications. To help establish trust and communicate findings, auditors allowed clients to operate their thermal cameras. This "role reversal" places increased emphasis on the thermal camera while deemphasizing the interpretative role of the auditor. In this way, the thermal camera becomes a sort of "inscription device" [32] that translates the complex or the contested into material fact but potentially obscures the full complexities of the instrument, the techniques required for proper use, and the skills necessary for interpretation. To support this social process and role reversal, how can future tools be designed to accommodate both expert and novice users (clients)? How can tools better support auditor-client interaction, both in real-time during the audit as well as post-hoc in the report generation process?

*Subjectivity*. Though thermography relies on sophisticated technology, the interpretation of its output is fundamentally subjective. Our participants desired greater objectivity in how to apply and interpret thermography but barriers included a lack of universal standards, varying levels of training in the auditing community, poor guidelines, and the inherent complexity of the task (echoing [50]). Participants with higher levels of training in our study (Level 2 or 3) felt that they had superior interpretative skills than those without. However, more work is needed to study how training and experience affects interpretation, how interpretations vary across thermographers for the same audit site (extending [21]), how these differences manifest in energy efficiency recommendations, and how tools can be better designed to aid analysis and reduce subjectivity.

*Ethical Concerns.* Subjectivity is also a concern in a transactional context where thermography is used not only to identify problems but also to make a sale. As noted in our findings, some clients are skeptical of auditor motives, particularly when the auditor works for a home improvement company (as 3 did in our study). In these cases, auditors may consciously or unconsciously be biased in their interpretations. If future thermographic tools can reduce subjectivity, ethical concerns may be mitigated.

### Automated Thermography

Our five design probes allowed us to explore thermographer reactions to various automation scenarios, including indoor and outdoor robotic data collection, 3D reconstruction, automatic anomaly detection, and advanced temporal analyses. We discuss challenges, privacy and policy implications, and a call-to-action.

*Challenges.* Though 9 of 10 participants reacted positively to one or more design probe(s), our findings surfaced important concerns regarding data quality, data overload, fear and privacy, and technical feasibility—none of which have been studied in the automation literature. For automated data collection, in particular, our auditors were concerned with the lack of environmental control compared with manual audits (*e.g.*, to establish pressure differentials), how to manage this large amount of data, and general data quality issues (*e.g.*, filtering). However, most were interested in how this “big data” may transform and enable new analyses (*e.g.*, historical comparisons). For 3D reconstructions, our auditors noted that thermal data alone, though useful, is insufficient—better models would include information about building materials, weather conditions during the scan, utility data, and even occupant behaviors.

*Privacy and Policy.* Though mentioned by only a few participants, the use of remote, automated data collection has privacy and policy implications. For example, if buildings can easily be scanned at scale, how may this change the way governments assess and regulate building energy efficiency and/or award and monitor “green” certifications (*e.g.*, LEED)? New business models are emerging (*e.g.*,[34]) based on automated thermography that sell exterior scan data and analyses to utility companies to help determine which houses “leak the most energy” and target energy-efficiency programs. Because exterior thermal scans can be performed remotely (*e.g.*, from the street or air), should a building’s thermal profile be considered public data? Can building owners opt-out of scans?

*Moving Forward.* As a pursuit framed purely as a technical challenge, the automation literature has been, unsurprisingly, focused on engineering. However, our findings further highlight thermography as a socio-technical problem where the interplay between auditor, client, and thermal camera plays a crucial role (*e.g.*, in building trust, communicating results). Future automation work should consider existing thermographic practices and engage in human-centered design with both auditors and clients to improve and validate their tools. As others have argued, the Sustainable HCI community needs to be more engaged in these emerging areas, especially those that are not necessarily consumer-facing. Thermography is a growing area that will likely become more popular as governmental institutions increasingly recommend thermographic-based energy audits and thermal devices become more prevalent (even as smartphone attachments[2] and low-cost sensors[3]).

### Limitations

There are four primary limitations to this work. First, we interviewed professional energy auditors who specialize in residential buildings. Reported practices and reactions to the design probes may differ from those of commercial and industrial energy auditors. Second, our design probes primarily emphasized UAV-based exterior data collection, anomaly detection, historical analysis, and 3D reconstruction. Future work should more closely examine other parts of the automation pipeline (*e.g.*, indoor robotic, data collection, report generation). Third, our study method relied on self-report from semi-structured interviews, complemented by a single observation of an energy audit (without thermography). More thorough and longer-term ethnographic fieldwork of energy auditors may yield new insights. Finally, we acknowledge the potential dichotomy in asking professional auditors about scenarios that could be perceived as replacing or undercutting their jobs; however, none commented on feeling supplanted. Instead, auditors expressed interest in automation because of its potential to increase their efficiency, enable new types of analyses, improve building models/simulations, and allow for greater coverage (*e.g.*, entire neighborhoods).

## CONCLUSIONS

This paper contributes the first human-centered investigation of thermographic automation. Through semi-structured interviews and a complementary observational case study, we assessed energy auditing practices and thermography’s role therein. Through five design probes, we critically examined emerging automated thermographic solutions and identified important challenges/concerns. Our findings have implications not just for the design of emerging thermographic tools but also for researchers focused on automation and human robotic interaction.

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[3] FLiR Dev Kit: https://www.sparkfun.com/products/13233

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