Exploring the Use of Thermal Imagery for the Promotion of Residential Energy Efficiency

Report prepared for the City of Vancouver
June 2016

Anne-Mareike Chu[1], Lisa Westerhoff[1], Stephen Sheppard[1], Stefan Storey[1]
Julie Goodhew[2], Matthew Fox[3], Steve Goodhew[3], Sabine Pahl[2]

[1] Collaborative for Advanced Landscape Planning, University of British Columbia
[2] School of Psychology, Plymouth University UK
[3] School of Architecture, Design and Environment, Plymouth University, UK

Executive Summary

Background

Fifty-five percent of greenhouse gas (GHG) emissions in the City of Vancouver come from buildings. To address this major source of climate-warming emissions, the City set a target to reduce HG emissions from existing buildings in the city by 20% from 2007 levels by 2020. One of the intended actions to achieve energy retrofits of existing buildings is to test the effectiveness of thermal imaging at the neighbourhood scale to identify poorly insulated homes and promote energy retrofits. January 2016, the City of Vancouver issued a request for proposal (RFP) to explore the potential of thermal imaging to encourage energy efficiency upgrades in single-family homes.

Summary

To inform this project, the City of Vancouver partnered with the University of British Columbia to identify best practices communication and engagement with homeowners on large-scale thermal imaging and relevant research on thermal imaging. This report is the result of a joint effort between the University of British Columbia and Plymouth University (UK) intended to provide the City of Vancouver with an overview and recommendations on the use of thermal imaging for energy efficiency retrofits. It summarizes current knowledge on large-scale thermal imaging approaches that can promote the uptake of energy efficiency measures amongst homeowners.

The report provides an overview of existing energy efficiency incentive programs available to homeowners in British Columbia (BC), as the backdrop to potential thermal imaging, followed by a discussion of their effectiveness and key challenges. In Section 2, thermal imaging (TI) technologies and their application are presented, including a review of the psychological dimensions of thermal imaging as tools for homeowner engagement. A number of studies from Plymouth University are used demonstrate the utility of thermal images in promoting the uptake of energy efficiency measures. The results of the research suggest that the provision of personalized thermal images that encourage viewers to connect their behaviours to the images, and promote an increase in retrofit activities.

In Section 3, we present an evaluation of the benefits and limitations of different TI types to encourage homeowners in undertaking energy upgrades and renovations of their homes (Section 3). Examples from North America and Europe are used to identify best practices and key achievements of thermal imaging projects at multiple scales, with a focus on large-scale urban projects. Two methods for large-scale thermal imaging are reviewed (aerial and pass-by thermography), using several case studies to illustrate the application of large-scale thermal imaging and its effectiveness.

Together, this research suggests that the use of large-scale TI approaches can be effective in encouraging energy efficiency retrofit as a result of the many dimensions that they offer, including:

- Access to several thousand homeowners through large-scale imaging;
- Highly practical and intuitive information on areas of energy loss;

- The ability to communicate abstract information on energy use and heat losses in a clear and understandable format; and
- A compelling image that invokes a personal connection to an intimately experienced home environment and that can be revisited and shared.

However, large-scale TI projects have also shown the significant limitations of both aerial and pass-by projects in identifying building deficiencies and allowing opportunities for direct homeowner engagement. Our analysis suggests that thermal images taken of building interiors through small-scale TI projects suffer from fewer technical limitations and result in a rich set of images that are more compelling for engagement compared to images of the external façade only.

Section 4 provides a review of smaller scale case studies in Canada and the UK that further point to the strength of coupling the use of TI technologies with volunteer-led neighbourhood engagement processes that draw on partnerships with local government and businesses. These community-based initiatives allow for a diversity of values and views to be drawn together into a program that can successfully initiate a higher percentage of retrofit activities across a localized neighbourhood.

Finally, Section 5 demonstrates that the deficiencies of the large-scale TI approaches can be mitigated, or complimented, by coupling them with the advantages of smaller-scale walk-through TI sessions. This coupled 'hybrid' approach can ensure that TI projects can benefit from a more detailed and accurate picture of sources and solutions to residential heat losses, as well as the opportunity for homeowners to interact with and receive direct and personalized advice from home energy auditors and other experts. Where both of these efforts are combined with opportunities for community-based interaction and engagement, improved uptake rates of project components and outcomes can be achieved.

Recommendations

Based on these findings, our recommendation for the City of Vancouver is to make use of a combined hybrid, or multi-facetted approach, to TI in order to increase the uptake of energy efficiency retrofits in single-family residences (Section 6). Our specific recommendations build on the City's existing request for a large-scale thermal imaging project as a Part A, with the additional recommendation of supplementary approaches to engagement in Part B and C in order to test a small range of additional programs and incentives:

Part A: Target Engagement to focuses on the identification of a subsection of Vancouver homes with a high retrofit potential is recommended as a first step to effectively engaging Vancouver residents. This recommendation builds upon the City of Vancouver's existing RFP by outlining the following additional considerations:

1. Prime Vancouver communities for the upcoming thermal imaging project through the use of mass and local media several months prior to the intervention.

2. Conduct a large-scale thermal imaging scan using a pass-by technology and evaluating thermal images using demographic and building-specific data in order to identify approximately 2,000 homes with the highest retrofit potential.

3. Segment the targeted homes based on findings and engage homeowners using targeted letters to raise awareness of energy upgrade potential.

4. Provide specific contact information in personalized letters, alongside follow-up options for further explorations.

5. Use an online database of thermal images and building specific data from the larger scan to continue targeting homes for specific outstanding energy upgrades over time.

Part B: Deepen Engagement to ensure that homeowners targeted in Part A will take actions to pursue energy upgrades through the following steps:

1. Incentivize uptake and to create a differentiated test population; to offer free and/or discounted energy audits with walk-through thermal imaging to a smaller number of homeowners on a timed basis.

2. Host and promote a competition between blocks and/or homes with the highest energy retrofit savings can be hosted and promoted to increase the total amount of energy savings. To help promote uptake, free energy audits may also be offered to a small number of buildings with high retrofit potential.

3. Consider city-wide subsidies for the first round of TI energy audits and/or a free follow-up thermal imaging visit following energy retrofits, as a way of allowing homeowners to see improvements and areas that still require attention.

Part C: Broaden Engagement to foster awareness of energy efficiency issues and opportunities in homes across the city. To do so, the following outreach activities should be taken both before and in parallel with Part A and B:

1. Combine large-scale thermal imaging outreach with block/neighbourhood-scale approaches through the use of:

    a. Information booths at block/neighbourhood events;
    b. Demonstration events of thermal imaging technologies at block/ neighbourhood/public places;
    c. Online forums that allow homeowners to report energy data and encourage neighbourhood competitions;
    d. Neighbourhood efficiency competitions that are promoted/awarded and that acknowledge energy efficiency achievements; and
    e. Local news coverage to widen public awareness of TI programs and results.

2. Build capacity and support for the use of thermal imaging techniques through:

    a. Training for local Fire Departments or other organizations;
    b. Support for volunteer-led thermal imaging surveys;
    c. The inclusion of thermal imaging into other mandatory inspections;
    d. Partnerships with energy advisors, businesses and non-profit organizations;
    e. Assistance for negotiations between community groups and utility companies or businesses; and
    f. Connections with NGOs, cultural and civic groups, and regional governments.

In preparation for the above 3-part project, we recommend the City of Vancouver to conduct the following **pilot projects** several months before the interventions:

1. Presentations and discussion of targeted engagement strategies (Part A) with selected citizen groups; and
2. Set up of convener experiments with selected citizen groups to test the alternative engagement strategies (Part B and C) and to obtain feedback and information about potential uptake and costs.

More broadly, research and practice in incentive programs highlight the importance of fostering consistent long-term approaches that encourage and motivate homeowners to reach their full potential in energy savings and GHG emission reductions. As part of a longer-term approach, cross-marketing mechanisms are needed that ensure that homeowners are aware and have access to the range of energy upgrades applicable to their home. This requires industry partners to be informed about energy incentive programs and strategies, as well as about retrofit potentials for the existing building stock. Therefore, we recommend developing a comprehensive database of homes that is based on publicly available information (such as data from *EnerGuide Rating System*) to serve as a cross-marketing platform for policy makers and industry partners in order to develop more targeted engagement strategies.

Table of Contents

1 Introduction

In the 2012 Greenest City Action Plan (GCAP), the City of Vancouver set a target to reduce GHG emissions by a total of 33% below 2007 levels by 2020. As 55% of GHG emissions in Vancouver come from buildings, the GCAP sets a specific target of a 20% reduction in emissions from existing buildings in the city.[1] Under the GCAP, several actions have already been undertaken with respect to energy and the built environment, including updates to retrofit requirement options in the Building Bylaw to improve energy efficiency and GHG emissions in new and existing buildings, and the launch of Green Condominium, Green Landlord, and Home Energy Efficiency Empowerment programs. Achieving the 20% target is projected to prevent the release of 160,000 tonnes of GHG per year into the atmosphere, or the equivalent of removing 40,000 cars from the road.[2]

While several of these programs seek to connect home and condominium owners with resources and incentives to undertake retrofit activities, further outreach strategies are required to reach and motivate a broader proportion of the City's population.[3] In 2014, the City Council approved the Energy Retrofit for Existing Buildings Strategy to help meet the GHG reduction targets over the next six years. Among the actions outlined in the strategy is the direction to "partner with BC Hydro and/or FortisBC to research and pilot the effectiveness of using neighbourhood scale thermal imaging (TI) to identify poorly insulated homes and to promote home energy retrofit opportunities".[4]

In response, the City of Vancouver issued a request for proposals (RFP) in January 2016 to explore the potential of thermal imaging to encourage energy efficiency upgrades in single-family homes. The pilot's aim is to perform thermal scans of 12,000-15,000 residential homes in in 3-4 selected neighbourhoods. Thermal images produced from the pilot are intended to function as engagement and communication tools for approximately 2,000-3,000 homes to encourage homeowners to pursue energy upgrades, with the end goal of 300-400 renovated homes. To assist in identifying potential engagement strategies, the City partnered with the University of British Columbia (UBC) to research best practice approaches in using thermal images in communication and engagement with homeowners and explore the relative benefits of different thermal imaging (TI) techniques.

This report summarizes the findings of research conducted by the Collaborative for Advanced Landscape Planning (CALP) in collaboration with researchers from the Plymouth University in the UK, an academic research group with established experience in techno-social research on thermal imaging. The team reviewed published literature (both peer reviewed and grey) on large-scale thermal imaging projects in North America and Europe to explore methods and uptake

---

[1] City of Vancouver 2014

[2] City of Vancouver 2014

[3] City of Vancouver 2016

[4] City Action 11, City of Vancouver 2014

rates of different thermal imaging programs. Different types of thermal images (i.e. aerial, pass-by, and walk-through) approaches were evaluated for their effectiveness in engaging homeowners to undertake energy upgrades. The effectiveness of the strategies (e.g. letters, personal contact, incentives, etc.) was determined using information on homeowner commitments to or completions of renovations/energy upgrades to their homes and altering social practices to conserve energy/reduce carbon emissions from homes.

The review was complemented with an in-depth survey of 27 thermal imaging projects in the UK, where thermal imaging has been extensively used as an engagement strategy. Project leads were contacted via e-mail or telephone, and where available and willing, were interviewed by researchers from Plymouth University on the following ten dimensions: 1) the size/area of the project; 2) the scale of the thermal imaging used; 3) project objectives; 4) the rationale for the thermal imaging methodology; 5) incentives used; 6) level of community involvement; 7) engagement strategies; 8) level of uptake; 9) long term effects, and; 10) lessons learned (summarized results in Supplemental Documents B & C).

This report begins with an overview of existing energy efficiency incentive programs available to homeowners in British Columbia (BC), as the backdrop to the potential of thermal imaging, followed by a discussion of their effectiveness and key challenges. Thermal imaging (TI) technologies and their application are presented, including a review of the psychological dimensions of thermal imaging as a tool for homeowner engagement. We draw on examples from North America and Europe to identify best practices and key achievements of thermal imaging projects at multiple scales, with a focus on large-scale urban projects. The report identifies the benefits and limitations of different types of thermal imaging to encourage homeowners in undertaking energy upgrades and renovations of their homes, and concludes with some recommendations for the City of Vancouver.

1.1 Incentive Programs for Energy Efficiency in British Columbia

Energy retrofitting is the process through which a building's energy-consuming systems, from light fixtures to furnaces, are upgraded or improved to reduce the total amount of energy they consume. These upgrades create a number of benefits, from reductions in GHG emissions, to improvements in operational efficiencies, lower energy bills for building managers and consumers, and improved comfort and health to building occupants. Retrofit activities can range from minor upgrades, such as sealing windows and doors with caulking to reduce air leakages, to deeper retrofits that can see the replacement of roofs or the large portions of a building's heating, cooling and/or ventilation systems.

Of the many possible approaches to energy retrofitting, addressing inefficiencies in space heating is particularly important, as it accounts for a considerable portion of total household energy demand. In 2008, space heating in typical Canadian homes accounted for 63% of the country's total residential annual energy consumption.[5] Building inefficiencies – gaps in wall insulation, for example – can furthermore account for as much as half of the total heating consumed in a building,[6] making the identification and remediation of sources of building heat loss a highly useful way of reducing building energy consumption.

In general, government support for homeowner retrofits has taken one of two approaches. The most common form of support is the provision of information on energy conservation and savings opportunities and their specific benefits to individual homeowners, often in the form of flyers or emails that contain lists of resources and statistics designed to influence consumer choices and behaviours. The kinds of "energy behaviours" that are targeted by such programs can include both *purchase* behaviours (one-time investments in more efficient appliances or building envelope upgrades), as well as *maintenance* behaviours (occasional activities that improve energy efficiency through e.g. switching to higher efficiency light bulbs).

A second and often complementary approach is to provide financial incentives to homeowners who undertake retrofits to offset the cost of upgrading their building envelope or heating and cooling systems. In BC, energy efficiency incentive programs are administered by provincial utilities. BC Hydro's Power Smart program offers information on behaviours to reduce energy use, sources of high efficiency products and technologies, and rebates for insulation upgrades, draft proofing, and improvements to heating and ventilation systems. These incentive programs offer up to $1200 for upgrading insulation, $500 for draft proofing, $88 for improving home heating systems, and $50 for improvements to ventilation systems. The program does not stand alone, but is linked to others in the utility's portfolio – in 2011, nearly 300,000 BC homes had already signed up for 'Team Power Smart', which offers rebates to households who cut their overall consumption by 10%. FortisBC similarly offers rebates for high efficiency natural gas water heaters and fireplaces, which are coupled with a number of other program streams for domestic hot water and space heating conservation. In 2014, FortisBC estimated a reduction in annual natural gas consumption of over 94,000 GJ across the 860,000 households covered by the programs. In the same year, BC Hydro and FortisBC launched Home Energy Rebate Offer (HERO) incentive program for specific building improvements that ran until March 2016.

1.2 Alternative Approaches to Incentivizing Retrofits

Despite these programs, homeowners are not easy to engage and the potential for encouraging retrofit action remains largely untapped. To gain insight into the uptake rates and limitations of current BC incentives programs, City Green Solutions provided the City of Vancouver with an evaluation of single-family homes that participated in the EnerGuide Rating System (ERS). The study found that between February 2007 and February 2015, over 7,900 single-family homes in Vancouver received ERS energy evaluations and completed more than 18,000 home energy and

[5] NRCAN OOEE Handbook Residential Sector, undated

[6] Fox et al., 2010

GHG reduction improvements, realizing over 22,009 tonnes of reduced GHG emissions and an average of 25% energy reductions per home.[7]

However, the study revealed that relatively few energy efficiency upgrades were undertaken in the single-family homes that participated in energy incentive programs. Programs of longer durations led to higher number of energy upgrades per home than shorter incentive programs. Short-term programs created challenges for the building industry to develop business and invest in broader marketing and staff capacity. The study also found that cross marketing between industries and word of mouth to stimulate consumer uptake were limited, particularly for rebate programs that focused on single services. This resulted often in singular energy upgrades, but did not motivate homeowners to reach their full energy saving and GHG reduction potential. Deep home energy upgrades often seemed to require additional time and financial resources than were budgeted for or offered through the available incentive programs.

Based on these findings, City Green Solutions recommended municipalities such as the City of Vancouver to develop a long-term, systematic approach to engaging and motivating home energy upgrades.[8] One suggested approach was to introduce municipality-wide ``GHG Reduction Incentives`` in order to re-engage homeowners to meet the energy targets of the City of Vancouver. More broadly, research has also shown that a lack of engagement in retrofit activities or other forms of energy conservation cannot be exclusively attributed to lack of adequate funding.[9] While fiscal rewards are certainly important to catalyzing retrofit activities,[10] research in the social science has shown the need to include these into a broader array of program components in order to be successful. Culturally-determined standards of what is comfortable or convenient, as well as the attitudes, values, and norms that shape our decisions, are often critical deciding factors in how and whether we engage in activities such as energy retrofitting.[11] Providing incentives and information – even if such information highlights opportunities for homeowners to save energy and money – is therefore often insufficient in stimulating a decision to retrofit one's home. Studies that have explored residential energy use reduction programs have identified a number of program characteristics that, when coupled with financial incentives, improve the success of higher levels of engagement. These include:

- The use of a broad mix of approaches that engage customers in multiple ways (e.g. financial, emotional, social);
- Market segmentation that effectively targets incentives and other program elements to the demographics most likely to participate;

---

[7] City Green Solutions 2015

[8] City Green Solutions 2015

[9] Munasinghe and Swart 2005, Pacala and Socolow 2004

[10] Hoicka et al 2014

[11] Bamberg, 2003, Kaiser and Fuehrer, 2003, Crompton and Kasser 2009, Kollmuss and Agyeman 2002, Stern 2000; Shove 2003

- Simple programs that involve the fewest possible mental or physical steps and/or disturbances to routines;
- Programs that engage homeowners directly to ensure that project outcomes are aligned with personal preferences and practices;
- Programs that are partnered with or administered by trusted local organizations; and
- Programs that rely on word of mouth and other community-based, attention-grabbing marketing techniques.[12]

Despite these findings, however, most residential energy efficiency programs rely on top-down methods of motivating homeowners and use financial incentives, communicated through conventional methods of information dissemination. They additionally focus on voluntary participation by individual households, rather than collective approaches that emphasize community-wide transitions and underlying shifts in local social norms.

2 Thermal Imaging: Applications & Limitations

These limitations illustrate the important need and opportunity to broaden and accelerate the uptake of retrofitting initiatives by using more compelling techniques and comprehensive processes for engaging Vancouver's citizens. One such opportunity lies in the use of powerful visual tools that engage and trigger a deeper understanding of retrofit needs and opportunities.[13] Thermal imaging represents a form of non-invasive, or "non-destructive testing" that allows for a detailed exploration of a building's structure, materials and/or components without any damage or destruction (e.g. opening up walls) to the envelope, while providing a real-time image of leakages and radiant heat emitted from homes. Thermographic cameras have been used for decades to pinpoint areas of moisture and damaged mechanical or electrical components in commercial buildings, but have more recently been introduced as a motivational tool to communicate with and engage householders and promote the uptake of residential energy efficiency retrofits. Thermal imaging provides a clear and specific picture of energy loss that can help to target retrofit actions and motivate both building improvements and changes in habitual behaviours. At broad city or neighbourhood scales, thermal images can also provide utilities and municipalities with data that can be used to target demand-side management (DSM) programs more effectively. The following sections provide an overview of the range of thermal imaging applications and their limitations.

2.1 Using Thermal Imaging for Building Investigations

Building thermography is typically used to detect radiant heat emitted from an object. Thermal cameras convert this radiation into an image, in which colour variations between each pixel

[12] Stern et al 1985; Gardner and Stern 2009; Stern, 2000; Gardner and Stern, 2009; Parker et al 2003; Fuller et al 2010; Egmond et al 2006; van der Linden et al 2015; Hoicka et al 2014; Mallaband et al 2013; Salter 2010; Nickerson, 2002; McKenzie-Mohr and Smith 1999; Sheppard et al 2015.

[13] Slovic, 2007; Bamberg and Moser, 2007; Stern, 2000; Burch et al, 2010; Sheppard et al., 2011; Shaw et al, 2009; Cohen et al 2012; Pahl et al., 2016

portray temperature differentials between warmer and cooler surfaces (Figure 1a). Trained thermal imaging professionals, or "thermographers", use thermal images to identify and interpret heat loss through one of two ways.

A *quantitative analysis* of radiation values is used for the more specific determination of rates of heat loss from a structure.[14] Great care is needed for such quantitative analysis, since accurate heat loss measurements require close to steady-state conditions, which are almost impossible to continuously achieve (Pearson, 2011). Schwoegler (2011) also raises caution over quantitative analysis for thermography thermal transmittance measurements, explaining that there are too many environmental variables that could lead to misleading results. In contrast, a *qualitative analysis* involves a review of the colour patterns present in an image to discern differences in thermal radiation by comparing colour differences between similar targets.[15] Qualitative forms of analysis are typically used to diagnose and detect potential building defects, including the following main four types of defects:

Conduction heat loss. While all building components experience some degree of heat loss, it is the *amount* of heat loss over time that indicates the thermal conductivity of a material. Using known measures of conduction, areas of missing or damaged insulation, as well as areas of "thermal bridging" can be detected (Figure 1b). This "bridging" effect occurs in instances where structural components provide a more conductive path between the interior and exterior of a building, creating a pathway for heat to escape more easily. The identification of unwanted areas of high conductivity in a building can help to minimize condensation and mould growth, which are more likely to occur in these areas.[16]

Ventilation heat loss. Often experienced as drafts, ventilation heat loss tends to occur around gaps and cracks in a building's envelope. Junctions between components such as doors and windows are a common source of unwanted air leakage. Infiltration losses can account for over half of a building's total energy use, and they can reduce building occupants' thermal comfort and create problems of condensation and mould (Figure 1c).[17]

Moisture-related defects. As noted above, condensation can be a by-product of other building envelope defects; however, other forms of moisture-related issues can also present problems (Figure 2d). *Moisture ingress* occurs when water penetrates the building fabric from the outside, either through capillary action or gradual sorption, or penetration. The amount of moisture in

---

[14] Madding (2008) and Fokaides & Kalogirou (2011); Great care is needed for such quantitative analysis, since accurate heat loss measurements require close to steady-state conditions, which are almost impossible to continuously achieve (Pearson, 2011). Schwoegler (2011) also raises caution over quantitative analysis for thermography thermal transmittance measurements, explaining that there are too many environmental variables, which could lead to misleading results.

[15] ITC, 2006; Beard, 2007

[16] Hart, 1991; Titman, 2001; Jeong et al., 2007; Snell & Spring, 2008

[17] Nowicki, 2004; Armstrong, 2008; Brooks, 2007; Kalamees, 2007

building materials impacts a building's thermal performance as it can result in an increase in thermal conductivity and evaporative cooling.[18]

Structural defects. Thermography can also be used to detect cracks and/or thermal expansion in building materials, structural failures, and material "delamination", in which materials made up of several layers begin to separate. However, some studies have shown that while delamination can be detectable using thermography, they should be further inspected using other forms of analysis.[19]

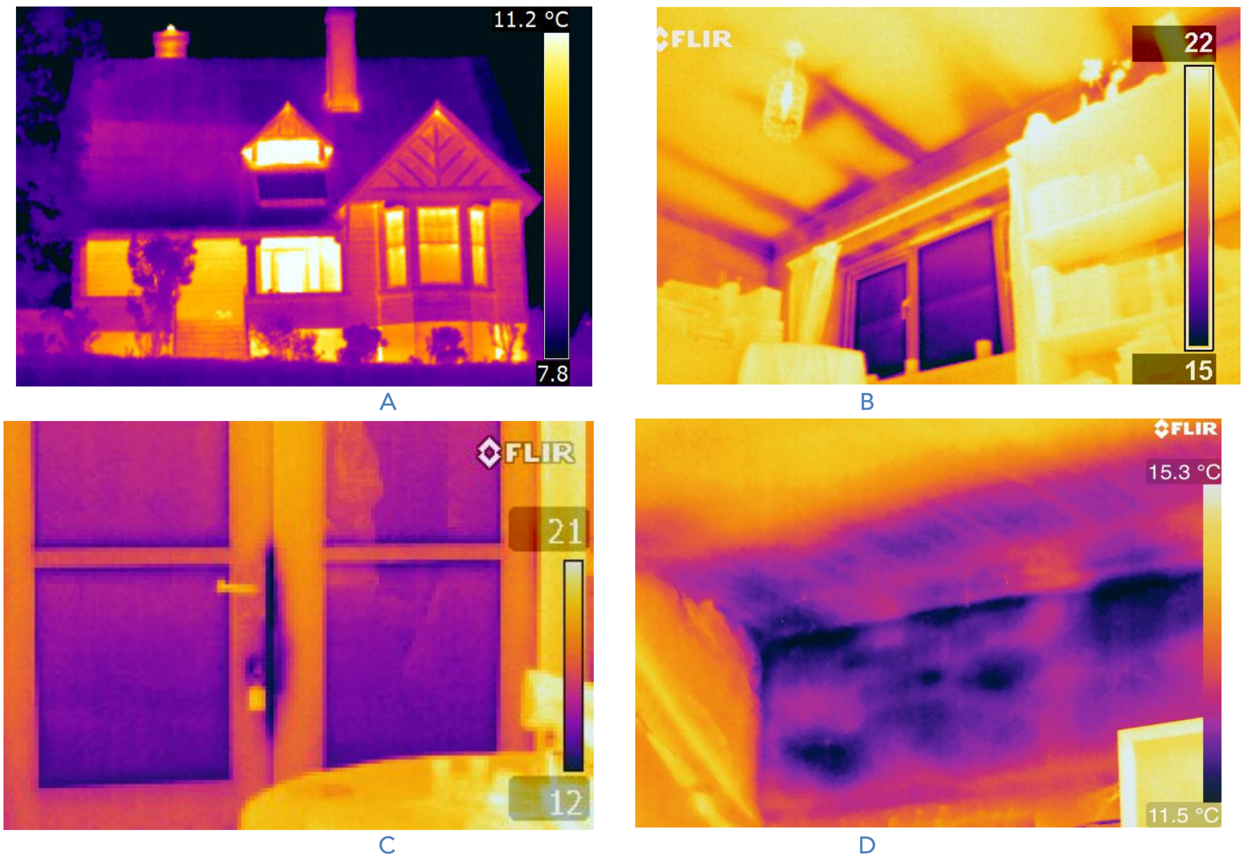


Figure 1: a) Thermal image of exterior front of a house in Vancouver (City of Vancouver); b) An example of conduction heat loss and thermal bridging; c) An example of ventilation heat loss from the interior of the home; d) An example of moisture ingress.

In Figure 1 above, the apparent surface temperature of the house is shown by the temperature scale to the right within each image. In image C, for example, yellow/white areas indicate a surface temperature of about 19 to 20 degree Celsius, while the blue/black areas of the image indicate colder temperatures of 12 to 14 degree Celsius. By comparing these varying temperatures around the image, it is possible to identify cold air ingress in between the doors,

---

[18] Vollmer & Möllmann, 2010) and material degradation (Avdelidis, Moropoulou & Theoulakis, 2003; BRE, 1997

[19] Clark, McCann & Forde (2003), NIBS, 2012

and infer that by weather proofing (e.g. sealing the gap), comfort in that part of the home can be improved and energy costs reduced.

2.1.1 Limitations to Building Thermography

It is important to note that building thermography is influenced by a number of factors that can limit the accuracy of thermal image interpretation. Key limitations that should be carefully considered during all inspections include emissivity variances, climatic conditions and operator expertise.[20] The status of the heating system is also an important influence on the final images as is occupant behaviour. In general, three major limitations to TI can be noted:

Emissivity variances. Emissivity is a property that relates to a material's ability to emit radiation in comparison to a known benchmark (or "blackbody"), and is measured on a scale between 0 and 1. Materials with *high* emissivity levels (i.e. closer to 1) will be viewed by a thermal camera as emitting most of their radiation value (rather than reflecting or transmitting), and will present a more accurate temperature value than for materials with *low* emissivity levels (closer to zero). Surface finish, geometry, angle of measurement, temperature and wavelength can all dictate a material's emissivity, and can cause variations in readings that might not be expected.[21] For example, non-metallic materials such as paints, stone and concrete have a fairly high emissivity and are suited to practical thermography applications. However, metals and polished metals in particular often have very low emissivity values causing inaccurate estimations of surface temperatures and introducing surface reflections. Such variations in emissivity can lead to misinterpretations, which might be mistaken as potential building defects.

Thermographers therefore need to be mindful of the potential for other radiative sources to be reflecting off the target surface and back to the camera, and how to mitigate the effects of reflections. Sources of reflected radiation might include other buildings, vegetation, the sky, and people (including the camera operator). External thermography is at greater risk from emissivity misinterpretations than internal inspections due to reflections from the sun and sky.[22] While understanding and setting the emissivity value within the thermal camera is essential for quantitative analysis, some have recommended the need to understand the impact of variances in surface emissivities for qualitative analysis as the effects from reflections can impact on pattern recognition. [23]

Climatic conditions. All building thermography inspections will be influenced in some way by the climatic conditions (i.e. weather) at the time of image recording. Again, while some internal climatic conditions can impact thermal imaging, external thermography is particularly susceptible to such variations. Thermographers should therefore adhere to certain standards of practice:

---

[20] ASHRAE 2009

[21] Vollmer & Mӧllmann, 2010; Hart, 1991

[22] Marinetti & Cesaratto 2012

[23] Maldague, 2001b; Vollmer & Mӧllmann, 2010; Hart, 1991; Marinetti & Cesaratto (2012); Moropoulou & Avdelidis (2001

- **Ensure minimum temperature difference across a construction.** To ensure that the flow of heat through a construction is sufficient enough to present a discernible signal using thermography, the internal to external air temperature difference throughout the survey needs to be at least 10 degree Celsius. To help achieve this, surveys are typically conducted during the 'cold season' (winter months) and at night/early morning, when domestic heating systems are more likely to be in operation.

- **Avoid solar loading.** During the day, the sun gradually warms up parts of a building. Once the sun sets, this heat will slowly dissipate. The effects of this slow dissipation can mask defects or mislead interpretation and needs to be considered. As a result, researchers have suggested that surveys should be conducted during cloud-covered conditions, and/or that building facades should have no solar exposure for at least 12 hours prior to a survey.

- **Avoid night sky radiant cooling.** Whereas the sun will warm a building during the day, a clear sky at night can emit temperatures in the region of -50 degrees Celsius. This low temperature can reflect off surfaces and impact on image interpretation. This has led some to conclude that thermographic surveys should only be conducted under cloudy night sky conditions.

- **Avoid the effects of moisture.** Atmospheric sources of moisture such as precipitation and humidity can attenuate the emitted radiation between a target and the camera, which can seriously impact image interpretation. Moisture can also impact upon material properties (via increased conduction, for example). To reduce these errors, thermal imaging during wet or damp conditions should be avoided.

- **Avoid windy conditions.** High air movement across an object will hasten heat loss due to a reduction in the surface boundary layer. Wind will also increase heat loss over damp surfaces through increased evaporative cooling. Thermal imaging should therefore take place during wind speeds of no more than 10m/s.[24]

It is important to stress that these limitations mainly apply to external thermography. Meeting these criteria can be challenging, as conditions will constantly change due to atmospheric circulation. With an absence of steady state conditions, attention to the effects that transient weather conditions can have on image interpretation is essential for qualitative analysis and makes accurate quantitative analysis using external thermography impractical.

---

[24] Lo & Choi, 2004; see also Maldague, 2001a; Holst (2000); Snell & Spring, 2008; Hart (1991); (Pearson, 2011; Möllmann, Pinno & Vollmer (2008); Balaras & Argiriou, 2002; Walker, 2004; Balaras & Argiriou, 2002; Vollmer & Möllmann, 2010; Pearson 2002; Asdrubali, Baldinelli & Bianchi, 2011; Gonçalves, Gendron & Colantonio (2007); Schatzmann & Leitl, 2011;

Image Interpretation. While the operation of a thermal camera is relatively easy, image interpretation is dependent on operator knowledge and expertise. This relates to all forms of thermal imaging that is taken through drive-by, aerial and walk-through methodologies. Where emissivity or climatic variances impact upon thermal properties and/or thermal images, for example, an unskilled thermographer might provide a false interpretation. Interviews with professional thermographers have found that, along with thermal sensitivity, image interpretation was the most challenging aspect to thermal imaging.[25] Results from thermographic inspections should be followed up with other inspection methods before major retrofits are undertaken.

Additionally, operators need to be able to tune a thermal camera in order to best portray a potential thermal anomaly, including accurate focus and composition. To improve operator interpretation, it is crucial that all thermographers are suitably qualified. Building thermographers should also have a deep understanding of building construction, defects and thermal physics. However, short-term training and thermal imaging under the supervision of a qualified thermographer might be suitable in certain contexts (see Supplemental Document A).[26]

Other limitations, such as the specification of thermal cameras with regards to spatial resolution (the smallest target that can be detected by the camera) and thermal sensitivity (the smallest temperature difference that can be detected by the camera) also exist, but by using high specification thermal cameras, this limitation can be mitigated.

2.2 The Potential for Thermal Imaging to Promote the Uptake of Energy Retrofits

Despite their potential limitations in technical precision, thermal imaging nevertheless presents an attractive opportunity to identify and address building envelope deficiencies and promote energy efficiency upgrades. While building users may feel warm or cold, they are unable to see heat escape or cold enter their home directly. They also have difficulty pinpointing problem areas within their home, or knowledge of how to address them. Such issues create a common disconnect between individual homeowners, the energy used to heat their home, and the program in place to assist them in reducing it.

Herein lies the utility of thermal imagery. A key step in changing behaviour is encouraging the active attention to energy issues. Psychology literature suggests that the visual nature of thermal images is important in motivating viewers to action. Thermal images *render invisible heat visible*, thereby presenting visual evidence of areas of heat loss and potential efficiency gains. Heat loss issues can be *easily communicated*, and the consequence of energy efficiency actions imagined. Thermal (and other) visualizations *communicate complex messages quickly and powerfully*, and can enable more fundamental learning about the physics of the energy system. There is a tendency to overlook the highly practical, household-specific skills or 'know-how' that people

[25] Mauriello, Norooz & Froehlich 2015

[26] Eads, Epperly & Snell, 2000; Snell & Spring, 2008; Stockton, 2007; Boomsma et al., 2016

need in order to reduce their heat consumption[26]. Viewing thermal images can aid the acquisition of energy 'know-how', as homeowners and other household members are often able to connect their decisions and behaviours to heat loss.[27]

Aside from attention and interest, visual images are strongly related to emotions – we respond quickly and viscerally to visual images as compared to the same information in textual form. In particular, vivid colours in images (red to blue spectrum) have been found to promote an increased emotional response compared to black and white representations. Images can more easily become internalized as mental images, which are more readily remembered and in turn connected to increased motivation and the formation of goals (see Figure 2). Overall, the use of visual imagery has been found to be useful in attracting attention, evoking emotions, facilitating recollection, and triggering the formation of energy reduction goals.[28] Thermal imaging can therefore be a powerful tool in motivating homeowners to undertake energy retrofits.

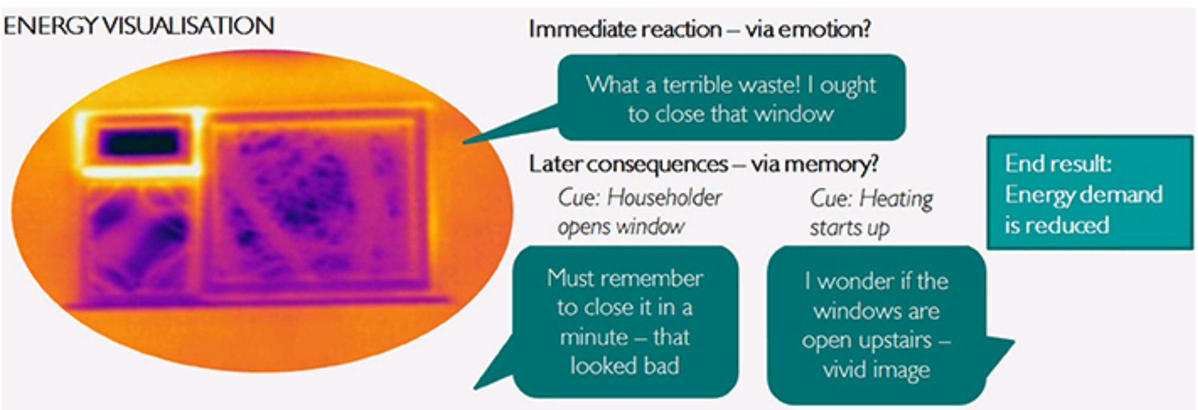


Figure 2: The psychological process from energy visualisation to behaviour (Pahl et al. 2016)

3 Large-scale Approaches to Thermal Imaging

Two primary methodologies for large-scale thermography have been used to undertake mass thermography projects: *aerial* and *pass-by*, each with a different approach to thermal image capture. While aerial thermography uses aircraft (e.g. satellite, airplane, helicopter or drone) to obtain thermal images of building roofs, pass-by thermography enables the building elevation to be imaged as a thermographer 'passes-by' on foot or by vehicle.

Both methodologies have been devised in order to lower the cost and time scales involved with conducting a single walk-through thermographic survey. Walk-through thermography is the common method by which commercial thermographic inspections are undertaken on buildings.[29]

---

[27] Fox et al., 2015; Pearson, 2011; Sheppard, 2001, 2005; Midden et al., 2007; Giacomin and Bertola (2012); Gardner & Stern, 2002; Page & Page, 2011

[28] Holmes & Matthews, 2010; Giacomin & Bertola, 2012; Andrade et al. 2012; Smith &Shaffer, 2000; Pahl, Goodhew, Boomsma & Sheppard, 2016

[29] Fox et al., 2014

While one in-depth walk-through survey can take considerable time (between 30 and 150 minutes) to complete, a single pass-by thermography inspection can take as little as 15 minutes, with single aerial thermography inspections taking even less time.[30] From a cost perspective, pass-by thermography can be up to 4½ times less expensive than a walk-through inspection; however, the resulting images provide less in-depth information.[31]

3.1 Aerial Thermography

Aerial thermography has been around for a number of years, with research documented as far back as the late 1970s and early 1980s. During this time, thermal cameras were increasingly used in building inspections following the 1973 energy crisis.[32] Areas in which aerial thermography have been commonly and successfully applied include roof moisture surveys on large flat roof buildings, and district heating inspections (e.g. the identification of defects in piping). In the latter case, defects are captured via heat transfer through to the surface of the ground.[33] Other methodologies for mass-scale inspections using aerial thermography include satellite infrared thermography; however, the spatial resolution in this use has been proven to be ineffectual at discerning detail and therefore inadequate in allowing a meaningful analysis.[34] Unmanned aerial vehicle (UAV)/drone mounted thermography is also being explored on a research and development basis, but the application of UAV equipment is heavily regulated, making this application impractical at present.

3.1.1 Aerial TI as Engagement: Examples from the UK

There are also several examples in which aerial thermal imaging has been used for large-scale energy assessments of buildings to evaluate residential heat loss and to encourage homeowners to undertake energy-efficiency measures. One of the earliest of these large-scale thermal imaging projects took place in 2001 in Aberdeen, Scotland, in which Aberdeen City Council piloted a city-wide aerial thermal imaging survey to "inform its fuel poverty[35] strategy, direct home energy efficiency assistance and to engage homeowners directly with the thermal inefficiency of their homes" (see Supplemental Document B).[36] Thermal images were made available via an online mapping tool that showed the heat loss of the surveyed building roofs via a colour spectrum, and allowed owners to search their home by postcode and street name on the resultant 'heat map'. According to the Council, this encouraged 'many' homeowners and

---

[30] Smale, 2014; Phan, 2012

[31] Miller & Singh 2015

[32] Artis & Carnahan, 1982; Brown, Cihlar & Teillet, 1981; Chang & Galowin, 1985; Schott, Biegel & Wilkinson, 1983; Treado & Burch, 1982; Maldague, 2001

[33] Stockton, 2013; Friman et al., 2014

[34] Baldinelli *et al.* 2015

[35] Fuel poverty describes a household for which fuel costs are so high that the remaining household income is below the official poverty line (Department of Energy & Climate Change, Fuel poverty statistics, UK Government, last updated May 28, 2015, https://www.gov.uk/government/collections/fuel-poverty-statistics, accessed Feb 25, 2016).

[36] Roberts & Starling 2004, p.2

tenants to seek advice for houses that were shown with high heat loss.[37] Follow-up thermal imaging surveys were conducted in 2007 and 2009 and published online. It was later determined that the images taken in 2007 were not well calibrated, and were furthermore taken over a period of time, resulting in a set of images that did not accurately represent the scanned areas. As a consequence, images were not used for further engagement strategies with homeowners leading to building energy retrofits.[38]

A second project in Nottingham, UK showed that for aerial thermography at altitudes of up 760m, each camera pixel represents only approximately a single square meter. Since dwellings are on average 80 square meters in size, this low spatial resolution makes discerning detail very challenging. The study concluded that aerial thermography did not provide a clear understanding of houses that are in need of thermal improvement.[39] The study also found additional problems with aerial imaging related to the unknown occupancy of individual buildings, as many buildings were unoccupied during the imaging process, making their thermal performance appear to be better than neighbouring occupied buildings.

3.1.2 Aerial TI as Engagement: Examples from Canada

In Canada, the Canada Centre for Remote Sensing (CCRS) used aerial thermography to survey a residential area in Ottawa from an airplane (approximately 500m from the ground) in the early 1980s. Conclusions from this study found that pitched roofs made such investigations particularly difficult due to ventilated attic spaces and the pitched angle of roofs. Aerial thermography was found to be most useful when combined with knowledge on individual house insulation levels.[40]

Since then, thermal imaging technology and web-based technologies have seen significant advancements, prompting several large-scale thermal-imaging projects in North America (see Supplemental Document C). The first large-scale study undertaken in Canada was the Heat Energy Assessment Technologies (HEAT) program. In 2010, HEAT conducted a pilot project of 368 residences in the community of Brentwood, in the northwest quadrant of Calgary, using aerial thermal images to create a mosaic of rooftops in the study area. Images were accessible through an open source website that showed residence buildings as polygons on a heat map. As in Aberdeen, houses were represented in different colours, based on a "HEAT Score" that compares the waste-heat levels of the buildings (see Figure 3).[41]

As a part of the project, *Free Geoweb Decision Support Service* software was developed by the University of Calgary to assist homeowners in improving home energy efficiency, save money,

[37] According to Roberts et al. (2004) Aberdeen City Council did not systematically collect data that quantified how 'many' homeowners contacted them.

[38] Hay et al. 2010

[39] Allinson 2007; Roys, 2008

[40] Brown, Cihilar and Teillet 1981

[41] Hay et al. 2011

and reduce GHG emissions.[42] An interactive tool enables users to click on individual buildings to retrieve detailed information on waste-heat, while an energy-use model shows potential energy savings and GHG emission reductions. Three hot spots[43] indicate the hottest locations on the building roof that may require retrofits. Homeowners are encouraged to participate in retrofit programs through a voluntary geographic information system that enabled them to define roof materials and help classify their buildings. Since the original pilot, the study has been extended to cover 37,914 single resident homes in Calgary. HEAT further estimates a total potential community savings of $4.915 million (for natural gas) and a reduction of 29,026 tonnes of CO_2 per year in the event that all recommended energy retrofits are undertaken. However, no actual savings via building energy retrofits have been documented.

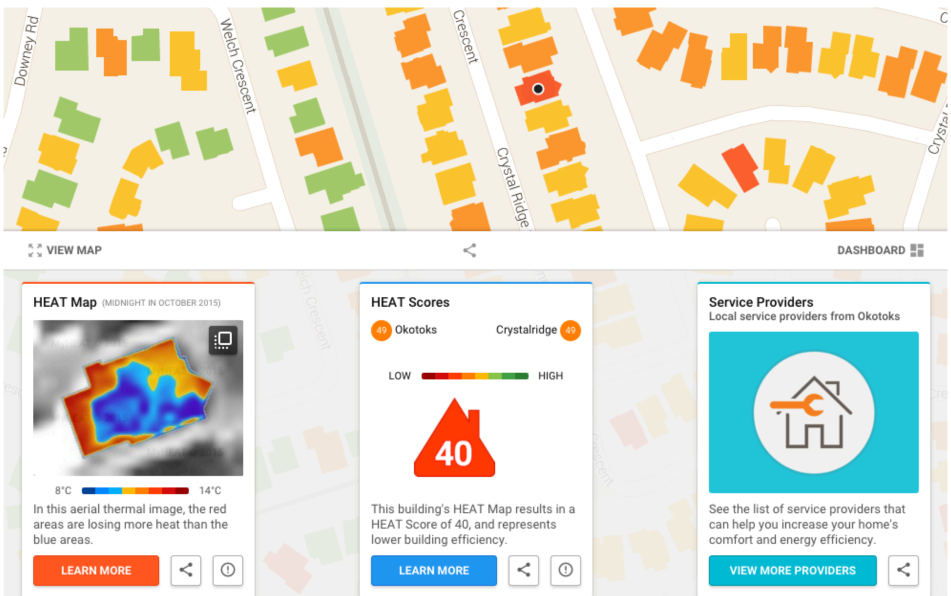


Figure 3: MyHEAT's heat map (myheat.ca/map)

In April 2014, the HEAT project moved out of the university context and into a new start-up company, called MyHEAT Inc. In January 2016, the town of Okotoks launched a pilot project with an online platform for residents to access relevant information about the thermal energy efficiency of their buildings. Homeowners are encouraged to visit the online platform to see their home's HEAT Map and HEAT score as a start to take action on waste energy. Through this program, the town of Okotoks hopes to encourage all homeowners to take steps to improve the energy efficiency of their homes, independent of the achieved HEAT score. In conjunction, the town is working on a rebate program for energy audits to support their residents in taking action. Energy audit kits will be provided at the public library to help homeowners identify potential

[42] Hay 2013

[43] Hot spots are areas of significantly higher temperature than the ambient temperature and can be measured with infrared thermographic equipment.

issues for hot spots in their home. Beside isolated media reports, the effectiveness of the tool has not yet been evaluated for Okotoks.[44]

3.2 Pass-by Thermography

While aerial thermography has seen extensive use and research, one key constraint is its limitation to the inspection of roofs alone. Conversely, pass-by thermography enables the inspection of building elevations (i.e. walls, roofs, windows and doors), with potentially powerful implications for engaging homeowners. Researchers at the Massachusetts Institute of Technology (MIT) have recently pioneered the *drive-by* method of TI, in which multiple thermal cameras are attached to the roof of a car.[45] As the car drives along residential streets, high-resolution thermal images of each dwelling elevation are captured. MIT use a technique known as *Kinetic Super Resolution* to enhance the quality of their thermal images.

In an alternative form of pass-by thermography, a thermographer can "walk-past" dwelling elevations to capture single thermal images in the same manner as drive-by thermography. As a pilot study in preparation for drive-by thermography, a research project from MIT made use of a walk-past methodology in 2010.[46] They found that using this methodology, between 20 and 30 dwellings could be inspected per evening session (during optimal times for thermal imaging, see 2.1.2). Similar research in South West England made use of walk-past thermography to inspect 77 dwelling, and demonstrated the ability of walk-past thermography to detect trends in defects in buildings of a similar construction[47]. In 2012, pass-by thermography was also used to inspect 30,000 housing association dwellings in the UK. Unfortunately, few details of this project have been published.[48]Since work using pass-by thermography only began development in 2011 with MIT's research, much of the literature is from grey and commercial sources, and analysis methods are rarely open to academic scrutiny because of commercial interest.

3.2.1 Pass-by TI as Engagement: Mass Save®, Massachusetts

A specific large-scale study of note in North America was initiated by the State of Massachusetts, in which a partnership between the State's utilities and municipal aggregators ran the statewide Mass Save® energy efficiency program from 2013 to 2015. Under Mass Save®, the Massachusetts Department of Energy Resources' Home MPG ("miles per gallon") initiative was established to increase utility customer awareness of home energy performance and the benefits of efficiency upgrades.[49] As a part of the initiative, Home MPG hired Massachusetts-based start-up Sagewell Inc. to undertake a thermal imaging scan of approximately 40,000 one and two-

[44] Quail 2016; Conrad 2016

[45] Essess, 2015; Miller & Singh, 2015; Phan, 2012

[46] Phan, 2012

[47] Fox, 2016

[48] Currie, 2012

[49] Larsen et al. 2014

family homes in the city of Springfield and seven surrounding communities. The Massachusetts Department of Energy Resources provided homeowners with an opt-out option of the thermal imaging scan of their building.[50] Homes were scanned using a drive-by technology that provided thermal images of the front envelope of the building (Figure 4). Thermal images were made available to homeowners through a secured online database, which was promoted via flyers that offered information on rebates and no-cost energy assessments. 2,000 buildings with the highest potential for energy savings were also sent letters, as well as those that had received an energy assessment (but that had not yet completed an upgrade). Approximately 1,300 homes pursued Mass Save energy audits, of which half had seen thermal images (as reported by Sagewell).

Evaluations of the program indicated that despite the availability of online images and notifications via letters and flyers, few owners were aware that thermal images could be accessed for their home.[51] However, a majority of survey participants indicated that they would have found it helpful to see thermal images of their home in order to make decisions on energy retrofits. The results of the more targeted form of outreach are unfortunately unknown, giving little information as to the effectiveness in achieving higher uptake rate in energy retrofits among targeted buildings.[52]

When approached for additional information, however, Sagewell reported that there was a 31% increase in home weatherization improvements (insulation and air sealing) by homeowners who saw thermal images of their homes during the Home MPG project (between 2012 and August 2014). For homes that received thermal images the household engagement rate increased from on average 1-2% without thermal imaging to approx. 7% in the first six months of the project. Sagewell found a similar increase in engagement rates for more recent projects (with the highest recorded increase in engagement rate of 15% in Belmont, MA, in the first six months). As Sagewell noted, these increased rates are based on a combination of thermal imaging methods and specific marketing methods and messages that are used by the company. None of these data and methods of assessment are published, however, and should therefore be treated with caution.

[50] DOER 2012.

[51] Larsen et al. 2014

[52] Larsen et al. 2014

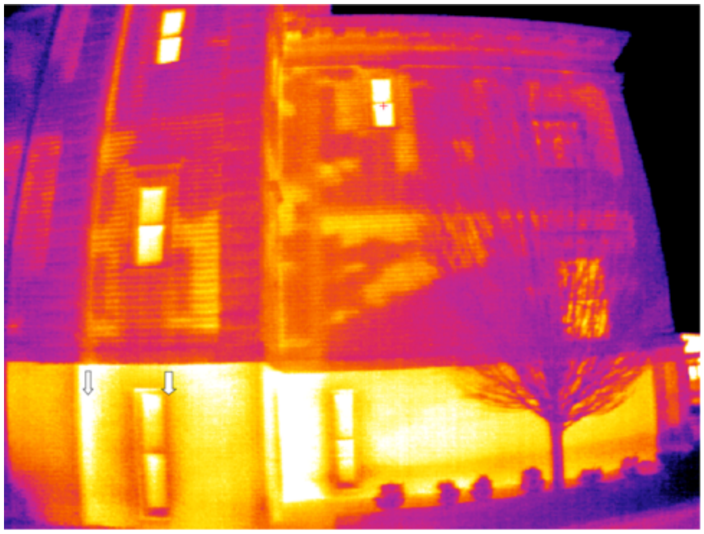


Figure 4: Thermal image of front building envelope, showing missing insulation (Sagewell)[53]

3.2.2 Pass-by TI as Engagement: Essess

Since 2011, Essess (a spin-off company of MIT) has provided large-scale thermal imaging scans. Like Sagewell, Essess uses thermal imaging cameras mounted on car roofs to create heat maps of thousands of homes. Essess' imaging technology provides 3-D images that discern building facades from the physical environment to improve the overall accuracy of the assessment. This information is combined with household and demographic data such as mortgage payments and the age of building occupants to identify homeowners most likely to realize energy upgrades. A thermal analysis program is supposed to further help maximize energy savings, increase uptake of programs, and drive online signups for audits and engagement. The company asserts that the technology can also be used to evaluate the energy efficiency of heating, ventilation, and air conditioning (HVAC) systems, but no information was available about successful applications. Between 2011 and 2014, the company has scanned more than 4 million residential and non-residential buildings across the US.[54] However, the usage of Essess' technology has been largely limited to scan buildings for military, research, and commercial purposes and only recently used for utility companies. [55]

3.3 Learning from Large-scale Projects

[54] Matheson 2015

[55] A table in the Appendix provides an overview of the exemplary large-scale thermal imaging projects that were introduced above. Key aspects such as project objectives, level of community involvement, and the level of uptake are presented, where available.

The examples reviewed above demonstrate the potential benefits and limitations in using aerial and pass-by thermography to encourage communities and residents to understand and address sources of residential heat loss. While aerial thermography allows for a large area to be covered at relatively low cost, the level of detail that they are able to provide limits their utility in accurately identifying building of higher or lower efficiency. Known limitations, such as climatic conditions, unknown occupancy levels and spatial resolution, quantitative analysis using aerial thermography, have also been found to be problematic[56]. As such, the use of aerial thermography for the identification and engagement of residents in energy efficiency activities should be done with caution. As with aerial photography, occupancy will be unknown for many buildings, which may produce misleading results. However, unlike aerial thermography, where quantitative thermal imaging analysis is limited by spatial resolution, pass-by thermography makes use of quantitative analysis to speed up housing assessments by estimating energy use and GHG emissions from the data.[57] Pass-by thermal imaging further provides more personalized images that can be used as engagement tools for homeowners.

3.3.1 Survey of Large-scale Projects in the UK

To further evaluate the effectiveness of large-scale thermal-imaging approaches, seven more recent large-scale TI projects in the UK were surveyed. The project size ranged between 11,000 and approximately 400,000 properties[58], including one medium-size community project.[59] Five of the projects used aerial thermography, two used pass by thermography (by car or on foot) (see supplementary material – Document C).

As with the City of Vancouver, the main objective of most projects was to identify thermally inefficient buildings from a large number of homes (e.g., in terms of poor insulation). In some cases, this was directly linked to a desire to identify those homes most in need of improvements so that incentives could be better targeted. Several projects chose thermography to correlate heat loss patterns with other data (e.g., receipt of social benefits, areas of fuel poverty[60], unregulated buildings). Other objectives were to support other work done by the council on energy efficiency, to meet regulation (e.g., the UK Home Energy Conservation Act), and to leverage funding for energy efficiency. Cost and cost-effectiveness was reported to be a major factor in deciding on the large-scale TI approach, as well as maximising the number of homes and the geographical area covered.

---

[56] Allinson, 2007

[57] Chandler, 2011

[58] These estimates preview a general lack of records and quantification we found throughout the research.

[59] The CHEESE project is community led but integrates a large-scale approach and has imaged around 11,000 homes.

[60] In England a household is considered to be in fuel poverty, if the fuel costs are that high that the remaining household income is below the official poverty line (Department of Energy & Climate Change, Fuel poverty statistics, UK Government, last updated May 28, 2015, https://www.gov.uk/government/collections/fuel-poverty-statistics, accessed Feb 25, 2016).

3.3.2 Engagement Strategies & Level of Uptake

In the projects surveyed, thermal images were used either solely internally within the council and/or housing association, or made available for public engagement. The most common forms of engagement were to make TI project information available on councils' websites or public events. For example, one council published thermal images on the council website and contacted the 500 'warmest' and 'coldest' homes. Another project ran community events and actively managed and monitored a website that was used to publicize an energy efficiency brand (i.e. to achieve local identification by residents of a named organisation offering energy efficiency advice). Other projects engaged 'a few' householders (e.g., owner-occupiers) and found that thermal imaging was 'a powerful tool for motivating improvements'.

Despite these findings, a large gap remains around the evaluation of thermal imaging programs, with little information regarding the effects of the taken thermal imaging approaches and engagement strategies (see supplementary material – Document C). While achieved grants and funding outcomes could in principle provide a quantifiable measure of success, these data were not made available.

3.3.3 Lessons Learned

The seven projects reported lessons learned that were similar to those found in the previous case studies from North America and Europe. Large-scale projects were seen as a good marketing and engagement tool, and it was pointed out that such communication was important and required funds. Web-based access to images was thought to be useful in this respect, while the importance of framing the messages and thinking carefully about the nature of images and associated text was stressed. The powerful visual nature of the images was seen as a key feature or 'eye opener'. Several respondents emphasized that TI projects need clear aims and objectives, and the purpose should be clearly defined from the start. It was also mentioned that thermal imaging could be also used to attract funding.

On the other hand, project leaders also pointed towards technical limitations such as false-negatives when only relying on thermal imaging. Several large-scale projects observed that the images 'merely confirmed existing knowledge'. Specifically, aerial thermography was criticized, as properties were not easy to identify on the images. Based on these experiences, respondents felt that aerial thermography could not accurately identify heat loss from roofs because of the complex interplay of different factors. Only when combined with other data did respondents feel thermal images could be really beneficial, and thermal images on their own were no substitute to local surveyor expertise. Other sources of data were mentioned that could help identify homes that needed upgrading (e.g. council or housing associations' databases).

To help address these limitations, a report by the Centre for Sustainable Energy was created for the City of Birmingham to guide aerial thermography surveys, which are also applicable for pass-by thermal imaging projects. Their recommendations included the following points:[61]

- Establish a clear purpose for the thermographic survey from the outset;
- Show thermal images to residents of their own homes compared to generic images, as this motivates actions to improve insulation levels;
- Provide a searchable web-base of images was a way of grabbing residents' attention;
- Target particular regions of poorly performing housing for further help (e.g., in aerial thermography);
- Consider the risk of 'false negatives' where some homes are heated to a higher temperature than others. Those that were cooler might have been the most needy in terms of assistance due to being 'fuel poor';
- Consider alternative methods of targeting retrofit schemes that might be cheaper than TI programs (using council data on building age and construction for example);
- Include communication and engagement in the strategy and costing (e.g. marketing, distribution, etc.); this is necessary to fully exploit the images and encourage the uptake of energy efficiency measures.

4 Small Scale Approaches to Thermal Imaging

The review above demonstrates the current practice of large-scale thermal imaging projects in identifying buildings that are suitable for energy retrofits and in increasing homeowners' interest in the implementation energy-efficiency measures. However, few of these existing initiatives made use of significant communication and engagement programs, or documented the effectiveness of their approach. While Mass Save® suggested that more targeted forms of engagement could have increased the uptake of retrofit actions and thus the success of thermal imaging programs, no direct evidence has been provided. Nevertheless, for municipal and provincial actors in BC to take advantage of the lessons learned from this existing work, it is important to consider how the utility of such programs might be maximized using more in-depth means of engagement. To do so, we explore alternative thermal imaging approaches, using smaller scale examples from Europe and from BC, based on the literature review of existing studies and a survey of small-scale projects in Europe.

4.1 Research from the UK

A large portion of existing academic research in this area has been conducted in the UK as part of a collaboration between building scientists and psychologists at Plymouth University. Plymouth University carried out four studies that investigated the connection between seeing thermal images and the uptake of energy efficiency behaviour in domestic homes. While this

[61] Roberts & Starling, 2004

body of work has not explored the effect of a mass thermal imaging (i.e. aerial or drive-by) approach, the findings contribute to an understanding of how visuals work to promote the uptake of energy efficiency retrofits.[62]

4.1.1 Encouraging Retrofits through In-depth Thermal Imaging

The first UK study reviewed here offers evidence of the utility of more in-depth forms of engagement, in that homeowners who saw thermal images of their homes were more likely to partake in energy efficiency upgrades. This small-scale study conducted in a UK town separated homeowners into three groups. Homeowners either saw thermal images of the exterior elevations of their home while completing a carbon footprint audit of their home (thermal image group, n = 17); completed the carbon footprint audit without seeing thermal images (audit only group, n = 17); or were placed in a control group (n = 9). One year after the intervention, the thermal image group had significantly reduced their carbon emissions by approximately 700 kg (as calculated from their household energy bills from the year before and after the intervention (see Figure 5), or by 14%. Additionally, retrofits that were undertaken directly correlated to the visual information present in the images (e.g. loft insulation and draught proofing, vs. boiler replacement).

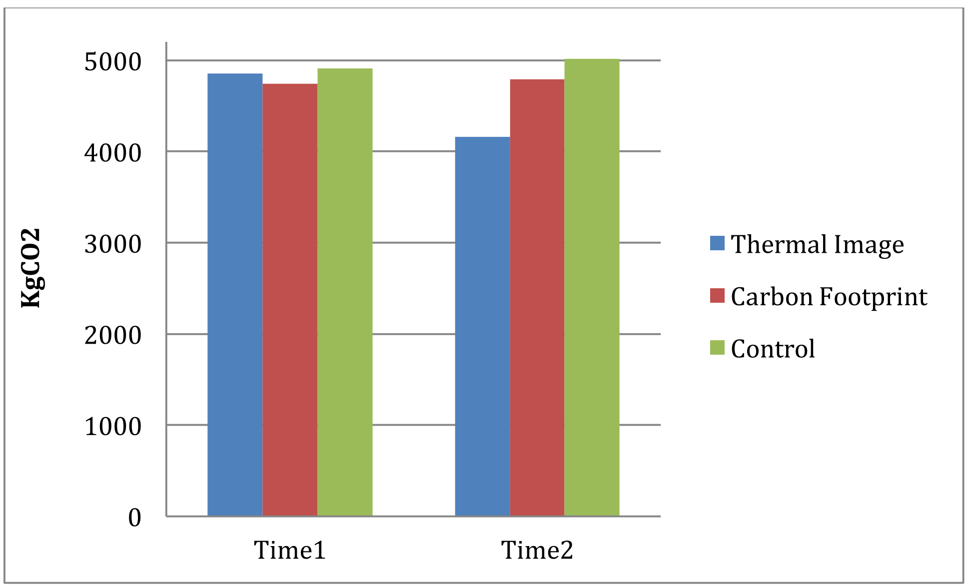


Figure 5: Mean annual carbon emission from domestic energy usage before (T1) and after (T2) viewing thermal images.

A second study employed a larger sample of 87 homeowners across England, who received a thermal inspection during a home visit from an energy auditor. Interior and exterior thermal images of 54 houses were taken, while the remaining 33 homes made up the control group and did not receive any images. After approximately 6 months, households that had received a

---

[62] Goodhew et al 2009; Goodhew et al 2015; Boomsma et al 2016; Pahl et al., 2016

thermal inspection were nearly 5 times more likely to have installed draught-proofing (e.g. caulking, weatherization) than those households that did not.

4.1.2 Personalized vs. Generic Thermal Images

While the two studies above provide evidence of the power of thermal imaging in promoting energy efficiency upgrades, they are also resource-intensive approaches in terms of staff time and effort. One way to reduce the costs associated with thermal imaging programs is to use generic thermal images that show common areas of heat egress and cold air ingress. To determine the relative effectiveness between more and less personalized thermal images, a third study was carried out to explore three separate conditions.[63] One group of homeowners received an e-mail report containing the internal and external images taken during a visit from a thermographer. A second group received the same type of report that contained thermal images of 'typical homes in your area', whereas a third group received a report with text-only information. Appendix A shows an example of the personalized report.

In a follow-up survey, respondents indicated that they were able to remember the personalised images more easily when compared to those who received only text information. Homeowners (N = 233) who received personalized images also reported looking at the images more often (Figure 6), and sharing them with others more than the comparison groups. Further, homeowners who saw the personalized thermal images reported a stronger belief that they would benefit from energy efficiency measures and were more likely to report that they had changed their plans for their homes.

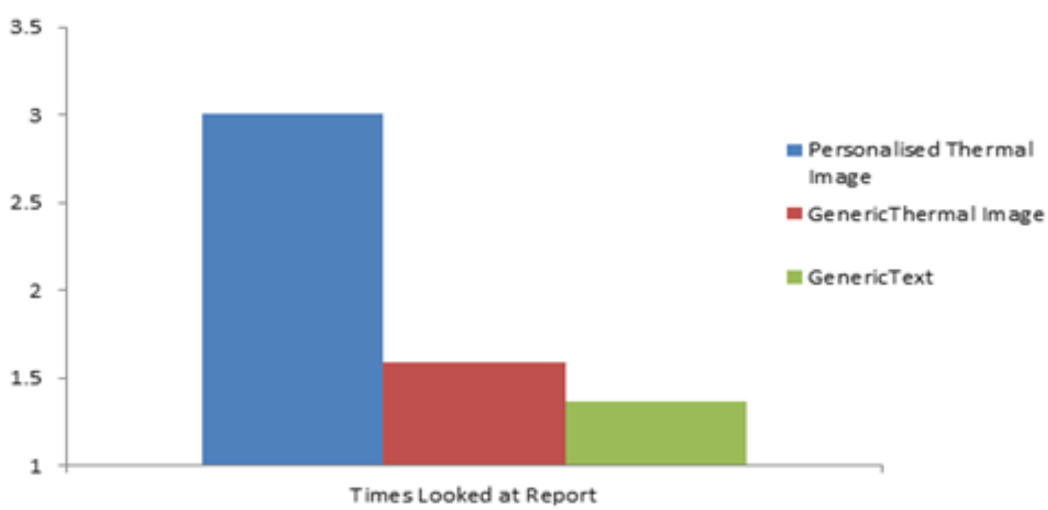


Figure 6: Study 3 – Number of times the occupants reported they had looked at the report

A fourth study also explored the efficacy of using thermal images in a mass communication by investigating whether inserting thermal images into a letter announcing a scheme to install solid

[63] Boomsma et al., 2016

wall insulation would promote its uptake.[64] 5,483 eligible homes were randomly allocated to one of 3 letter types announcing the insulation scheme. One letter contained thermal images of two 'homes like yours,' one of which showed a house without solid wall insulation and one showed a house with solid wall insulation. A second letter included one thermal image of a house without insulation, and a third control letter contained text only. The study sought to determine whether homeowners of different groups were more likely to enquire about the scheme, but call rates were extremely low (1.6%) and no observable difference in the frequency of the telephone calls between letter types was observed. These were attributed to the need to physically open the letters, which many homeowners may have immediately discarded as junk mail.

4.2 Examples from Vancouver's North Shore

A final and local example of the utility of thermal imaging comes from the case of Eagle Island, a small island community of approximately 30 older homes off the shore of West Vancouver. The island is home to a demographically mixed group of residents, ranging from young families to retirees. The community also represents a "grassroots" effort to improve residential energy efficiency using TI, and has sparked interest in thermal imaging across the municipality.

Initiated by a local neighbourhood resident/champion, the Eagle Island neighbourhood retrofit initiative developed a series of informal social events and community dinners, during which the champion collected and distributed information about rebate and incentive programs, including the federal ecoENERGY and provincial LiveSmart programs. Members agreed to submit their homes to an energy audit using thermal imaging. Arranged by a staff member of the District of West Vancouver, a member of the local Fire Department visited each home and took images of the home using a hand-held device. Initially, a trained energy expert conducted the thermal imaging. However, the West Vancouver Fire Department carried out thermal imaging for the remaining Eagle Island homes in order to gain training and experience in the use of the cameras.[65] In most cases, the homeowner was present during these visits and was able to interact with the thermographer. Following these TI sessions, the project coordinator organized a 'Seal Team' of volunteer BCIT students to visit each of the participating homes to carry out remedial measures (at cost to the homeowner), such as caulking windows and doors.

The Eagle Island initiative demonstrates the power of community-based approaches in its achievement of a 100% participation rate, with 26 of the total 30 homeowners going on to retrofit their homes. While the receipt of financial support from rebate programs was a motivating factor for participation for some (with an 86% uptake rate), it was not the only incentive. Initial inspiration for this grassroots initiative came from the champion's concern for her children and their future security in light of climate change. Other homeowners were similarly motivated, but many reported additional reasons for joining the program, including:

- a desire to be included in neighbourhood gatherings;

[64] Goodhew, et al., under review

[65] Sheppard et al. 2015

- peer pressure from neighbours;
- the novelty of using thermal imaging in their homes;
- discounts from local industry partners for renovation supplies;
- the convenience of having someone organize the audit and other activities; and
- the financial savings that would ensue from reduced energy consumption in their homes.

Other factors that residents found notable about the experience included the compelling nature of the images that were provided, which clearly indicated areas of heat loss; the use of a hand-held device, which allowed the resident to point to certain areas of the house; and the opportunity to converse with an expert over different options and implications. The participation of the Fire Department was also noted as a factor in the program's success, as participants considered them to be inherently trustworthy.

Figure 7: A thermal imaging expert conducts a real-time assessment of heat loss using a hand-held infrared camera with a homeowner. Photo credit: S. Sheppard

These findings are consistent with other research in climate change and sustainability engagement that shows that community-led actions may be more effective than targeting individuals, in that they address important social norms, notions of quality of life, attachments to place, and community identity. Neighbourhoods offer high visibility of actions taken by community members, spurring action across the community.[66] In 2012, the Eagle Island organizers estimated that average carbon footprints from the homes had dropped from 5 tonnes

[66] Sheppard et al. 2011, Lewis and Sheppard 2006; Dilling 2007, citing Rogers, 1995; see also Seyfang & Smith 2007; Luederitz et al., 2013; Boyer, 2015

of CO_2/year to 1.7 tonnes.[67] In 2013, participation in the program resulted in a total estimated emissions reduction of approximately 387 tonnes/year. The Eagle Island approach has since spread to 18 other neighbourhoods on the North Shore and Bowen Island and has been increasingly supported and endorsed by municipal authorities.

4.2.1 Scaling up Community Efforts

The Eagle Island approach has since spread to 11 other neighbourhoods on the North Shore and has been increasingly supported and endorsed by municipal authorities. The non-profit organization *Cool North Shore* has scaled up the Eagle Island project into the 'Cool Neighbourhoods' program[68] by hiring staff and developing guidance for other communities (see Figure 8).

Figure 8: Sign template for neighbourhood recognition having undergone a program like the Cool Neighbourhoods program by Cool North Shore

"Cool Neighbourhoods aims to engage people through friendly, informal social interactions that provide an opportunity to ask questions, obtain information, and learn about opportunities for improving home energy use. It focuses on reducing barriers to taking action, and supports people to move from awareness and education, to action and behavior change."[69]

Cool North Shore works closely with the three North Shore municipalities and local industry partners to offer free TI appointments to homeowners since 2013.[70] Municipal Fire and Rescue Services conduct the TI visits in homes that requested an appointment. During the visits, interior walls, windows, roofs, attics and floors are scanned with an infrared camera and TI images are shown to the homeowner. In addition to the TI inspection, fire inspectors provide information and tips on fire safety in the home. After the TI appointment, *Cool North Shore* follows up with homeowners to offer further advice and available resources.

---

[67] Pers Comm: Tara Stafford, August 15, 2012

[68] www.coolnorthshore.ca/action/cool-neighbourhoods

[69, 70, 71] Cool North Shore Program Update 2015 (provided by Cool North Shore representative Barbara McMillan, March 14, 2016)

[70] www.coolneighbourhoods.org/news-views/thermalimaging

The three North Shore municipalities are invested in this strategy, philosophically and practically, committing human and financial resources in a multi-year partnership. Together, the Eagle Island project and *Cool North Shore* were able to procure grants worth approximately $150,000 from BC Hydro, the Real Estate Foundation, and the Federal Government to conduct thermal imaging in 1,000 homes across the North Shore. In a one-year period (2013), GHG reductions through participation in this program amounted to a total of approximately 6,257 tonnes over the life of the measures or 387 tonnes per year.[71]

4.3 Survey of Small Scale Projects in the UK

To further evaluate the effectiveness of smaller-scale TI projects, a survey was conducted of 10 European projects that ranged in size between approximately 20 and 300 properties and that used more in-depth walk-through approaches across the UK (see supplementary material – Document C). The survey found that the key objectives for the 10 small-scale projects were fairly evenly split into three categories:

a) Raising awareness, educating and informing people;
b) Identifying unexpected heat loss (and demonstrating success afterwards); and
c) Encouraging action to reduce energy consumption.

Another interest was to bring residents together to share the thermal imaging experience and work together in developing solutions, sharing knowledge and ideas. The involvement of volunteers and community engagement was a key rationale, while wider sustainability considerations such as energy efficiency was only a minor aspect. Other projects mentioned more comfortable temperatures and health outcomes as objectives, as well as making TI accessible to a wider user group (of technical experts as well as non-experts).

For most of the projects, an increasing energy awareness and energy 'knowhow' were desired outcomes, as well as the desire to visualize ordinarily invisible heat loss for residents, including school children. In general, small-scale projects were chosen because of their feasibility: TI equipment was simple to use and cost-effective, while previous projects provided useful information.

4.3.1 Engagement Strategies & Level of Uptake

As with the survey of large-scale projects, few small-scale projects provided any further incentives beyond the provision of thermal images. Some provided free energy monitors or even low-cost materials for improving energy efficiency such as draught-proofing and insulation materials. A small number of projects provided free workshops for thermal imaging training or for installation of energy efficiency measures as well.[72] However, all small-scale projects involved community engagement, starting with in-depth thermal imaging visits and social events to discuss and share

[72] Some of these incentives seem very close to what the project aimed to achieve and might only be attractive to those already engaged in the topic.

the results. In some, community volunteers were trained to use TI cameras in return for imaging their own homes, as well as those of friends, families and neighbours. One project even provided TI Parties to engage community members, using the images as a 'hook' to invite householder to engage in other activities.[73] Networks, school visits, word of mouth and media links were also used to publicize activities. In several cases, small-scale projects were linked with much broader energy efficiency or sustainability events beyond heat loss, such as smart metering and eco-gadgets.

The small-scale community groups reported a range of indicators that they were actively trying to monitor or were planning to monitor in the future. These generally did not capture actual retrofits or quantify energy savings. Instead, they focused on reach, intentions and use of the thermal camera (e.g. one respondent pointed out that there was a 'waiting list' for the camera). Some figures were reported relating to the recognition of the brand or project, or the number of people attending workshops and public feedback sessions.

4.3.2 Lessons Learned

Some of the benefits and drawbacks from large-scale projects were also reflected in the responses from those working at smaller scales. The projects reported that TI was especially useful in

a) identifying novel areas of heat loss; and
b) engaging and motivate householders and others with the topic of energy efficiency.

Project leads also reported that thermal imaging was useful for showing improvements after the installation of energy efficiency measures, and that additional audiences, such as school children, could be engaged. In general, small-scale programs were reported to be very well received and popular among homeowners, while highlighting how important it was to communicate well before the start of a project and get the community on board.

However, the feasibility of the project was an important aspect for most smaller scale projects, as TI visits could be difficult to coordinate in the community, in order to take thermal images under the appropriate weather conditions and to provide sufficient training for volunteers. Respondents indicated that thermal imaging would benefit from being integrated with broader programs and that additional support was needed to translate from the interest and motivation generated to action. Finally, several projects expressed the challenges of acquiring sufficient funding over time to meet demand and provide continuity. In this respect, volunteer groups could help to provide additional 'workforce' that tends to be highly motivated and passionate about their cause.

5 Summary of Thermal Imaging Approaches

[73] Smarter Communities Project

The review of large and small-scale thermal imaging projects presented above highlights that there are specific benefits and limitations for the two approaches. These benefits and limitations cover technical as well as social and behavioural aspects of thermal imaging. In the following sections, we compare large versus small-scale thermal imaging approaches and discuss the most effective engagement strategies available for these approaches.

5.1 Large versus small-scale approaches

The results above demonstrate a number of key benefits of using mass thermal imaging, particularly in terms of time and cost. Mass thermal imaging:

- ✓ is a fast and low cost methodology for inspecting large numbers of homes;
- ✓ does not require access to dwellings or for occupants to be at home for inspection;
- ✓ can be used to inspect large numbers of dwellings under similar external climatic conditions;
- ✓ requires fewer resources (e.g. thermographers, cameras) for a larger number of dwellings; and
- ✓ can help to observe patterns/trends in common defects between buildings of similar construction through databases, digital maps and online platforms.

However, there are several technical drawbacks of large-scale thermal imaging approaches when compared to walk-though thermography:

- *x* **Fewer thermal anomalies** are detectable using external thermography compared with internal thermography. Aerial thermography is constrained by spatial resolution, pitched roofs and unknown locations, in particular of loft insulation, making defect detection particularly challenging.

- *x* **Single elevation analysis.** Both aerial and pass-by thermography are constrained by their single façade observation. This is important to remember, since aerial thermography will miss information on façades and pass-by thermography will only capture one (max. two) street façade. Defects on other elevations will therefore be missed.

- *x* **Unknown occupancy.** When conducting mass thermography programs, it is very difficult to ascertain whether a dwelling is occupied, heated and to what internal temperature leading up to and during the survey. Without this information, it can be very difficult to determine whether one dwelling is thermally 'better' than another. This can lead to 'false negatives', or dwellings that were not/poorly heated or unoccupied.

- *x* **Weather changes.** Although mass thermography projects benefit from conducting multiple dwelling investigations under similar climatic conditions, some conditions, such as moving cloud cover or variations in wind speeds (gusts of wind) might change from one dwelling image to the next. This could impact upon the quality of image results as one dwelling might reflect a clear night sky in the region of -50°C and another, later in the evening, a cloudy sky in the region of -6°C.

- *x* **Different building orientations.** Due to directions of wind, solar loading and precipitation, results from dwelling elevations will vary depending on their orientation and exposure to these elements. Such differences might make comparing one elevation with another more difficult. Different viewing angles can lead to thermal mass variations in materials.

- *x* **Spatial resolution.** To ensure speed of survey, mass thermography projects tend to inspect dwellings from afar (outside the dwelling boundary). This means that the thermal camera pixels at distance cover a larger surface area on the dwelling and therefore might miss defects, which are too small to be discerned by the sensor.

- *x* **Foreground obstructions.** This limitation poses more of a challenge to pass-by than aerial thermography. Cars, trees and bushes can mask parts of a façade, which may mean certain defects are missed.

- *x* **Emissivity variations.** By using fixed viewpoints for mass thermal imaging methodologies, it is harder to mitigate (than walk-through thermography) the effects of low emissivity materials and reflections from surrounding radiative sources. Pitched roofs in particular pose problems to fixed viewpoint methodologies, since acute angles to the surface of the roof increase the effects of low emissivity from typically smooth surfaces, which can mask potential defects.

In addition, large-scale thermal imaging approaches are limited in their effectiveness as an engagement tool:

- *x* **Privacy issues.** Inspecting every dwelling in one area carries privacy issues. As experienced by Google street view in Germany (using ordinary photography rather than TI), there may be some people, who would not like their dwelling to be imaged or publicly accessible. It is therefore important to consider mass scale techniques of providing advanced notice to residents/participants.

- *x* **Impersonal.** Mass thermal imaging methodologies do not allow for real-time occupant interaction, which limits the opportunity to question the expert thermographer on what the thermal image is portraying.

- *x* **Limited tool.** Similar to the occupant interaction, singular thermal images of the exterior building provide limited information of energy upgrades that may be required for a home to reach its energy saving and GHG reduction potential. Exterior thermal images require subsequent energy evaluations or auditing in order to provide information about full energy upgrade potentials of a home.

Many of these draw backs of large-scale approaches can be better addressed through small-scale thermal imaging projects that can

- ✓ help identify up to 75% more defects internally than observable from the exterior;[74]
- ✓ adapt better to current weather changes;
- ✓ increase the spatial resolution without foreground obstructions; and
- ✓ reduce the risk of emissivity variation.

Small-scale thermal imaging projects have also key benefits in terms of successful engagement with homeowners, as the case studies have shown:

- ✓ **Occupant interaction.** During walk-through thermography, occupant interaction can be encouraged where real-time discussions on the thermal images can be made between resident and thermographer. Thermal images can be explained in real time and related to personal experiences in the indoor home environment.

- ✓ **Encouraging behaviour change**. Homeowners that see thermal images of their home during energy audits can increase the number of energy upgrades that are detectable through thermal imaging (e.g. loft insulation and draught proofing), as the case study from the UK has shown.

- ✓ **Flexible tool.** Small-scale thermal imaging projects can be implemented and combined more flexibly with other engagement activities, such as energy audits and mandatory building inspections.

On the other hand, small-scale projects have been often more limited in terms of required resources and time to reach out to a large number of homes. They also tend to be costlier and require more human capacity from volunteers and experts to reach a similar numbers of assessed homes compared to large-scale approaches. In sum, a greater number of thermal anomalies are detectable using internal thermography compared with external thermography. A pass-by thermal imaging approach will result in only one exterior image of the property, missing the opportunity to capture the nuances of draughts and heat loss around the whole home and to motivate homeowners through personal interaction.

5.2 Effective Engagement Strategies

Overall, the review of both large and small-scale thermal imaging projects have highlighted a number of key lessons for successful engagement strategies with homeowners:

- **Personalized Images.** The opportunity to use images for engagement strategies will be stronger if personal information is included in the images (i.e. a draught at a homeowner's

[74] Fox 2016

specific window) and where the images are of recognizable features of the home. Homeowners that receive personalized thermal imaging report/letters increased their interest in energy efficiency measures and understanding of benefits from energy upgrades, as the UK studies have shown. Furthermore, personalized images seemed to be remembered more easily; through this memory advantage they can act as a better trigger for action.

- **Web-based access.** Online tools that provide access to personal thermal images often times acted as an eye opener for homeowners, when combined with messages that underline the importance of the thermal defects shown in the images. An online database was also useful as project-internal platform (e.g. for energy experts), but only when combined with other building data (e.g. age, type of heating system) that allow for proper interpretation of the thermal images.

- **Personal Contact.** There is a potential importance of personal contact with homeowners when using thermal images to motivate homeowners to undertake energy retrofits. The interaction with a thermal imaging expert or trained volunteer can help to ensure that thermal images are well understood by homeowners and used as a more informative tool.

- **Community events.** Personal engagement through community events and outreach motivated homeowners to join energy efficiency programs and to reduce their energy consumption. Furthermore, community-based activities helped bring neighbours together to share thermal imaging experiences and to develop ideas and solutions for thermal defects.

- **Community-led initiatives.** Community-scale initiatives particularly encouraged homeowners to take action, due to the convenience of the program, peer pressure from neighbours, financial savings, and a desire to be included in neighbourhood gatherings. Partnerships with local community groups and public organizations helped to reduce costs, increase numbers of volunteers, and facilitate easy access to resources and local industry partners.

- **Combined with other incentives.** There are clear benefits to combining thermal imaging technology with stronger forms of engagement to encourage retrofits in the residential context. The integration of thermal imaging projects in broader programs such as existing incentives and rebate programs can be crucial to translate the generated interest and motivation for energy upgrades into action. Easy access and consistent long-term support for energy audits and upgrades have led to higher conversion rates.[75]

[75] City Green Solutions 2015

5.3 Combining Large and Small

While each approach reviewed above has their own unique set of strengths and advantages, a few projects have sought to combine them both together. A recent example of this 'hybrid' approach can be found in the Cold Homes Energy Efficiency Survey Experts (CHEESE) Project in Bristol, UK, which adopted a 2-stage approach to encourage homeowners to pursue energy efficiency upgrades. The CHEESE Project is an excellent example of a community and volunteer-led TI project that combines several opportunities for engagement for householders to interact with thermal images and the information contained within them.

The CHEESE project began by providing training to volunteers on the use of low-cost thermal imaging cameras that could be used with personal iPhones. Volunteers used these cameras to take thermal photographs of the external façade of several homes in Bristol's residential areas, which were then made available online (via both heatview.co.uk and cheeseproject.co.uk). On each site, residents are able to find their own home in a Google street view layer, as well as a corresponding thermal image. Information on exemplar properties, details of how to interpret the images, and suggestions for reducing heat loss are also offered.

These external images are used as a wider engagement tool to generate initial interest, allowing homeowners to compare thermal images of their home with other properties. However, homeowners interested in learning more about how to reduce the losses can arrange for a second, low-cost and more in-depth thermal imaging survey of their home. During the visit, a trained TI surveyor provides additional details on existing 'faults' and opportunities to improve home energy efficiency. During the survey, a film is recorded to indicate cold spots and their potential solutions, which is left with the homeowner on a memory stick for future viewing, obviating the need for an additional thermal imaging report. In addition to these methods of engagement, the project hosts 'CHEESE parties', in which volunteers are trained to help increase energy awareness, help homeowners to request a thermal imaging survey, and motivate them to make energy reduction pledges.

This 'hybrid' project shows that relatively few resources are needed to scan a large number of homes and provide an online platform to raise awareness and interest through the use of volunteers. Resources are instead focused on providing thermal imaging surveys for a smaller number of homeowners to detect more defects, provide expert feedback, and encourage energy upgrades. Events such as the neighbourhood 'cheese' parties help to communicate the benefits of energy retrofits while increasing interest and action community-wide action. Of course, funding is still required: the pilot project was grant funded as part of the *Bristol European Green Capital* initiative in 2015, which created the city-wide scheme to help reduce residential energy consumption and thus the carbon footprint of Bristol homes.[76] The project is ongoing and aims to double its reach of 11,000 homes externally surveyed during winter 2016/17. Funding is now

[76] bristolgreencapital.org/projects/cheese-stands-for-cold-home-energy-efficiency-survey-experts

provided by the UK Department of Energy and Climate Change's Community Energy Fund (via Bristol City Council).[77]

6 Discussion & Recommendations

This report summarizes both current practices and methodologies for thermal imaging, as well as the evidence for their potential in promoting the uptake of energy conservation measures among homeowners. Despite limited project documentation on energy efficiency upgrades, the review presented above suggests several features that are key to building a successful large-scale thermal imaging project for energy efficiency. In general, the use of large-scale TI approaches has been found to be effective in encouraging engagement as a result of the following key advantages:

- Rapid access to several thousand homeowners through large-scale imaging;
- Highly practical and intuitive information on areas of energy loss;
- The ability to communicate abstract information on energy use and heat losses in a clear and understandable format; and
- A compelling image that invokes a personal connection to an intimately experienced home environment and that can be revisited and shared.

However, large-scale thermal imaging projects have also shown the significant limitations of both aerial and pass-by projects in identifying building deficiencies and allowing opportunities for direct homeowner engagement. The deficiencies of these broader approaches can be mitigated, or complimented, by coupling them with the advantages of smaller-scale walk-through TI sessions. In doing so, TI projects can benefit from a more detailed and accurate picture of sources and solutions to residential heat losses, as well as the opportunity for homeowners to interact with and receive direct and personalized advice from home energy auditors and other experts. Finally, where both of these efforts are combined into a 'hybrid' approach with opportunities for community-based interaction and engagement, improved uptake rates of project components and outcomes can be achieved.

6.1 Recommendations

In May 2016, the findings above were presented to a group of representatives of the City of Vancouver and transformed into a set of recommendations for a future TI project. The primary recommendation that emerged from both research and the engagement with City staff is for the use of a combined 'hybrid' or multi-facetted approach to TI in order to increase the uptake of energy efficiency retrofits in single-family residences. More specific recommendations build on the City's existing request for a large-scale thermal imaging project as a Part A, with the

[77] To contact the group: info@heatview.co.uk

additional recommendation of supplementary approaches to engagement in Part B and C in order to test a small range of additional programs and incentives.

Part A: Target Engagement

A targeted engagement strategy that focuses on the identification of a subsection of Vancouver homes with a high retrofit potential is recommended as a first step to effectively engaging Vancouver residents. The City of Vancouver's existing RFP and associated proposal already outlines a process through which a large number of homes are to be surveyed in order to identify this sub-set. Our first recommendation builds upon this requirement by outlining the following additional considerations:

1. Vancouver communities can be primed for the upcoming thermal imaging project through the use of mass and local media (e.g. local newspapers, social media) several months prior to the intervention. A point of contact for interested householders to connect with questions or concerns should be provided.

2. A large-scale thermal imaging scan of 12,0000 to 15,000 homes can be conducted using a pass-by technology. These images should be evaluated using demographic and building-specific data in order to identify approximately 2,000 homes with the highest retrofit potential (i.e. owned vs. rented, age of building, past retrofit activities, etc.)

3. Based on these findings, the target homes should be segmented and engaged using targeted letters used to raise awareness of energy upgrade potential. Targeted letters should be:
    a. Clear and simple in the language that is used, and should take care to avoid jargon or unfamiliar terms (e.g. kWh);
    b. Tailored and personalized, using actual names and referenced wherever possible to demographic circumstances (e.g. tailored to families vs. couples, singles);
    c. Tied to relevant concerns and activities that improved household energy efficiency can support, such as improved sleep, reduced health and safety concerns, or entertaining comfortably;
    d. Able to provide comparisons with homes in the city, neighbourhood or even block scales; and
    e. Utilize both individual (e.g. saving money, improving comfort) and collective (e.g. reducing impact on climate change) themes to incent action.

4. In each letter, specific contact information (i.e. a telephone hotline and e-mail address) should be provided, alongside follow-up options for further explorations. Additional services (e.g. hand-held TI walk-through services or energy audits) should be framed as 'opt-out' to encourage interested homeowners to follow up with additional action.

5. An online database of thermal images and building specific data from the larger scan should be used to continue targeting homes for specific outstanding energy upgrades over time, while carefully considering privacy issues.

With appropriate marketing and information dissemination by the City, this targeted approach will also help to raise interest in energy upgrades and motivate targeted homeowners to retrofit of their homes.

Part B: Deepen Engagement

In order to ensure that homeowners targeted in Part A will take actions to pursue energy upgrades, a deeper form of engagement should also be provided. To do so, the following steps are recommended:

4. To both incentivize uptake and to create a differentiated test population, free and/or discounted energy audits with walk-through thermal imaging should be offered to a smaller number of homeowners on a timed basis (e.g. first 100 to sign up).

5. To increase the total amount of energy savings, a competition between blocks and/or homes with the highest energy retrofit savings can be hosted and promoted. To help promote uptake, free energy audits may also be offered to a small number of buildings with high retrofit potential (e.g. the 10 buildings with the highest retrofit potential). A 'Top 10' list of retrofitted homes can be created and promoted later in the program (complete with information on home energy use, retrofit activities, and homeowner profiles) to help increase program visibility and uptake.

6. City-wide subsidies for the first round of TI energy audits and/or a free follow-up thermal imaging visit following energy retrofits should be considered as a way of allowing homeowners to see improvements and areas that still require attention. Before and after images may also be used in promotional activities.

Overall, this second step will help targeted and motivated homeowners to learn about their full energy retrofit potential and to follow through with actual upgrades.

Part C: Broaden Engagement

To foster awareness of energy efficiency issues and opportunities in homes across the city, the following outreach activities should be taken before and in parallel with Part A and B:

3. Combine large-scale thermal imaging outreach with block/neighbourhood-scale approaches through the use of:

    a. Information booths at block/neighbourhood events (e.g. at Farmers Markets, Community Centres) that raise awareness and spark the interest of local homeowners;

b. Demonstration events of thermal imaging technologies at block/neighbourhood/public places (e.g. Community Centres, City Hall) to help familiarize residents with thermal imaging;

c. Consider the use of online forums that allow homeowners to report energy data and encourage neighbourhood competitions (e.g. through a crowd sourcing online tool);

d. Neighbourhood efficiency competitions that are promoted/awarded and that acknowledge energy efficiency achievements; and

e. Local news coverage to widen public awareness of TI programs and results.

4. Build capacity and support for the use of thermal imaging techniques through:

   a. Training for local Fire Departments or other organizations interested in the use of thermal imaging equipment (see Supplemental Document A);

   b. Support for volunteer-led thermal imaging surveys via the purchase or loan of low-cost thermal imaging equipment;

   c. The inclusion of thermal imaging into other mandatory inspections (e.g. fire sprinklers and gas);

   d. Partnerships with energy advisors, businesses (e.g. Home Depot), and non-profit organizations (e.g. City Green Solutions and Embers) to assist homeowners in pursuing retrofits;

   e. Assistance for negotiations between community groups and utility companies or businesses to secure financial aid and bulk-buying coupons for home upgrades; and

   f. Connections with NGOs, cultural and civic groups, and regional governments to provide and organize thermal imaging programs and events.

In preparation for the above 3-part project, we recommend the City of Vancouver to conduct the following **pilot projects** with Vancouver citizen several months before the interventions:

1. Presentations and discussion of targeted engagement strategies (Part A) with selected citizen groups (e.g. neighbourhood groups/blocks) in order to obtain feedback and gain support for the large-scale thermal imaging survey prior to the project start.

2. Set up of convener experiments with selected citizen groups to test the alternative engagement strategies (Part B and C) and to obtain feedback and information about potential uptake and costs.

In the bigger picture, current experiences from incentive programs highlight the importance of fostering consistent long-term approaches that encourage and motivate homeowners to reach their full potential in energy savings and GHG emission reductions. As part of a longer-term approach, cross-marketing mechanisms are needed that ensure that homeowners are aware and have access to the range of energy upgrades applicable to their home. This requires industry partners to be informed about energy incentive programs and strategies, as well as about retrofit potentials for the existing building stock. Therefore, we recommend developing a comprehensive database of homes that is based on publicly available information (such as data from *EnerGuide Rating System*) to serve as a cross-marketing platform for policy makers and industry partners in order to develop more targeted engagement strategies.

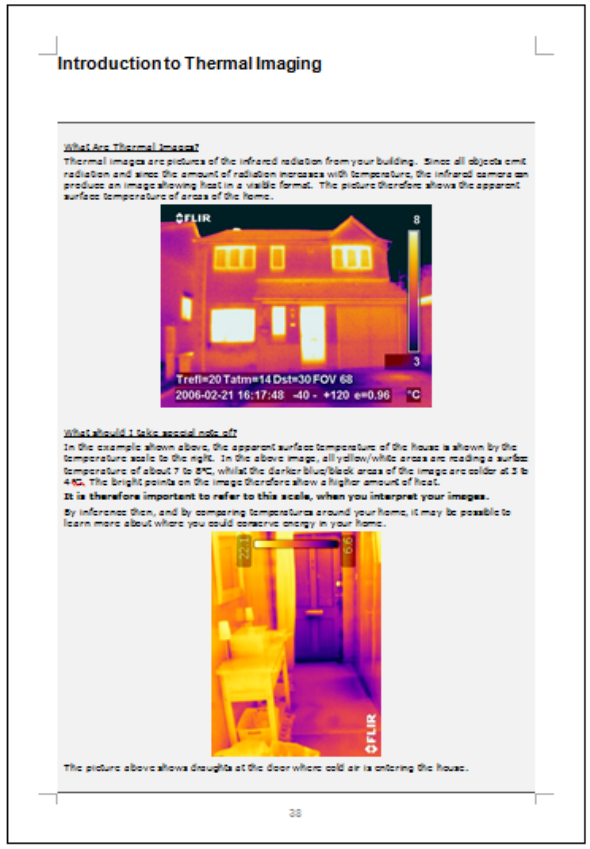
Appendix A

Sample Personalized Thermal Image Report sent to Householder

Cornwall Together
Building Thermograph Report

Address	
Thermography date	4th March 2013

37



Introduction to Thermal Imaging

What Are Thermal Images?

Thermal images are pictures of the infrared radiation from your building. Since all objects emit radiation and since the amount of radiation increases with temperature, the infrared camera can produce an image showing heat in a visible format. The picture therefore shows the apparent surface temperature of areas of the home.

What should I take special note of?

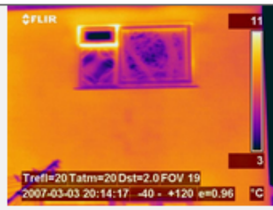
In the example shown above, the apparent surface temperature of the house is shown by the temperature scale to the right. In the above image, all yellow/white areas are reading a surface temperature of about 7 to 8°C, whilst the darker blue/black areas of the image are colder at 3 to 4°C. The bright points on the image therefore show a higher amount of heat.

It is therefore important to refer to this scale, when you interpret your images.

By inference then, and by comparing temperatures around your home, it may be possible to learn more about where you could conserve energy in your home.

The picture above shows draughts at the door where cold air is entering the house.

38



The picture above shows a bright area where the window is partially open when the heating inside the home is on.

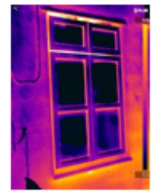
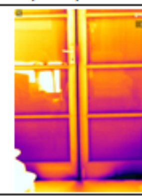
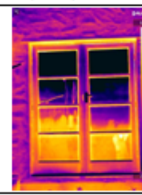
<u>How accurate is the image?</u>

The infrared cameras should be operated by a trained practitioner and need to be interpreted carefully. Infrared radiation is affected by other things than temperature and this can affect the accuracy of the image. Objects with different surfaces can appear to be at different temperatures when in reality they could be at the same temperature. Some buildings materials store heat for longer than others making the analysis of a situation difficult. Shiny surfaces also reflect radiation from their surroundings sometimes making the task of working out where a heat source is very difficult.

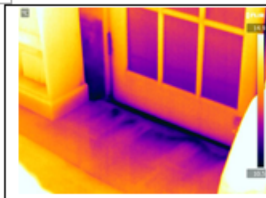
It needs to be pointed out that this report is compiled to attempt to measure how infrared images may affect your energy related behaviour and does not constitute an in depth building performance survey. Infrared images are one tool in a range of diagnostic methods that can be applied to buildings and therefore should never be used as the sole reason for undertaking work. It is recommended that, if you wish to investigate or act upon any of the findings or images, you seek professional advice.

39

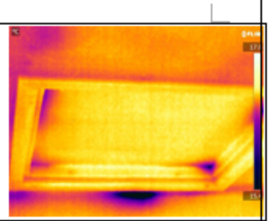
Your Images

	
Front elevation (exterior)	Front window (external)
	
Front window (internal)	Internal backdoor
	
External backdoor	External front door

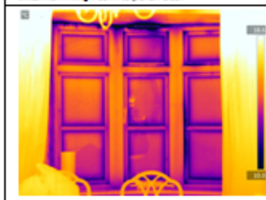
40



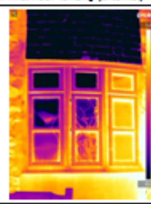
Internal living room to porch door



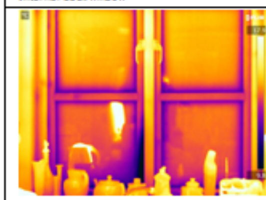
Loft hatch first floor landing (Internal)



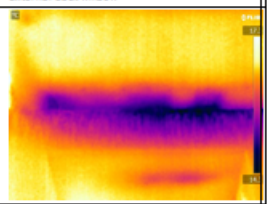
Internal back window



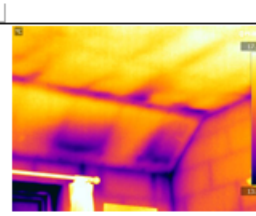
External back window



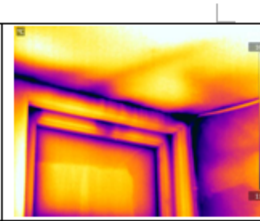
Kitchen window (Internal)



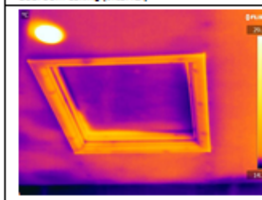
Bedroom in newer part of house ceiling (Internal)



Bedroom ceiling (Internal)



Window living room (Internal)



Loft hatch kitchen (External)

Rear elevation (External)

Comments

- Roof insulation can reduce heating costs in most house types by up to 20%, especially if there is no existing insulation. The optimal depth is 250-300mm, anything less should be topped up.*
- Insulate and draught proof the loft hatch or buy a proprietary new one.*
- A major source of energy loss is through windows and doors.*
- Use of lined curtain, blinds and shutters can help keep in the heat and prevent draughts.*

(* Source: Domestic energy efficiency primer (CE101/GPG171) available as a download from the Energy Savings Trust

http://www.energysavingtrust.org.uk

The thermal imaging survey provided for the Cornwall Together project was intended to supply you with basic images that might help you to conserve energy at home. A more detailed infrared survey, intended to identify building defects can be undertaken to the standard BS 13187 (Thermal Performance of Buildings – Qualitative detection of thermal irregularities in building envelopes – Infrared Method ISO 6781:1983).

No warranty given or implied

References

Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. (2005). A review of intervention studies aimed at household conservation. Journal of Environmental Psychology, 25, 273-291.

Adger, W N, Agrawala, S, Mirza, M. M. Q,, Conde, C, O'Brien, K, Pulhin, J, Pulwarty, R, Smit, B and Takahashi, K. (2007). Assessment of adaptation practices, options, constraints and capacity, in M. L Parry, O. F. Canziani, J. P. Palutikof, P J van der Linden and C E Hanson, eds: *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group ii to the fourth assessment report of the intergovernmental panel on climate change.* Cambridge, UK: Cambridge University Press.

Adger, W N, Brooks, N, Kelly, M, Bentham, S and Eriksen, S. (2004). New indicators of vulnerability and adaptive capacity. *Technical Report 7*. Tyndall Centre for Climate Change Resource.

Allinson, D. (2007) *Evaluation of aerial thermography to discriminate loft insulation in residential housing*. University of Nottingham.

Andrade, J., May, J., and Kavanagh, D. (2012). Sensory imagery in craving: from cognitive psychology to new treatments for addiction. *J. Exp. Psychopathic.* 3, 127–145. doi: 10.5127/jep.024611

Armitage, C and Conner, M. (2001). Efficacy of the theory of planned behaviour: A meta-analytic review. *British Journal of Social Psychology* 47: 471-99.

Armstrong, J. (2008) *CIBSE Concise Handbook*. ed. Butcher, K., London: CIBSE Publications Department.

Artis, D. A. & Carnahan, W. H. (1982) 'Survey of Emissivity Variability in Thermnography of Urban Areas'. *Remote Sensing Of Environment*, 12 pp 313-329.

Asdrubali, F., Baldinelli, G. & Bianchi, F. (2011) 'A quantitative methodology to evaluate thermal bridges in buildings'. *Applied Energy*, Volume 97 pp 365–373.

ASHRAE Handbook - Fundamentals (I-P Edition) (2009). American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.. Online version available at: http://app.knovel.com/hotlink/toc/id:kpASHRAE22/ashrae-handbook-fundamentals/ashrae-handbook-fundamentals

Avdelidis, N. P., Moropoulou, A. & Theoulakis, P. (2003) 'Detection of water deposits and movement in porous materials by infrared imaging'. *Infrared Physics & Technology*, 44 pp 183 - 190.

Balaras, C. A. & Argiriou, A. A. (2002) 'Infrared thermography for building diagnostics'. *Energy and Buildings*, 34 (2). pp 171-183.

Baldinelli, G., Bonafoni, S., Anniballe, R., Presciutti, A., Gioli, B. & Magliulo, V. (2015) 'Spaceborne detection of roof and impervious surface albedo: Potentialities and comparison with airborne thermography measurements'. *Solar Energy*, 113 pp 281-294.

Bamberg, S., & Moser, G. (2007). Twenty years after Hines, Hungerford and Tomera: A new meta-analysis of psycho-social determinants of pro-environmental behaviour. *Journal of Environmental Psychology, 27*(1), 14-15.

Barron, S., R. Tooke, S. Cote, S.R.J. Sheppard, R. Kellett, L. Holy. (2013). An Illustrated Guide to Community Energy. Prepared for Neptis Foundation, Metro Vancouver, Vancouver Foundation, and PICS. CALP, UBC, Vancouver.

Barr, S. (2007). Factors influencing environmental behaviours and attitudes: A UK Case study of household waste management *Environment and Behaviour* 39: 435-73.

B.C. Climate Action Plan. http://www.livesmartbc.ca/government/plan.ca

B.C. Community Energy and Emissions Inventory. (2010) http://www.env.gov.bc.ca/cas/mitigation/ceei/index.html

BC Hydro (2014) Demand Side Management Milestone Evaluation Summary Report F2013 February 2014. Accessed March 12 2016, from https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/regulatory-planning-documents/revenue-requirements/directive-66-f2013-demand-side-management-milestone-evaluation-summary-report.pdf

Beard, J. (2007) 'Introduction to Infrared Thermography'. p. 39.

Berry, B. (2014) 'Thermography of buildings (myth no 8)'.[in *Building Thermography*. Dunboyne, Co Meath: Thermal Vision. 2016. Available at: http://www.thermalvision.ie/2014/10/quantification-of-buildings-with-thermography-myth-no-y/ (Accessed:Berry, B. 19/01/2016).

Boden, T. Blasing, T.J. (2010). Record High 2010 Global Carbon Dioxide Emissions from Fossil-Fuel Combustion and Cement Manufacture. Carbon Dioxide Information Analysis Centre (CDIAC). http://cdiac.ornl.gov/trends/emis/prelim_2009_2010_estimates.html

Boomsma, Christine, et al. (2016) "Improving the visibility of energy use in home heating in England: Thermal images and the role of visual tailoring." *Energy Research & Social Science* 14: 111-121.

Brady, J. (2008) 'Thermographic Inspection of Building and Roof Water Intrusion in the State of Florida'. IR INFO 08: Brady Infrared Paper. 16.

Bramley, M. 2011. Is Natural Gas a Climate Change Solution for Canada? David Suzuki Foundation, Pembina Institute, Pembina Foundation. Page 37

BRE (1997) *Diagnosing the causes of dampness.* Good Repair Guide 5 vol. CI/SfB (L31). Watford: Construction Research Communications Ltd.

British Columbia Government. 2008. Local Government (Green Communities) Statutes Amendment Act, Bill 27-2008 (Section 850, 877). http://www.leg.bc.ca/38th4th/3rd_read/gov27-3.htm

British Columbia Provincial Greenhouse Gas Inventory Report (2008). Emission by Sector. http://www.livesmartbc.ca/learn/emissions.html#Sector

Brooks, N, Adger, W N and Kelly, P M. (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change* 15: 151-63.

Brooks, P. (2007) Testing Building Envelopes with Infrared Thermography: Delivering the "Big Picture". *Interface*,

Brown, R. J., Cihlar, J. & Teillet, P. M. (1981) 'Quantitative Residential Heat Loss Study'. *Photogrammetric Engineering and Remote Sensing*, 47 (9). pp 1327 - 1333.

BSi (1999) *Thermal performance of buildings – Qualitative detection of thermal irregularities in building envelopes – Infrared method (ISO 6781:1983 modified).* BS EN 13187:1999. BSi.

Burch, S. (2010a). In pursuit of resilient, low-carbon communities: An examination of barriers to action in three Canadian cities. *Energy Policy* 38: 7575-85.

Burch, S. (2010b). Transforming barriers into enablers of action on climate change: Insights from three case studies in Columbia, Canada. *Global Environment Change* 20: 287-97.

Burch, S., Sheppard, S., Shaw, A., & Flanders, D. (2010). Addressing municipal barriers to policy action on climate change: Participatory integrated assessment of climate change futures and the use of 3D visualizations as decision support tools. *Journal of Flood Risk Management, 3*(2), 126-139.

Burchell, K., Rettie, R., Roberts, T., (2014). Working together to save energy? Report of the smart communities project. Available at: http://business.kingston.ac.uk/sites/all/themes/kingston_business/charmproject/smartcommunities.pdf (Accessed: 09/03/2016).

Chandler, D. L. (2011) 'The big picture on energy loss. MIT system, tested in Cambridge, gives comprehensive view of energy inefficiency across large areas.'. MIT News. [Online]. Available at: http://www.web.mit.edu/ (Accessed: 10/10/2012).

Chang, Y. M. & Galowin, L. S. (1985) 'Aerial Thermography And Spot Radiometer Applications For Detecting Thermal Anomalies Of Office Buildings', Kantsios, A.G. (ed. *Proc. SPIE 0520, Thermosense VII: Thermal Infrared Sensing for Diagnostics and Control*. Cambridge October 23, 1984.

Chown, G. A. & Burn, K. N. (1983) 'CBD-229. Thermographic Identification of Building Enclosure Effects and Deficiencies'. National Research Council Canada. [Online]. Available at: http://www.nrc-cnrc.gc.ca/ (Accessed: 05/03/2012).

City Green Solutions, 2015. 'City of Vancouver EnerGuide Rating System Existing Homes Data Analysis Report', Report to City of Vancouver, Sustainability Group, September 2015.

City of Vancouver, (2014). *Energy Retrofit Strategy for Existing Buildings*, Vancouver.

City of Vancouver COV (2016) Request for Proposals: thermal imaging for residential retrofit targeting. RFP No. PS20152048, Jan. 20th 2016. Accessed March 12 2016 at http://former.vancouver.ca/fs/bid/bidopp/RFP/documents/PS20152048-RFP.pdf

Clark, M. R., McCann, D. M. & Forde, M. C. (2003) 'Application of infrared thermography to the non-destructive testing of concrete and masonry bridges'. *NDT&E International 36*.

Cohen, S., Sheppard, S., Shaw, A., Flanders, D., Burch, S., Taylor, B., . . . Hamilton, S. (2012). Downscaling and visioning of mountain snow packs and other climate change implications in North Vancouver, British Columbia. *Mitigation and Adaptation Strategies for Global Change, 17*(1), 25-49. doi: 10.1007/s11027-011-9307-9

Conrad, K., (2016). Residents heated up about program. *Okotoks Western Wheel.* Available at: http://www.westernwheel.com/article/Residents-heated-up-about-program-2016020 [Accessed March 3, 2016].

Cornish, L. (2013). Can 4D Visioning Foster Community Responses on Climate Change? MSc. Thesis, Resource Management and Environmental Studies, UBC.

Crompton, T and Kasser, T. (2009). Meeting Environmental Challenges: The Role of Human Identity. WWF-UK

Currie, S. (2012) 'SFHA Carbon Portal –A Housing Associations Perspective'. Clyde Valley Housing Association.

Darby, S. (2006). The Effectiveness of Feedback on Energy Consumption. Environmental Change Institute, University of Oxford. Available at: http://www.eci.ox.ac.uk/research/energy/downloads/smart-metering-report.pdf. Last accessed 15 February 2010.

Dobson, A. (2007). Environmental Citizenship: Towards Sustainable Development. *Sustainable Development* 15: 276-285.

DOER, (2012). Massachusetts Captures Home Energy Waste. *energy.gov*. Available at: http://energy.gov/eere/better-buildings-neighborhood-program/massachusetts-captures-home-energy-waste [Accessed February 25, 2016].

Eads, L. G., Epperly, R. A. & Snell, J. R. (2000) Thermography. *ASHRAE Journal*, (Practical Guide) 51 - 55.

Essess (2015) 'Essess. Thermal Technology. Scale'. Essess. [Online]. Available at: http://www.essess.com (Accessed: 25/02/2015).

FLIR (2011) *Thermal Imaging Guidebook for Building and Renewable Energy Applications.* FLIR Systems AB.

Fokaides, P. A. & Kalogirou, S. A. (2011) 'Application of infrared thermography for the determination of the overall heat transfer coefficient (U-Value) in building envelopes'. *Applied Energy*, 88 (12). pp 4358-4365.

Fox, M. (2016) *Thermography Approaches for Building Defect Detection* . Plymouth University.

Fox, M., Coley, D., Goodhew, S. & Wilde, P. D. (2014) 'Thermography methodologies for detecting energy related building defects'. *Renewable and Sustainable Energy Reviews*, 40 pp 296 - 310.

Friman, O., Follo, P., Ahlberg, J. r. & Sjökvist, S. (2014) 'Methods for Large-Scale Monitoring of District Heating Systems Using Airborne Thermography'. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 52 (No. 8). pp 5175 - 5182.

Fuller, M.C., Kunkel, C., Zimring, M., Hoffman, I., Soroye, K.L., and Goldman, C. (2010). Driving demand for home energy improvements. Lawrence Berkeley Nat. Lab., p. 3960

Gardner, G.T., & Stern, P.C. (2002) Environmental Problems and Human Behaviour, Boston: Pearson.

Gardner and Stern, (2009). http://www.environmentmagazine.org/Archives/Back%20Issues/September-October%202008/gardner-stern-full.html

Gatersleben, B, Steg, L and Vlek, C. (2002). Measurements and determinants of environmentally significant consumer behaviour. *Environment and Behaviour* 34: 335-62.

Giacomin, J. & Bertola, D., (2012) Human emotional response to energy visualisations, *International Journal of Industrial Ergonomics, 42*, 542- 552.

Giudice, P., (2011). *Infrared Scanning and Analysis*, Boston: Massachusetts Department of Energy Resources.

Gonçalves, M. D., Gendron, P. & Colantonio, A. (2007) 'Commissioning of Exterior Building Envelopes of Large Buildings for Air Leakage and Resultant Moisture Accumulation using Infrared Thermography and Other Diagnostic Tools'. *Thermal Solutions 2007*. Sarasota, Florida.

Goodhew, J., Goodhew, S., Auburn, T., De Wilde, P., Pahl, S. (2009) " A Preliminary Investigation of the Potential for Thermographic Images to Influence Homeowners Understanding of Home Energy Consumption" *In: Dainty (Ed) Procs 25th Annual ARCOM Conference, 7 -9 September 2009*, Nottingham, UK, ARCOM, 971-79.

Goodhew, J., Pahl, S., Auburn, T., Goodhew, S. (2015) Making Heat Visible; Promoting energy conservation behaviors through thermal imaging. *Environment and Behavior* (Published online 9th Sept 2014) DOI: 10.1177/0013916514546218.

Goodhew, J., Pahl, S., Boomsma, C., & Goodhew, S. (2015). Can visualisation shed a light onheating? *Proceedings from the European Council for an Energy Efficient Economy 2015, France.*

Hart, J. M. (1990) 'An introduction to infra-red thermography for building surveys'. *BRE Information Paper*, (IP7/90).

Hart, J. M. (1991) *A practical guide to infra-red thermography for building surveys*. Building Research Establishment, Cl/SfB (Q7)(M2)(Aq).

Hay, G.J., HEAT - Empowering Urban Energy Efficiency™. *saveheat.co*. Available at:

http://www.saveheat.co/heat-scores.php [Accessed March 7, 2016].

Hay, G.J., (2013). Whose Home is wasting more energy, yours or your neighbours?, pp.1–10. Available at: http://climatecolab.org/contests/2012/reducing-consumption/c/proposal/1304134 [Accessed February 25, 2016].

Hay, G.J. et al., (2011). Geospatial Technologies to Improve Urban Energy Efficiency. *Remote Sensing*, 3(12), pp.1380–1405.

Hay, G.J. et al., (2010). HEAT - Home Energy Assessment Technologies: A Web2.0 Residential Waste Heat Analysis Using GEOBIA and Airborne Thermal Imagery. In GEOBIA. Ghent, Belgium, pp. 1–3. Available at: http://www.isprs.org/proceedings/XXXVIII/4-C7/pdf/HAY_201.pdf.

Hoicka, Christina E., Paul Parker, and Jean Andrey (2014). "Residential energy efficiency retrofits: How program design affects participation and outcomes." *Energy Policy* 65: 594-607.

Holmes, E. A., and Mathews, A. (2010). Mental imagery in emotion and emotional disorders. *Clin. Psychol. Rev.* 30, 349–362. doi: 10.1016/j.cpr.2010.01.001

Holst, G. C. (2000). *Common sense approach to thermal imaging.* Bellingham, Washington USA: SPIE - The International Society for Optical Engineering.

Hopper, J., Littlewood, J. R., Taylor, T., Counsell, J. A. M., Thomas, A. M., Karani, G., Geens, A. & Evans, N. I. (2012) 'Assessing retrofitted external wall insulation using infrared thermography'. *Structural Survey*, Vol. 30 (Iss: 3). pp pp. 245 - 266.

ITC (2006) *Thermography Level 1 Course Manual.* vol. Rev 1.1. Stockholm Sweden: Infrared Technology Centre, FLIR systems AB.

Jeong, Y., Choi, G., Kim, K. & Lee, S. (2007). The Heat Transfer Simulation for Thermal Bridge Effect of the Corner Walls of Building According to Thermal Condition. *Building Simulation 2007*. Beijing, China: September 03-06, 2007, pp 169-174.

Kaiser, F. G., Wolfing, S., & Fuhrer, U. (1999). Environmental attitude and ecological behaviour. *Journal of Environmental Psychology, 19*, 1-19.

Kalamees, T. (2007) 'Air tightness and air leakages of new lightweight single-family detached houses in Estonia'. *Building and Environment*, 42 pp 2369 - 2377.

Kollmuss, A and Agyeman, M. (2002). Mind the gap: Why do people act environmentally, and what are the barriers to pro-environmental behaviour. *Environmental Education Research* 3: 239-60.

Larsen, W., Pignatelli, B. & Whiteman, A., (2014). *Catalyzing the Home Energy Remodeling Market*, United States. Available at: http://www.osti.gov/scitech/servlets/purl/1133629.

Lee, M., Kung, E. and Owen, J. (2011). Fighting Energy Poverty in the Transition to Zero-Emission Housing: A Framework for BC. CCPA-BC and UBC.

Lee, E and Perl, A. (2003). The integrity gap: Canada's environmental policy and institutions. Vancouver, Canada: UBC Press.

Leiserowitz, A. (2006). Climate change risk perception and policy preferences: The role of affect, imagery, and values. *Climatic Change* 77: 45-72.

Lewis, J L and Sheppard, S R J. (2006). Culture and communication: Can landscape visualization improve forest management consultation with indigenous communities? *Landscape and Urban Planning* 3: 291-313.

Livegreen Tenant Engagement on Sustainability Guide for Social Housing, http://www.bchousing.org/Partners/Ongoing/ECET

LiveSmart BC (n.d.) B.C.'s Greenhouse Gas Emissions. Accessed Feb 6 2016 from http://www.livesmartbc.ca/learn/emissions.html

Lo, T. Y. & Choi, K. T. W. (2004) 'Building defects diagnosis by infrared thermography'. *Structural Survey*, Vol. 22 (Iss: 5). pp 259 - 263.

Lorenzoni, I, Lowe, J A and Pidgeon, N F. (2005). A strategic assessment of scientific and behavioural perspectives on 'dangerous' climate change. Tyndall Centre for Climate Change Research Technical Report No. 28.

Madding, R. (2008) 'Finding R-Values of Stud Frame Constructed Houses with IR Thermography'. *InfraMation 2008*

Maldague, X. P. V. (2001a) *Theory and Practice of Infrared Technology for Nondestructive Testing.* New York; Chichester: John Wiley & Sons.

Maldague, X. P. V. (2001b) *Infrared and Thermal Testing.* ed. Moore, P.O., Nondestructive Testing Handbook. Third Edition edn. vol. Volume 3. Columbus, OH: American Scociety for Nondestructive Testing.

Marinetti, S. & Cesaratto, P. G. (2012) 'Emissivity estimation for accurate quantitative thermography'. *NDT&E International*, 51 pp 127 - 134.

Matheson, R., (2015). Drive-by heat mapping. *MIT News*, pp.1–6. Available at: http://news.mit.edu/2015/startup-essess-heat-mapping-cars-0105 [Accessed February 9, 2016].

Mauriello, M. L., Norooz, L. & Froehlich, J. E. (2015) 'Understanding the Role of Thermography in Energy Auditing: Current Practices and the Potential for Automated Solutions'. *CHI 2015. Crossings*. Seoul, Korea: April 18 - 23 2015.

McKenzie-Mohr, D., & Smith, W. (1999). Fostering Sustainable behavior: An introduction to community-based social marketing. Canada, New Society Publishers.

Midden, C.J.H., Kaiser, F.G., McCalley, L.T. (2007). Technology's four roles in understanding individuals' conservation of natural resources. *Journal of Social Issues,* 63 (1), 155-174.

Miller, J. P. & Singh, N. (2015) *Kinetic Super-Resolution Long-Wave Infrared (KSR LWIR) Thermography Diagnostic for Building Envelopes.* ERDC/CERL TR-15-17 (Final Report) (ERDC), T.U.S.A.E.R.a.D.C. Washington, DC: Environmental Security Technology Certification Program (ESTCP).

Möllmann, K.-P., Pinno, F. & Vollmer, M. (2008) Night Sky Radiant Cooling – Influence on Outdoor Thermal Imaging Analysis, *Inframation*. Reno, Nevada Brandenburg University of Applied Sciences, Germany.

Moropoulou, A. & Avdelidis, N. P. (2001) 'Emissivity measurements on historic building materials using dual-wavelength infrared thermography'. *SPIE 4360, Thermosense XXIII, 224.* Orlando, FL: SPIE.

Munasinghe, M and Swart, R., (2005). Primer on climate change and sustainable development: Facts, policy analysis and applications. Cambridge University Press: Cambridge; New York.

Natural Resources Canada, Energy Use Data Handbook Tables. (2013) https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/res_ca_2_e_4.cfm?attr=0] Accessed 24 May 2013.

NIBS, National Institute of Building Science, (2012). NIBS Guideline 3-2012 Building Enclosure Commissioning Process, BECx, April 25.

Nowicki, A. N. (2004) *Volume Two - Applications.* Infrared Thermography. Northampton: BINDT.

Pacala, S and Socolow, R. (2004). Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science* 305: 968-72.

Page M., Page N. (2011). Green behaviour change: HOT topics. In Bartlett D., editor. (Ed.), Going green: The psychology of sustainability in the workplace. London, UK: British Psychological Society; Vol. chapter 8, p. 65-75

Pahl, S., Goodhew, J., Boomsma, C., Sheppard, S. (2016) The Role of Energy Visualization inaddressing Energy Use: Insights from the eViz Project. *Frontiers in Psychology.* 7. DOI:10.3389/fpsyg.2016.00092.

Parker, P.; Rowlands, I.H.; Scott, D., (2003). Innovations to reduce residential energy use and carbon emissions: an integrated approach. Can. Geographer/Le Géographe canadien, 47 (2), pp. 169–184

Parmesan, C and Yohe, G W. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421: 37-42.

Pearson, C. (2002) *Thermal Imaging of Building Fabric.* BSRIA, Technical Note TN 9/2002. *A best practice guide for continuous insulation.*

Pearson, C. (2011) 'Thermal Imaging of building fabric'. *BISRA Guide*, BG39

Phan, L. N. (2012) *Automated Rapid Thermal Imaging Systems Technology*. Massachusetts Institute of Technology.

Pond, E., Cavens, D., Miller, N. Sheppard, S.R.J., (2011). The Retrofit Challenge: Re-thinking Existing Residential Neighbourhoods for Deep Greenhouse Gas Reductions. Collaborative for Advanced Landscape Planning, University of BC. 93 pp.

Quail, R., (2016). Town of Okotoks Launches the MyHEAT Energy Efficiency Platform O. M.

Government, ed. Available at: http://www.okotoks.ca/municipal-government/newsroom/news/town-okotoks-launches-myheat-energy-efficiency-platform [Accessed March 4, 2016].

Raupach, M, Marland, G, Ciais, P, Le Quere, C, Canadell, J, Klepper, G and Field, C. (2007). Global and regional drivers of accelerating co2 emissions. *Proceedings of the National Academy of Sciences* 104: 10268-93.

Roberts, S. & Starling, G. (2004) *Making the Most of Birmingham City Council's Aerial Thermographic Study.* Bristol, UK: Centre for Sustainable Energy. Available at: http://www.cse.org.uk (Accessed: 30/07/2013).

Rosenow J, & Eyre N. (2015) Re-energising the UK's approach to domestic energy efficiency. Paper 2-0001-15, eceee, Summer Study on energy efficiency. 2015. Toulon/Hyères, France, 1st – 6th June 2015.

Roys, M. (2008) 'Housing space standards: a national perspective', *Research Symposium 2008: Space at Home*. London, UK 23/09/2008. RIBA.

Salter, J. (2009). Of hammers and nails: What is the role of information in the promotion of pro-environmental behavior? Unpublished Manuscript, University of British Columbia, Vancouver, BC.

Schatzmann, M. & Leitl, B. (2011) 'Issues with validation of urban flow and dispersion CFD models'. *Journal of Wind Engineering and Industrial Aerodynamics*, 99 pp 169 -186.

Schott, J. R., Biegel, J. D. & Wilkinson, E. P. (1983) 'Quantitative Aerial Survey Of Building Heat Loss', Courville, G.E. (ed. *Proc. SPIE 0371, Thermosense V*. Detroit October 25, 1982.

Schwoegler, M. (2011) 'Thermal Imaging of Cambridge, MA in the News'. *IRTalk,* The Snell Group. [Online]. Available at: http://www.thesnellgroup.com (Accessed: 10/10/2012).

Shaw, A., Sheppard, S., Burch, S., Flanders, D., Weik, A., Carmichael, J., Cohen, S. (2009). Making local futures tangible - Synthesizing, downscaling, and visualizing climate change scenarios for participatory capacity building. *Global Environmental Change, 19*(4), 447-463.

Sheppard, S.R.J., Mathew Iype, D., Cote S., Saulter, J. (2015), PICS Special Report – A Synthesis of PICS-funded Social Mobilization Resarch, Collaborative for Advanced Landscape Planning, University of British Columbia, version 35 (for public review), March 2015.

Sheppard, S. R. J. (2001). Guidance for crystal ball gazers: Developing a code of ethics for landscape visualization. *Landscape Urban Plan*.54, 183–199. doi: 10.1016/S0169-2046(01)00135-9.

Sheppard S. R. J. (2005). Landscape visualisation and climate change: The potential for influencing perceptions and behaviour. Environmental Science and Policy, 8, 637-654.

Shove, E. (2003). Comfort, cleanliness and convenience: The social organization of normality. Berg: Oxford.

Shove E. (2010). Beyond the ABC: climate change policy and theories of social change. *Environment and Planning A* 42(6) 1273 – 1285

Slovic, P., Finucane, M. L., Peters, E., & MacGregor, D. G. (2007). The affect heuristic. *European Journal of Operational Research, 177*, 1333-1352.

Slovic, P, Finucane, M L, Peters, E and MacGregor, D G. 2007. The affect heuristic. *European Journal of Operational Research* 177: 1333-52.

Smale, A. (2014) 'Thermal Imaging Survey'. Expert Energy. [Online]. Available at: http://www.expert-energy.co.uk (Accessed: 03/12/2014).

Smith, S. M., and Shaffer, D. R. (2000). Vividness can undermine or enhance message processing: the moderating role of vividness congruency. *Pers. Soc. Psychol. Bull.* 26, 769–779. doi: 10.1177/0146167200269003

Snell, J. (2008) Infrared Thermography: (Nearly) A Daily Tool - The potential returns of using IR thermography for retrofitting of existing homes are immense. *Home Energy*, (March/April 2008) 31 - 34.

Snell, J. & Spring, R. (2008) 'Testing Building Envelope Systems Using Infrared Thermography'. The Snell Group. [Online]. Available at: http://www.thesnellgroup.com (Accessed: 24/09/2012).

Stern, P.C.; Aronson, E.; Darley, J.M.; Hill, D.H.; Hirst, E.; Kempton, W.; Wilbanks, T.J., (1985).The effectiveness of incentives for residential energy conservation. Eval. Rev., 10 (2), pp. 147–176

Stern, P C. (1992). Psychological dimensions of global environmental change. *Annual Review of Psychology* 43: 269-302.

Stern, P C and Dietz, T. (1999). A value-belief-norm theory of support for social movements: The case of environmental concern. *Human Ecology Review* 6: 81-97.

Stern, P C. (2000). Toward a coherent theory of environmentally significant behaviour. *Journal of Social Issues* 56: 407-24.

Stockton, G. R. (2007) 'Infrared (IR) Thermography for Building Managers'. *Stockton Infrared White Paper*,

Stockton, G. R. (2013) 'Methodologies of Finding, Analyzing and Prioritizing Moisture Problems in Roofing Materials Using Infrared Thermal Imaging', *IR/INFO 2013.*

Titman, D. J. (2001) 'Applications of thermography in non-destructive testing of structures'. *NDT&E International 34*. Elsevier Science Ltd.

Treado, S. J. & Burch, D. M. (1982) 'Field Evaluation Of Aerial Infrared Surveys For Residential Applications', Grot, R.A. and Wood, J.T. eds.). *Proc. SPIE 0313, Thermal Infrared Sensing Applied to Energy Conservation in Building Envelopes*. Ottawa, Canada March 12, 1982. National Bureau of Standards (United States).

Vollmer, M. & Möllmann, K.-P. (2010) *Infrared Thermal Imaging. Fundamentals, Research and Applications.* Weinheim, Germany: Wiley-VCH.

Walker, N. J. (2004) *Volume one - Principles and Practice.* Infrared Thermography. Northampton, UK: BINDT.