Assisting NatHERS Compliance Literature Review

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EXECUTIVE SUMMARY

This study provides a literature review of available methods and techniques for residential post-construction assessment to gain insights into the potential effectiveness and feasibility of employing these approaches in Australia. Currently there are concerns that there is an energy efficiency performance gap between predicted and as-built dwellings. This gap can be attributed to occupant behaviour and/or poor construction quality in buildings. The latter has been addressed here, finding that a combination of thermography and blower door testing provide the best currently available means of identifying faults post-build both in terms of their ability to identify and cost-effectiveness of this combined approach. However, further research is required and the adoption of more stringent construction compliance requirements may be necessary, dependant on the extent of this issue.

The energy consumption by Australian buildings accounts for approximately 19 per cent of Australia's greenhouse gas emissions. Of this, space conditioning of residential buildings contribute 13 per cent, and of commercial buildings 10 per cent, to building energy consumption. Improving the thermal performance and energy efficiency of new and refurbished buildings is an important component in the Australian Government's strategies to address climate change, mitigate greenhouse gas emissions and reduce energy use (ASBEC 2011). Overall growth in the Australian population, and hence the number of new houses being constructed, has driven an increase in residential energy consumption. The Building Code of Australia (BCA) attempts to alleviate the rise in energy use to some degree by introducing more stringent requirements every few years, but beyond this there are a number of available methods including:

- Mandatory codes and standards, which include Federal equipment standards, state building energy codes and equipment standards, and local building energy codes.
- Voluntary "green" building certification programs such as Green Star and NABERS in Australia and LEED, BREEAM, etc. internationally.
- Policies and incentives such as Federal and state tax credits; utility rebates and pricing structures; and government-backed research to develop energy-efficient technologies.

In many parts of Australia high performance homes are being constructed and marketed as an area of growth. However there may be a disconnect between the construction and post-occupancy stage of these buildings as measures are not in place to ensure buildings are actually performing the way they are predicted to. This can be due to numerous reasons including a lack of clear auditing measures for construction techniques, absence of clear guidelines in the National Construction Code (NCC) regarding minimum air infiltration rates, as well as a lack of incentive to ensure standards are being met. Often an energy efficiency report is handed over to the local council or private certifier to gain a building permit and henceforth there may be a discrepancy between what is proposed and built. Although assumptions are made in the software about how well-sealed a new building should be, the NCC does not include a minimum air infiltration rate. Consequently new residential buildings may not be achieving the intended energy efficiency standard and this may present a good opportunity to further improve the energy efficiency performance of residential buildings in Australia. Assessment of the built fabric during and/or post-construction could ensure high build quality which impacts on the energy efficiency performance.

This report aims to summarise and quantify the potential of blower door testing, thermography and other remote inspection technologies to assist in post-construction evaluation of new homes in Australia. In addition, it reviews existing codes and standards available internationally based on merit and extent of application. Whilst every attempt was made to be

exhaustive, there are many technologies and developments, some peripheral, and selection was inevitable. Therefore this study is restricted to papers and proceedings published in peer-reviewed journals from Europe, the United States or Australia. A significant fraction of the documents reviewed herein relate to the following methods of testing:

- Thermal imaging
- Fan pressure (blower door) testing
- Glazing system identification
- Sound transmission
- Other remote sensing technologies.

These assessment techniques have been reviewed, and recommendations made based on the findings. Thermography and blower door testing were deemed to be the most suitable post-build test methods, but alternative methods have also been suggested, such as pre- and post-build performance calculations, and sample surveys of building stocks across each state. Visual inspection of the building fabric at various stages of construction, as undertaken by building surveyors in Australia prior to deregulation, presents another method to improve build quality which impacts energy efficiency.

In general, further research into this area will be required in order to quantify the impact of poor build quality on energy efficiency performance for new dwellings throughout Australia and better understand what areas most need to be addressed, to find cost-effective ways of combatting these issues, and to look into the possibility of implementing mandatory or voluntary programs such as those seen in Europe and the United States.

INTRODUCTION

This report has been commissioned by the Department of Resources, Energy and Tourism (DRET) to investigate potential methods to test whether as-built residential buildings adhere to existing minimum energy efficiency performance requirements. Concerns have been raised throughout the industry that new dwellings may not be constructed properly to meet minimum energy efficiency standards. While there is some research which demonstrates the effectiveness of increased stringency regulations to reduce operational energy use by residential buildings, the concern is that the regulations may not be as effective as they should be due to an absence of as-built assessments. As the current national regulatory requirements do not mandate the assessment of as-built dwellings, regulated minimum energy efficiency performance standards remain theoretical.

Within Australia there are three primary methods to determine that residential buildings comply with energy efficiency regulations:

1. The star rating method which using predictive energy efficiency modelling using Nationwide House Energy Rating Scheme (NatHERS) software;
2. The prescriptive Deemed-to-Satisfy method; and
3. Verification using a reference building which also uses predictive energy modelling software.

An increase in the stringency of energy efficiency regulations in recent years has encouraged a shift towards the use of the predictive energy modelling software for compliance purposes in Australia and it is our understanding that the star rating method is the most frequently used of the three methods. Although there are no minimum air infiltration rates in the National

Construction Code (NCC), the NatHERS software incorporates some modelling assumptions about building air infiltration rates. Like a poorly sealed refrigerator, poor building sealing has the potential to substantially impact energy efficiency performance. A recent, unpublished study by the CSIRO applied blower door testing to 20 homes in Melbourne to show that residential building can be constructed with air infiltration rates up to three times higher than the energy rating software assumes. Several other published and unpublished studies and anecdotal evidence also indicate that, at least in some instances, dwellings are being constructed with higher air infiltration rates than anticipated meaning that they may not fully deliver predicted savings in operational energy. However the extent of this issue and the impacts on energy efficiency, either theoretically or practically, remains largely unknown in Australia. An accompanying report by Sustainability House, *Impacts of Variable Air Infiltration Rates and Insulation Installation on Residential Energy Performance: Case Studies using NatHERS Predictive Energy Modelling Software,* provides some theoretical predictions about the impacts of variable air infiltration rates on energy efficiency performance throughout Australia.

Post-construction testing methods can help identify defects which may have been hidden within the depth of the structure during construction. The building envelope, fabric or 'shell' determines the energy exchange between the outdoor environment and indoor spaces and hence needs to be appropriately constructed to achieve not only thermal comfort but a reduction in energy efficiency and HVAC loads. A well-insulated thermal envelope without thermal bridges is a passive way to obtain a low heating and cooling demand as well as improve thermal comfort. There are two key components to a well-insulated building shell: high levels of insulation with minimum thermal bridges and airtight constructions. Given that the demand for energy efficiency has risen, significance needs to be placed on the function of thermal insulation, glazing and air tightness of the residential stock, and measures put in place to ensure they are functioning as designed.

Fabric defects could lead to increased running costs, discomfort from draughts and deterioration of the building fabric caused by moisture. These testing methods are also useful in increasing stakeholder awareness of the many building envelope failures and promoting training to alleviate them. Some of these failures include:

- Inadequate sealing around windows and doors, architraves, skirting, and subfloor;
- Incorrect installation of insulation such as gaps, thermal bridging and compression;
- Tears in reflective foil or sarking which affect not only the thermal performance but is also ineffective in keeping moisture at bay;
- Incorrect air gaps to ensure insulation functions, particularly important in roof blankets and cavity brick wall constructions;
- Different glazing system installed than specified; and
- External shading, including pergolas and window awnings installed or not installed variable to the NatHERS model.

The objective of this review is to collect and analyse data on the available methods and techniques of residential post-construction assessment, as well as its costs and benefits. The results of this work will potentially provide new insights on how to address the problems of energy, and indirectly indoor environmental quality, in new and existing houses. Although not directly related to energy efficiency, improving the building envelope quality has the potential to provide a wide range of benefits, particularly with regards to indoor environmental quality and occupant health. Air leakage has been shown to cause moisture accumulation or condensation which leads to microbial growth in dwellings and assists in the transport of

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contaminants (Kalamees 2006). This report aims to identify standardised, robust, cost-effective and accurate tools and techniques for verifying residential energy performance. It identifies potential to adapt existing techniques or develop new ones.

This literature review of possible as-built assessment methods has been driven by industry concerns and commissioned by DRET in conjunction with two accompanying reports that relate to this issue, incorporating:

1. Market research of thermography and blower door testing service providers and product suppliers in Australia: and
2. A theoretical study using NatHERS energy rating software to appraise the potential impact of variable air infiltration rates and insulation installation on residential energy performance.

The International Energy Agency has declared that infiltration will become the primary concern for energy efficiency of new builds in the future. Infiltration and ventilation are left as unknown variables in energy assessments, largely due to a lack of understanding in the industry (MABEL 2007). Studies carried out by the Lawrence Berkeley National Laboratory found that infiltration is responsible for between 20-50% of the energy demand of houses depending on the climate zone and constructions of the envelope (Fernandez-Aguera et al. 2011). There are numerous other studies which reinforce this statistic such as one carried out by Jokisalo in Finland (Jokisalo et al. 2008), Sinott and Dyer in Ireland (2011). Furthermore the average infiltration rate and heat energy use increase in a linear manner with the building leakage rate. Moisture carried by infiltrating air impacts the long-term performance of the building fabric and the longevity of the materials and structural integrity. Infiltration through the roof leads to increased heat transfer and a reduction in the thermal performance of the insulation (Silberstein and Hens 1996). High infiltration rates also burden a building's HVAC system resulting in over-consumption of energy (Younes et al. 2012). The figure (Fig. 1) below shows the typical contributors to air leakage in residential buildings (Alfano et al. 2011). The DRET report *The Pathway for Low-Energy Low-Carbon Buildings in Australia: Indicative Stringency Study* (Pitt & Sherry 2010) states that air-tightness, after insulation, offers the most cost-effective area for improvement in residential energy performance however building sealing is barely addressed in part 3.12.3 of the BCA Volume 2. Nowhere does it define sealing, but simply states that buildings must be "well sealed" and gives options for doing so. There are no testing schemes which verify whether a building is well sealed or not, although visual inspections were carried out in Australia by building surveyors prior to deregulation. The most sophisticated NatHERS rating software *AccuRate* determines air-tightness as a simple function of external wind speed and stack infiltration.

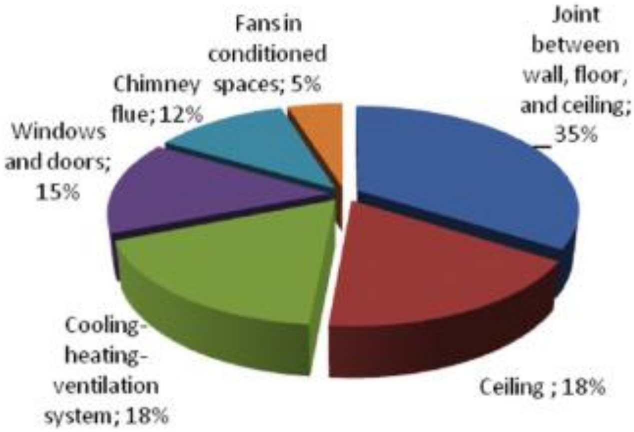

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Fig. 1- typical contributors to air leakage in residential buildings

Evaluating the air flow rates in buildings is a difficult task, with it being affected by external climatic conditions such as wind velocity and temperature differences. However studies have been conducted in northern Europe, Canada, the US and Australia to some extent, which aim to measure infiltration and the air-tightness of buildings envelopes. There are various methods of measuring infiltration but the main ones are the fan pressurisation technique commonly known as the *blower-door* test (BDT), the tracer gas diffusion method, and thermal imaging.

Alfano (2011) states that the tracer gas diffusion method is more accurate than the BDT, but it is less repeatable. BDT is also comparatively quicker and cost-effective (ABT 2011) therefore the tracer gas diffusion method is not investigated in depth in this review. Both methods are fairly intrusive and difficult to implement on a large scale due to the personnel required to undertake the measurements and analysis. BDT requires specialist training in the use of the equipment and the interpretation of the results. The cost required to undertake a BDT is relatively inexpensive – UK studies have shown this to be about $800, and the cost of retro-fitting works is about $1000 according to a Sustainability Victoria report (ABT 2012).

Thermography or thermal imaging is well documented globally as having extensive applications. This method tests thermal performance, detects missing insulation, identifies thermal bridging, and can be used as a comparative assessment. Costs associated with the hire of the equipment may be high but it is a non-invasive technique which has seen substantial developments in recent years with new technology involving aerial data collection.

Glazing system identification is an important factor in energy efficiency. Glazing is often not verified on site, and there is a discrepancy between reported and installed systems. Anecdotal testimony from building surveyors suggests that in the current regulatory framework they rarely confirm that the correct glazing has been installed. Methods such as laser gauges can be used to measure the physical properties of glass and are fairly inexpensive, but thereon a specialist is required to infer the U-values or Solar Heat Gain Coefficients.

Developments are also being made in non-invasive, large scale measurement techniques and remote-sensing technologies such as aerial thermography and laser scanning. These techniques are resource intensive but hold vast potential for rapid assessments.

REVIEW OF CURRENT STANDARDS AND CODES

There are a growing number of voluntary initiatives overseas which aim at improving building air-tightness, and reducing the energy consumption over its total life span. These initiatives range from mandatory testing for low-energy certification schemes or voluntary programmes. However, measurement checks before the building is occupied are rarely implemented, more common are spot checks or sample testing on existing stock. Most of these initiatives apply to commercial buildings rather than the residential market.

Sustainability Victoria initiated a program to undertake on-ground assessments of the energy efficiency of existing houses in Victoria, with the aim of addressing the information gap between what is proposed and constructed. The report is one of few in Australia that aims to quantify the likely costs of upgrading the housing stock as well as inform policy (2010). This study looked at 15 Victorian houses, and whilst actual upgrades were not undertaken, the authors employed energy modelling to quantify the potential savings. Results suggest that shell upgrades could result in an average greenhouse gas reduction of 3.2 tonnes per year and an annual energy cost saving of at least $600 per year. They also recognised that comprehensive sealing and insulation delivered the greatest savings at the lowest cost. Whilst the Nationwide House Energy Rating System (NatHERS) is a reliable method to estimate the thermal performance of residential buildings in Australia, the Prime Minister's Task Group has found several barriers to prevent Australia from taking up more stringent energy efficiency codes such as those in Europe. These include split incentives for investments amongst various stakeholders, lack of market understanding, and skill gaps (DRET 2010).

Since 2006 the Energy Performance Building Directive has required all EU member states to introduce a performance-based assessment method or energy-label scheme. Whilst the uptake has been slow, there exist several schemes, which are reviewed below.

MANDATORY SCHEMES

Building regulations in the UK have become more stringent since 2010 and Part L (conservation of fuel and power) has been updated to include air-tightness testing. Within Part L1A (new dwellings) the standard for air permeability of 10m3/h/m2 at 50 Pascal remains, however, in order to achieve the required CO2 emissions target significantly better targets must be met. It is noteworthy that Part L is lenient when compared to other European countries such as Estonia which limits air permeability to 3 m3/h/m2 and the PassivHaus standard which requires 0.6 air changes per hour (Sinnott and Dyer 2011). Sample testing is also a requirement of Part L, and a penalty has been introduced for non-compliance, increasing builder awareness. Sampling rules also exist in France and Germany.

The introduction of the Code for Sustainable Homes acts as a ladder to future Building Regulations. This Code is based on the UK building regulations but is entirely voluntary; however builders are encouraged to build to the Code's sustainability principles in preparation for the Government's consideration to make assessment under Code standards mandatory, in order to meet their zero carbon policy goals.

National building codes were released in the late 1970s in the United Sates as a response to the energy crisis, and were based on the International Energy Conservation Code (IECC) guidelines. There is a notable lack of federal residential building codes in the US, which adds to the complexity of the market. However it allows each individual state to develop their own standard, and most have opted to make voluntary standards mandatory practice, such as San Francisco's requirement that all commercial buildings must obtain LEED silver status. States which rely on the IECC standards will need to comply with infiltration tests which were implemented in 2012, and meet 3 air changes per hour at 50 Pascal. Another voluntary program mandated by some states is RESNET. The Residential Energy Services Network (RESNET) in the US has developed standards to ensure that accurate and consistent home energy ratings are performed by accredited home energy rating providers to increase the credibility of the rating. It states that all service providers shall maintain an electronic database of information for each home rated, and this includes a post-occupancy assessment (RESNET 2013). RESNET is also responsible for the certification of residential code-complaint software.

VOLUNTARY SCHEMES

Throughout Europe there are various voluntary standards for highly energy efficient buildings. These include Passivhaus, Zero-energy, 3-litre, Plus energy, Minergie®. and Effinergie. Both Passivhaus and Minergie® rating methods and tools are effective in achieving energy efficient and thermally comfortable buildings, contain a post-construction assessment methodology, and have been tested extensively.

Minergie-P® and Minergie-A® were built specifically for cold climates, but along with PassivHaus, they recognise that the building envelope leakage has a large impact on the energy use of a building. To achieve accreditation, Passivhaus and Minergie-P® and Minergie-A® must have a high level of air-tightness (< 0.6 ach at 50 Pa). Buildings undergo an air-tightness test (in this case, a fan pressure test) at an appropriate time to ensure quality is maintained once the building is constructed. A report commissioned by the ISS institute highlights the applicability of European standards in the Australian context. The author has provided a thorough examination of the codes and their relevance to the Australian context, in particular the climate, and states that when comparing Passivhaus standard to the NatHERS rating system, the thermal performance is equivalent to a nine-plus star house (Morris 2013).

The Passivhaus standard sets the following criteria:

MAX **15 kWh/year/m²** for heating
MAX **15 kWh/year/m²** for cooling

Total maximum of 30 kWh/year/m² = 8.3 MJ/year/m²

This is comparable to achieving over 9 stars in NatHERS:

NATIONWIDE HOUSE ENERGY RATING SCHEME

5 stars	=	125 MJ/year/m²
6 stars	=	96 MJ/year/m²
7 stars	=	70 MJ/year/m²
8 stars	=	46 MJ/year/m²
9 stars	**=**	**22 MJ/year/m²**
10 stars	=	3 MJ/year/m²

Fig. 2 – Comparison of the PassivHaus standard with NatHERS star ratings in Climate Zone 16 (Adelaide)

The Green Deal is another government initiative available to UK businesses and households which aims to facilitate energy efficiency improvements to existing buildings. It is unique in that there is no upfront investment but the cost of works is paid back in instalments through the consumers' energy bills. The Green Deal is a component of the Energy Act 2011 which intends to retrofit 14 million homes by 2020 and cut CO2 emissions by 29% for the housing sector.

The Building Research Establishment Environmental Assessment Method (BREEAM) is a voluntary green building rating tool developed in the UK. Initially established as a tool to measure the sustainability of non-domestic buildings, it now includes dwellings and refurbishments. Like most voluntary tools, it contains a two-stage assessment process, as-designed and post construction, and has been applied to 200,000 buildings worldwide.

Leadership in Energy and Environmental Design, (LEED) is the US Green Building Council's voluntary rating tool, the equivalent to Green Star in Australia. The LEED certified rater is expected to conduct on-site performance tests and visual inspections of various measures in the home and typically, two onsite inspections are required for each project; one is conducted during construction of the home, usually just prior to drywall installation, and one is conducted upon completion of the home. Prior to deregulation of the building inspection process in Australia there were additional inspections at other stages of the construction process to ensure high build quality. The current certification process for the completed new home involves two components, firstly, field inspection and performance testing. The accredited rater conducts a final inspection of the green measures on the project's LEED for Homes checklist and conducts the required performance tests, named Exhibit 2. The performance tests in Exhibit 2 deem envelope leakage testing a pre-requisite for LEED certification.

Performance Tests		Responsible Party	Type of Measure	
Category			Prerequisite	Credit
EA	Envelope Leakage	Rater	X	
	Duct Leakage	Rater	X	
	HVAC Refrigerant Charge	HVAC	X	
EQ	Outdoor Air Flow	Rater		X
	Local Exhaust	Rater		X
	Supply Air Flow	Rater		X

Fig. 3 – LEED for Homes Exhibit 2 (performance tests)

In Europe, the Passivhaus Institute since the late 80s has found that mandatory air-tightness testing is an effective way to increase building quality by leading professionals to pay more attention to construction details and follow up on site (Carrie 2012). There is also difficulty enforcing such post-construction testing due to the reliability of the test and the results. Such measurements require specialist knowledge on building physics, HVAC systems as well as data analysis and field constraints. Some countries have derived competent tester schemes including trainings with an array of subsequent procedures—e.g., for training bodies, auditors' trainings, centralized test data collection.

Training schemes in Europe and the US include:

- FLiB (Germany) – certified checker of air-tightness for energy saving regulation
- The Building Envelope Society (Denmark) – certification scheme for air-tightness testers and infrared testers
- Qualibat (France) – qualification which was initially required for the BBC-Effinergie voluntary label, and is now required for measurements in all new buildings under the Réglementation Thermique 2012 energy performance of buildings regulation.
- BINDT (UK) – The British Institute for Non-Destructive Testing. This institute offers testing in accordance with the requirements of Part L in the UK.
- Resnet (USA) – certified experts check compliance with Energy Star and the Guaranteed Performance program. RESNET has developed standards as well as training schemes to develop competent auditors.

ISO standards are voluntary schemes that are an internationally recognised symbol for quality assurance and endure rigorous testing prior to publication. There also exist several ISO standards to regulate the testing of building fabric, listed below:

- ISO/NP 16956 - Thermal Performance in the Built Environment -- Determination of Air Flow Rate in Building Applications by Field Measuring Methods
- ISO/DIS 6781-3 - Performance of buildings -- Detection of heat, air and moisture irregularities in buildings by infrared methods -- Part 3: Qualifications of Equipment Operators, Data Analysts and Report Writers
- ISO 6781:1983 - Thermal insulation -- Qualitative detection of thermal irregularities in building envelopes -- Infrared method

TEST METHODS

Thermography

Existing buildings contain anomalies such as missing insulation, insulation settling in a wall, or uneven distribution over a ceiling, all of which impact thermal performance. The simplest technique for evaluating the thermal performance of the building envelope is onsite visual inspection which includes thickness measurements and sample extractions to determine insulation density. However this procedure is only viable during construction and difficult to implement on existing houses. More advanced methods exist which are non-invasive and do not require the building envelope to be dismantled, and one such method is infrared thermography. Thermography helps determine the location of envelope leaks and missing insulation and hence is useful in the refurbishment of existing buildings and quality control of new builds (Wray et al. 2000) and is formally defined as detecting and measuring variations in heat emitted by an object and transforming them into visible images (Eads et al. 2000).

Thermography measures surface temperatures by using infrared video and still cameras. Images on the video or film record the temperature variations of the building's skin, ranging from white for warm regions to black for cooler areas (see Fig. 4). The resulting images help the assessor determine where insulation is needed. They also serve as a quality control tool, to ensure that insulation has been installed correctly and have the additional capability of detecting the presence of moisture in the building envelope.

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Fig. 4 – Typical thermal imaging camera and results

Thermal imaging can:

- Visualise and detect energy losses;
- Detect missing or defective insulation;
- Source air leaks;
- Find moisture in the insulation, in roof and walls, both internal and outside;
- Detect mould;
- Locate thermal bridges;
- Locate leaks in flat roofs;
- Detect humidity and pipe leaks;
- Detect construction failures;
- Locate hydronic floor heating faults;
- Monitor the drying of buildings; and
- Detect electrical faults (Morris 2013).

In terms of building energy performance modelling, thermography is a robust tool in recording, analysing, and reporting actual energy performance of existing buildings. Thermal imaging offers a number of advantages for a post-construction assessment:

- It allows rapid scanning of large spaces, as surveys can be carried out from ground level or from the air;
- The rapid scanning leads to quick assessments and reduced calculation time;
- It is an accurate yet non-invasive method;
- Results not only show insulation defects but also highlight the effects of thermal bridging; and
- Comparative assessments before and after refurbishments can be carried out.

It has several limitations, such as:

- Best results are obtained when there is a marked temperature variation between the internal and external temperatures, such as in winter months when space heating is required, causing the building to be heated above the outside temperature. It can also be applied in summer months if a building is cooled below the outside temperature, or early mornings or evenings;
- Costs associated with equipment hire;
- Specialist knowledge of building physics is required; and
- Data obtained is qualitative rather than quantitative (Morris 2013).

Morris also recognises that whilst thermal imaging is now being used by building inspectors and thermal performance assessors in Australia, its use is primarily to identify defects rather than for quality control on new projects (2013).

The European Standard project prEN15203 (Energy performance of buildings – assessment of energy use and definition ratings) offers an in-depth explanation of the acceptable methods to be used on site in order to measure the thermal transmittance of the building envelope. The thermal flow meters method is mentioned following the ISO 9869:1994 standard, which is partially invasive and slow and the results strongly depend on the outer environmental conditions and on the users' behaviour in the building during the survey. Albatici and Tonelli (2010) mention an Italian standard which describes a qualitative test method based in infrared thermography in order to survey existing buildings but does not go into depth how accurate levels of insulation can be measured. The authors have since offered a less invasive infrared thermo vision technique which helps acquire quantitative data.

Aerial thermography has been carried out on a large scale to evaluate roof insulation levels of existing buildings (Burch 1982; Brown et al. 1981). Aerial thermography assumes that provided the ambient air temperature is lower than the interior temperature of the house, the roof surface of a poorly insulated house will be warmer than that of a well-insulated house, other conditions being equal. Hence its application in Australia may be limited because the best results are achieved in cold climates.

As previously mentioned, thermographic studies are qualitative, based on detection of differences of temperature between points; and they only include thermal measurements on specific points or areas, associated to many other factors such as the thermal properties of the materials and environmental temperature and humidity. There are a lot of limitations with this method, as there is no way of executing precise quantitative measurements, because thermographic models are simple in geometry and thermographies include geometrical distortions introduced by the camera they are taken with. Other studies have suggested laser scanning technology as an ideal complement for thermography, because it provides the metric information that allows the quantification of the thermal studies. GIS data is coupled with LIDAR scans to generate energy maps which are accessible to the end user. The software then allows building owners to enter gas and electricity consumption in order to find out where they lie in relation to the rest of the site (Kolter and Ferreira 2011).

Light Detection and Ranging (LiDAR) is an active remote sensing technology that emits and receives laser pulses from which three-dimensional data can be extracted. Remote-sensing technologies such as LiDAR and multi-spectral satellite imagery can be used to rapidly measure thermal data and the geometries of buildings which can then be used to extract urban form and estimate energy use as well as carbon emissions (Christen et al. 010). This method has been laboratory tested and several field experiments have been carried out on both residential and small commercial buildings in the US (Wang 2012).

These recent technologies for building energy modelling (such as laser scanners and environmental sensor networks) hold promise to eliminate non-value adding tasks within manual building and energy data collection process, and reduce time in modelling. However, they have severe practical challenges as they are not necessarily adaptable to all existing building conditions. For example, the application of laser scanners for building data collection can be very costly, requires manual post processing of the data and several experts to operate the device.

To advance both the measurement and the interpretation of energy performance, there is a need to consider 3D thermal modelling. A 3D model containing thermal information enables to recognize how temperature values are spatially distributed in a given space in a holistic manner (Ham 2012). The results show the effectiveness of 3D thermography, yet due to the manual process involved in creating image mosaics and performing texture-mappings, the proposed approach is time-consuming and labour-intensive. Cho and Wang (2011) introduced 3D thermal modelling using a LIDAR scanner and a thermal camera. The 3D geometrical information of existing building envelopes are first collected using the laser scanner, and then temperature values are mapped to building exterior surfaces using the thermal camera. Similarly, Borrmann (2012) proposed constructing 3D thermal models of indoor environments using a robot equipped with a laser scanner and a thermal camera. To collect the building and energy data, these two studies require a large and dedicated equipment to support both a laser scanner and a thermal camera at the same time.

Hay et al. (2011) describe a Canadian project which uses remote sensing to visualise heat loss in buildings. The *HEAT* project is a free geoweb mapping service which uses aerial thermography to improve urban energy efficiency. Their aim was to make this data publicly available, through Google Maps, and use it to educate the public.

The International Association of Certified Thermographers offers standards and guidelines for the use of thermal imaging in buildings. Survey and reporting mechanisms:

- A temperature difference of 10ºC between indoors and outdoors at least four hours prior to the survey;
- Avoid sunlight on facades for at least four hours prior to the survey for lightweight buildings and six hours for heavyweight structures ideally. Therefore it should be carried out before sunrise or late at night;
- The building surfaces must be dry, with no rain or snow during the survey; and
- Wind speed must be less than 8 m/s (a moderate breeze).

Thermography can be carried out internally as well, which strengthens the survey results. The results need to be analysed comprehensively for a successful survey, and the aforementioned Standards offer guidelines for characteristic defects such as:

- Missing insulation, which produces a defined shape with a relatively even temperature distribution;
- Air leakage at joints or junctions of an envelope often produces irregular shapes with large temperature variations; and
- Moisture present in the structure is also evident by a mottled or diffused pattern.

The application and interpretation of thermal imaging requires a high level of expertise as well as large upfront costs. It is important also that the interpretation is informed by knowledge of the construction being studied. It is however the least invasive, most thorough method of assessment, and should be used in conjunction with other assessment methods in order to enable remedial action. The following international organisations offer guidance for auditors:

- **ISO 18436-7:** Requirements for thermography training and certification of thermography personnel in condition monitoring and the diagnostics of machines, as established by the International Organization for Standardization (ISO) TC 108/SC 5, (Example: PCN scheme run by the British Institute of Non-Destructive Testing (BINDT))
- **EN473:** Recommendations for qualification and certification of non-destructive testing (NDT) personnel, as established by the European Federation and accepted by the American Society of Mechanical Engineers (ASME)
- **ISO 9712:** Specifying proficiency in infrared thermography testing as related to the qualification and certification of personnel involved in non-destructive testing (NDT), as established by the International Organization of Standardization (ISO) TC 135/SC 7
- **ASNT-SNT-TC-1A:** Recommendations for thermal/infrared testing, as established by the American Society for Non-Destructive Testing (ASNT).

Fan Pressure Testing

The air-tightness of a building envelope affects the energy consumption as well as indoor environmental quality of a building. Infiltration is a significant contributor to the overall HVAC loads in a building. Studies have shown that 20-50% of the total energy loads are due to infiltration (Fernandez-Aguera et al. 2011).

Air permeability is the metric used in Part L of the building regulations in the UK. The test involves either pressurising or depressurising the inside of a building with an industrial fan to a differential of 50-Pascal from the outside, and measuring the air flow rate required to maintain that differential. The measurement used for this test is m3/(h.m2) @ 50Pa, or air leakage per square metre of building envelope, including all wall, roof and floor areas that are exposed to the external environment. There can be significant differences between measurements taken by pressurising and depressurising buildings. For dwellings, the Chartered Institution of Building Services Engineers (CIBSE) claims that it is common for the difference between the pressurisation and the depressurisation test results to be more than 10% for the same building.

Air change rate is tested using the same physical testing method, however the calculation relates to the building's internal volume and the volume of air that needs heating, in ac/hour @50Pa. This is a less common metric in the UK, but is used as a standard measure in Passivhaus buildings.

ASHRAE, with reference to Dickerhoff et al. (1982) estimates the percentage distribution of infiltration air leakage by building components as follows:

- Walls: 18%–50%, with an average of 35%;
- Ceiling details: 3%–30%, with an average of 18%. This leakage undermines the purpose of insulation in attics, residential houses, and ceiling insulation in buildings;
- Forced-air and/or cooling systems: 3%–28%, with an average of 18%. This category represents air leaks in conditioning/heating air paths and ducts; and
- Windows and doors: 6%–22%,with an average of 15%.

Fan pressure testing or the *blower door test* (BDT) is one method of assessing the air-tightness of new and existing buildings. It can be used to:

- Assess the potential for reducing air leakage in existing buildings;
- Identify air-leakage paths;
- Compare the air-leakage characteristics across the building stock;
- Measure the impact and effectiveness of leakage reduction techniques; and
- Provide an opportunity for test results to be used in simulation software to estimate air-infiltration rates.

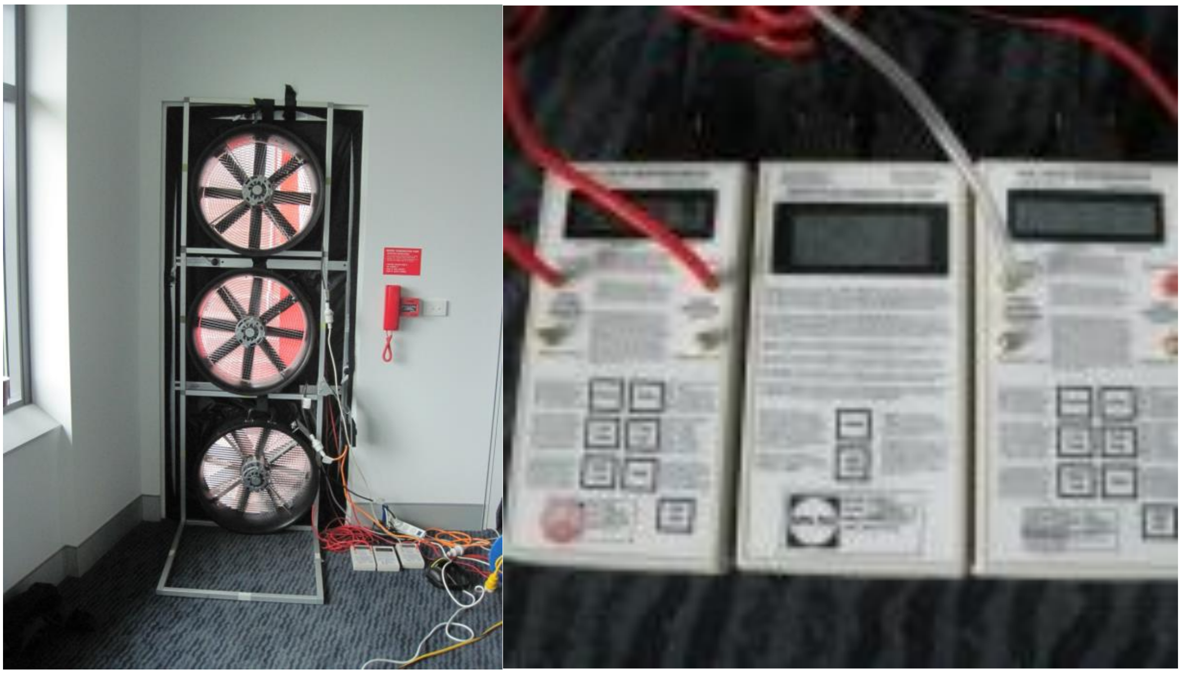

Fig. 5 – BDT equipment (fans mounted to an external door and meters)

The method involves a fan mounted to move air into or out of the building. The rates of air flow through the fan are then measured too and the pressure differences between the outside and inside of the building are maintained. Additional equipment is required to measure the wind speed, temperature and barometric pressure.

The major disadvantage of this method is that it is fairly invasive, as preparation for the test involves the closure of all openings in a building and the sealing of any extract fans. In addition:

- Resource intensive, and requires manual labour;
- If pressure differences are not maintained, results can vary as much as 20%; and
- Each house can take up to 2 hours for an experienced operator to assess

There exist many standards the fan pressure test needs to adhere to, such as BS EN 13829 and CIBSE TM23. It also needs to be carried out by an accredited professional. The Air Tightness Testing and Measurement Association (ATTMA) is a professional body established in the UK with recognised certifications in air tightness testing.

The number of companies offering fan pressurisation tests is growing in Australia. One study which used this method of assessment was conducted by Sustainability Victoria (2010), and results show that draught sealing improved the house energy rating by 16% while costing a mere 3% of total upgrade cost.

ABT have been testing the air change effectiveness of Australian houses since 2001 using the BDT method. A test carried out on star rated and non-star rated homes indicated that star ratings did help reduce infiltration rates but the small sample of houses tested cannot represent a trend in the industry (2011). ABT studies also identified that the average air changes per hour for a sample of 8 Victorian homes was 35 (2012). These houses were then retrofit and a reduction of approximately 55% in air changes per hour was achieved at an average cost of $1090. The retrofit methods used to achieve this reduction were varied and the authors identified that there is no specific method of achieving this on a nationwide basis. ABT have since started offering a TAFE course in housing air tightness and BDT.

Glazing System Identification

The thermal conductance of individual windows and opaque elements, often denoted by the assembly R or U-value, is an important measure in the thermal performance of a building envelope. Heat gain and loss occurs mostly through these opaque elements and no procedures are in place in Australia to verify that the correct glazing units have been installed. Ideally, building surveyors will confirm the glazing units during construction. However for existing buildings, it is difficult to identify glazing for an as-built assessment without removing the units and laboratory testing using the hot-box method.

Commercially available laser gauges are one piece of equipment which can be used to measure the physical properties of glass. Measurements can be taken from the outside of the building, deeming it a non-invasive procedure. Whilst it can determine the presence of a low-e film, it is limited in that an argon or similar gas filling cannot be detected. A trained professional can then infer the type of glazing system installed and corresponding U-value.

Studies have recognised that whilst replacing windows may not be a cost effective method of upgrades to the fabric, it is possible to retrofit additional panes of glass to single glazed windows by using a desiccant strip as a spacer (Sustainability Victoria 2010). This is an economic alternative to improve the thermal performance of existing homes.

Fig. 6 –a commercial laser gauge to help identify the type of glazing installed within a window

Other

Acoustic method:
Traditional approaches to estimate the leakage air flow for existing buildings present a series of disadvantages. The mathematical prediction models present errors up to 100%, whereas the current experimental measuring approach is expensive and weather dependent. Other 'fringe' methods are being investigated, such as the relation between the air and noise transfer phenomena through window joints (Iordache and Catalina 2012). The authors have proposed that both the infiltration air flow and the airborne noise transfer through window joints for the same building façade are measured in order to determine the air change rate and the airborne noise transfer. They found that the air change rate is inversely correlated to the sound transmission loss; the higher the sound transmission loss, the smaller the air infiltration rate. Their method of acoustic estimation for the building air permeability presents several advantages compared to fan pressure testing, or even thermography, due to less expensive measurement devices, the ability to operate free of climate changes and its speed for evaluating building air permeability.

Ultrasonic scanning is often used in historic buildings to determine areas of weakness and can be particularly helpful in timber framed construction to identify the extent of decay. Radar examination which uses low power radio pulses to determine structural integrity of buildings.

CONCLUSIONS

Fabric performance testing can highlight areas of weakness and so help to raise the construction quality of buildings. Many low energy projects being studied and monitored are experimental and are built under special circumstances, in which additional resources might

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be available to solve problems and correct mistakes. In practice however there is a limited time and budget to complete buildings so to improve the quality of new buildings, it is necessary to improve the building process, educate the public, and implement monitoring technologies. The research reported here has aimed to provide guidance in this area. Other crucial factors in the energy performance of buildings are the occupant's behaviour, embodied energy of materials and life cycle assessments. If Australia is to effectively respond to and continue to manage the issue of energy conservation it is vital to design and construct buildings that embody better environmental performance over their entire life cycle and it starts with an as-built assessment.

Recommendations and further work

Bridging the gap between the design intention and the actual performance of the constructed building requires extensive post-construction commissioning and expertise. Studies have shown that actual building performance, rather than regulated performance, has not been sufficiently addressed in Australia. Research in the UK suggests that this may be a major obstacle to delivering actual net zero energy type buildings which create no direct greenhouse gases as the building industry needs to be re-skilled (Morris 2013). As a first step towards improving build quality which impacts energy efficiency, fact sheets could be developed, for example by the Australian Building Codes Board, which detail correct building construction techniques and common mistakes made. Face-to-face or online training could be readily integrated into existing training programs or provided as standalone short-courses. Beyond improving education standards there are numerous viable options to improve building quality relating to energy efficiency of residential building in Australia.

One possible approach to rectify the energy efficiency performance discrepancy between as-designed and as-built dwellings is to reintroduce requirements for building surveyors to complete visual inspections of insulation installation before plasterboard is installed as well as checking building sealing at the post-construction stage. This could provide a relatively cost effective solution and there is further potential to integrate the use of thermal imaging by building surveyors at the post-construction inspection stage. As building surveyors cannot inspect insulation installation at every stage of the process, thermography provides a viable solution to verify correct insulation installation. Feedback from building surveyors as part of the market research component to this study supported the feasibility of this approach. This approach however raises other questions about how poor insulation installation would be rectified, if at all, considering the high cost and difficulties with amending insulation faults after construction is completed. It is likely that the insulation installation would improve throughout the industry if builders were merely aware that installation would be verified using thermal imagery, hopefully avoiding unnecessary costs and time delays.

A more comprehensive and rigorous approach would be mid- and/or post-construction assessments using both BDT and thermography. These techniques are complementary and address air leakage and insulation installation issues. The least intrusive way of introducing this into the build process is before the building fit-out stage. As indicated by the market research, the average cost for both assessments would be approximately $600, which is a small investment when considering the net benefits of this scheme. From a home buyers perspective this additional cost would provide quality assurance on a significant investment, though in the absence of a mandatory disclosure scheme there are limited financial incentives for a home owner to outlay this cost, beyond the ongoing operational energy savings. However on a poor quality build it is likely that the payback period on a $600 investment would be relatively short. Further research would be necessary to quantify the discrepancy between as-designed and as-built energy efficiency performance to provide financial justification for this additional cost to home owners and/or builders.

In order to implement such a scheme, one option is to target high volume builders and apply a prerequisite for display homes to be tested post-construction. A sample of houses could then be audited to make the builders responsible for fixing any identified problems and maintain quality assurance. Another solution would be to have both measured as well as calculated performance figures, similar to a NABERS commitment agreement. Assessments should be carried out in two phases, where an initial assessment is carried out at the design stage. This is based on documented evidence and commitments which results in an interim certificate of compliance. The final assessment and certification should be carried out at the post-construction stage. Based on the design review, this includes a confirmation of compliance certificate. Where the above is not possible, a sample survey assessing the building envelope could be carried out periodically on a selection of the housing stock across all states and climate zones in the country. This may include auditing of at least one assessment per as-built energy assessor per year.

If a combined BDT and thermography approach was adopted, to maintain coherence it would be important that standard methods for collecting, analysing and reporting data were established and all buildings tested using equipment with minimum performance requirements, including thermal imaging camera resolution. Blower door testing equipment would also require calibration for Australian conditions to ensure consistency in methodology. Energy performance scales may need to be adjusted to accommodate the tightening of the regulations and prevent the need for frequent changes. Quality assurance is vital to any certification scheme. Their introduction must be well timed, transparent with clear achievable goals. The scheme should be inherently motivational and educational to ensure its uptake and endurance.

A central database may be set up, such as RESNET in the US, which acts as an information repository while allowing quality checks or identification of trends in energy performance. As-built performance certificates could also be a requirement when selling or renting an existing house.

More clearly defining and establishing a performance baseline for maximum air change rates per hour in the building code would be necessary if blower door testing became standard practice in Australia. Beyond this clearer definition of what constitutes “well sealed”, as well as development of educational material for builders and product manufacturers about building sealing and insulation installation, would improve build standards which impact on energy efficiency performance in Australia.

In general, it is recommended that further as-built research is undertaken to develop a better understanding of areas that need to be addressed, to find cost-effective means of achieving reductions in energy use, and catch up to European and American counterparts. Studies need to be carried out on a large scale across a range of climate zones for a thorough assessment of the housing stock. Such research can then inform the development of policies and schemes, such as the residential building mandatory disclosure, and aid in developing rebates or incentives to increase the uptake of energy efficiency measures in Australia. As Australia moves towards more intensive testing for thermal performance including the aforementioned fan pressure testing and thermography, it seems appropriate to adapt either the ISO standards or similar accreditation scheme.

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