

Effectiveness of methods to calculate the greenhouse gas emission reduction of residential refurbishments

John Shiel^{1, 2}, Dr Steffen Lehmann³, Dr Jamie MacKee¹

¹University of Newcastle, Callaghan, Australia

²EnviroSustain, North Lambton, Australia

³University of South Australia, Adelaide, Australia

ABSTRACT: The building stock of 2020 largely exists today! The enormous task of the next decade is to retrofit and refurbish these buildings to reduce Greenhouse Gas (GhG) emissions. These retrofitting strategies are of particular relevance for the future of the inefficient model of the Australian suburb. This paper considers the methods that are used to calculate residential refurbishment savings in GhG emissions e.g. using actual calculations in case studies, and using thermal modelling software, and provides examples. It also includes a residential performance upgrade case study which used thermal modelling research to select the most practical and cost-effective strategies. This research is currently being applied to the case study, and logged and modelled temperatures are compared. The comparison of methods provides guidance for a research methodology for practical and cost-effective strategies to lower GhG emissions of residential buildings in Australia. The paper incorporates cross-disciplinary approaches in practice and academia, and considers the integration of architecture, engineering, building and science.

Conference theme: Sustainability Issues

Keywords: reducing greenhouse gas emissions, existing residences, refurbishment methods, thermal modelling

1. INTRODUCTION

The building stock of 2020 largely exists today! Few buildings meet the Building Code of Australia's 2005 thermal performance provisions although buildings can endure for over a hundred years. The enormous task of the next decade is to retrofit and refurbish these buildings to prevent Greenhouse Gas (GhG) emissions. These retrofitting strategies are of particular relevance for the future of the inefficient model of the Australian suburb. (Lehmann 2007)

The greatest challenge is the development of effective strategies for retrofitting existing buildings due to their slow turnover... (and)...buildings offer the largest share of cost-effective opportunities for GHG mitigation among the sectors examined... (Levine et. al 2007:390)

Peer-reviewed scientists agree on global warming, and that its cause is due to mankind's increases in greenhouse gas concentrations (IPCC-SPM 2007), (Journet 2008). All foremost scientific and engineering institutions are also in agreement (Scientific Opinion on Climate Change 2010). Since Carbon Dioxide (CO₂) lasts over 100 years, we **urgently need to reduce our GhG emissions to zero** to avoid 1) catastrophic impacts on rainfall and glacier melting patterns affecting food supplies, 2) disastrous tropical cyclones and floods, and 3) rising sea levels. . We are already exceeding some of the worst predictions of the IPCC (Garnaut 2008), (Copenhagen 2009), (BZE 2010), (Shiel 2009).

While research has been conducted into energy use in the Australian residential sector (DEWHA 2008), and into the energy efficiency and thermal comfort design of new buildings, there has been little research into cost-effective strategies to reduce GhG emissions in the existing building stock. Specific questions to be addressed include:

1. What methods can be used to calculate residential refurbishment GhG emissions?
2. What criteria should be used to compare the effectiveness of residential refurbishment GhG emission methods?
3. How effective are these methods?

The approach used to answer these questions included investigating energy auditing approaches and building thermal modelling rating tools, surveying recent literature for residential GhG emissions measurements, conducting thermal modelling, and the modelling and monitoring of a house being refurbished to reduce GhG emissions.

Section 2 considers the importance of the existing residential building stock in reducing GhG emissions, now and in the future. Section 3 presents methods to calculate GhG emissions while Section 4 illustrates the case study that selects refurbishment strategies using AccuRate modelling and compares actual and predicted temperatures. The discussion is in Section 5 and the conclusion is reached in Section 6.

2. EXISTING RESIDENTIAL BUILDING STOCK

Many building GhG abatement strategies are *net positive* investments over the lifetime of the strategy (McKinsey 2008), (Levine et. al 2007) and so make excellent economic sense as well as lower GhG emissions.

Performance refurbishments of existing buildings are needed because:

- New homes are constructed at a slow rate (around 2% per annum),
- Operational GhG emissions, which can account for up to 80% of the total (WBCSD 2007), need reduction,
- They prolong the lifetime of buildings, greatly reducing the embodied emissions required for a new building,
- They lower the building emissions of fossil-fuel-dependent OECD nations (Urge-Vorsatz et. al 2007), and
- They can reduce emissions by up to 90% at low cost e.g. if major repairs are needed (Steinmüller 2008).

Globally, residential buildings produce the most GhG emissions, especially in rich nations, although emissions are increasing faster from commercial buildings (WBCSD 2007), (Shiel 2009a).

The demand for energy for space heating and cooling, with consequent GhG emissions, is projected to grow strongly in the next ten years because (DEWHA 2008), (Pears 1998):

- Insulation levels of the existing building stock are poor,
- Space cooling is increasing substantially, with air conditioners more than doubling in the past 10 years to about 65%, and some suburbs in western Sydney having a new install rate of over 90%,
- Many heating technologies are inefficient (Pears 1998), and central heating is increasing,
- More dwellings for the increasing population, with fewer occupants per household,
- There are a large number of leaseholders, who find it difficult to improve the building shell,
- Our population is ageing, increasing home occupancy levels and GhG emissions, ,
- The floor area of new and renovated residences is growing rapidly, offsetting building shell efficiency gains from more stringent energy provisions of the Building Code of Australia, and
- Climate change effects of higher temperatures are still accelerating.

3. METHODS TO CALCULATE GHG EMISSIONS

There are two basic approaches to calculate GhG emissions of refurbished houses, based on:

- Historical Emissions – where the annual delivered energy consumption is measured over one year for an existing building before and after the refurbishment. The GhG emissions are calculated for each fuel source by converting the delivered energy into Primary Energy, and uses the fuel source intensity factors, and
- Predicted Emissions – where the annual required energy values to keep a building in the comfort range of temperatures before and after refurbishment are calculated using a building thermal energy computer simulation package. The required energy is then converted to delivered energy using an efficiency factor heating and cooling appliances. Then the GhG emissions are calculated in the same manner as the Historical approach from the Primary Energy.

Historical Emissions Method

An example of the Historical approach is the NSW Energy Smart Home Rating Scheme (ESHRS) (SEDA 2004) where local councils paid for an Assessor to conduct a home rating, calculate GhG emissions and advise on improvements by:

- Discovering occupancy patterns for numbers of persons, weekly occupancy and annual holidays,
- Gathering details of the house such the floor area,
- Obtaining the energy consumption from the annual accounts, and fuel sources,
- Making a list of the major appliances and their power ratings,
- Calculating the star ratings and GhG emissions using a National Australian Built Environment Rating System (NABERS) spreadsheet.

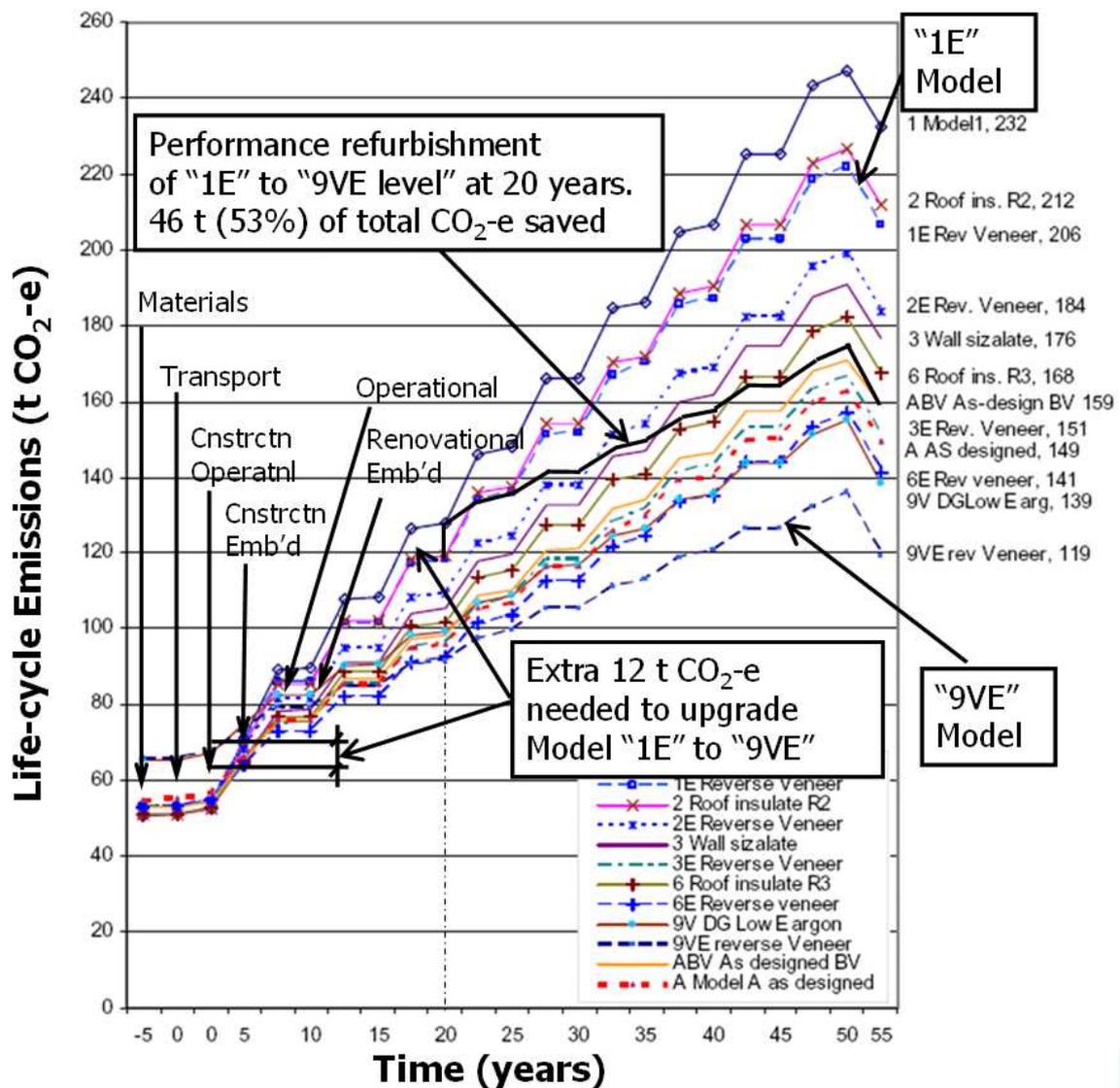
Then the Assessor would prepare an Energy Action Plan of possible refurbishment strategies and behavioural changes based on a template. The NSW government would verify the results and advice, and issue a certificate of energy and water star ratings for the house, both from 0 to 5, and of total annual operational GhG emissions. Another assessment would later measure the new GhG emissions.

Examples of other historical methods to calculate residential GhG emissions savings are the NABERS HOME rating scheme, the Federal Green Loans scheme (DCCEE 2010), and the UK's NHER (EHA 2008).

Predicted Emissions Method

An example of this approach to calculate GhG emissions is from Henriksen (Henriksen 2005) who used a full Life-Cycle Analysis (LCA) approach with construction, embodied, renovation and recycled emissions. She used the NatHERS 1st generation thermal modelling tool and a temperature discomfort-hours air-conditioning approach.

Figure 1 shows LCA emissions for a 50 year life-cycle for twelve new house design models, with one house upgraded as a "performance refurbishment" as annotated. The initial emissions are interesting: embodied emissions for materials, materials transport emissions, site construction and embodied emissions. Then each set of 5 years,



Source: (Based on Henriksen, 2005: p5:64)

Figure 1. Lifecycle CO₂-e Emissions for Model "1E" House, Refurbished at 20 years to Super-insulated "9VE"

there are operational emissions (although these only for heating and cooling) and component replacement (renovation) embodied emissions until at the end, the final point shows a credit, for the recycled embodied emissions.

House type "1 Model 1", is 2 storey with 2.4m ceilings, brick veneer/ weatherboard, slab on ground, single glazed Al windows, timber framed roof, 450mm eaves, with standard ventilation levels, sheet metal roofing on foil backed blanket. All models labelled with "E" (i.e. 1E, 2E etc.) are reverse brick veneer versions of the same model number, and these can be seen in Figure 1 to have lower GhG emissions than their brick veneer counterparts.

House models with lower overall slopes have fewer emissions due to more efficient forms and insulation, with the lowest slope house, super-insulated reverse brick veneer model 9VE, having efficient windows with a thermal break, and with total emissions of only 119 tonnes CO₂-e, including its embodied energy after demolition and recycling. These results correlate well with other high-performing refurbished LCA GhG emissions house research (EHA 2008).

Another Australian predictive method is the Victorian STEPS rating tool (MCC 2010), and international predictive methods are used in tools such as ARUP's ENERGY2 (Hacker et. al 2008), the EU's EPA-ED (Poel et. al 2007), EQUER which relies on the Thermal Simulator COMFIE (Peuportier 2001), and the global SBTool (iISBE 2009).

LCA Emissions - Refurbish or Demolish?

Life-cycle emissions due to refurbishment are illustrated in Figure 1 where house Model 1E (a reverse brick veneer version of Model 1) is refurbished to Model 9VE (the super-insulated version). It is assumed refurbishment embodied emissions of approximately 12 tonnes CO₂-e are needed to carry out the refurbishment (shown in Figure 1 at 20 years, and obtained from the difference in their initial construction and embodied emissions at "+5 years").

If the building was demolished and replaced with a new super-insulated Model 9VE, it would emit over 100 tonnes of GhG in 30 years. However, the refurbished building used only a further 40 tonnes (160 - 120) of GhG emissions, saving 46 tonnes (206 - 160), a LCA emission decrease of 53% (46/(206 - 120)) from Model 1E emissions.

Method Effectiveness

The criteria used to compare the effectiveness of residential refurbishment GhG emission methods are 1) the scope of energy consumed e.g. all delivered energy including for all services, or just the energy required for heating and cooling the property; and 2) the assumptions used. For the Henriksen method, assumptions include embodied carbon and thermal appliance efficiencies, and for both methods - standard climate data, occupant behaviour including the house occupancy periods, and assumptions in the emission calculations such as with Primary Energy conversion.

The ESHRS method is effective in calculating the actual operational household annual emissions in arrears, but it does not calculate embodied carbon, nor provide detailed refurbishment strategies due to the limitations of the small time spent at the house, and the lower skill levels of the Assessor. A return visit is needed to measure the difference in full house GhG emissions, at least one year after a refurbishment.

The Henriksen method is effective in predicting the refurbishment embodied and operational emissions as shown in Figure 1, although Henriksen developed her method for new houses. The embodied carbon is comprehensive although it relies on source assumptions (extraction, manufacturing, travel), and the operational carbon is limited in scope to heating and cooling energy, not the whole house as in ESHRS. This method requires more investment in time, plans, material specifications, skills and tools to calculate refurbishment lifecycle emissions.

4. CASE STUDY

House Description

Figure 2 Part a) shows the case study which is a small 120 m² project home located in Newcastle, Australia with a mild subtropical climate. The 10-year-old home has two bedrooms plus study and was purchased in 2009 with the intentions of undertaking a performance refurbishment, and then installing solar photo-voltaic (PV) panels. The envelope conditions were slab-on-ground, brick veneer with wall sarking, plasterboard for internal walls and ceiling, no ceiling insulation, colorbond roof with sarking, single-glazed aluminium framed windows and 60cm eaves.

Local contours mean that houses to the North East and South East overshadow the garage and rear bedroom walls all morning, and there is about 10% tree shading on the South Eastern side. The house has town gas which is used for hot water and cooking only, and has no air-conditioning. The living/kitchen wall has 70% glass and is oriented 50 degrees North of West, introducing high heat loads with summer discomfort. The house is occupied by two adults, who work at home and have energy efficient appliances e.g. a desk 160W panel heater (Thermofilm 2010), and use zoning techniques and night purging.

Refurbishment Strategy Method

The Architect used AccuRate (Delsante 2005), (Saman et al. 2008) a building thermal modelling program, in a design manner to find the most cost-effective refurbishment strategies. An example of one strategy is the Pergola design in Part b) of Figure 2 (Hunt 2010) and its energy impact is shown in Figure 4. The AccuRate temperatures were also generated to check the impact of the strategies. USB calibrated data loggers (DigiTech 2010) tracked temperatures at 30-minute intervals from three locations: outside on SE in shade, in the Living/Kitchen room and in Bedroom 1.

Accurate Simulation & Temperatures

The initial evaluation indicated that the home had low thermal performance, with an AccuRate rating below average of 1.9 Stars. Part a) of Figure 3 shows the Living and Bedroom1 temperatures predicted by AccuRate, before and after R4 ceiling insulation was installed in "free running" mode – with no ventilation behaviour or heating and cooling .

Logged Temperature Data

Figure 4 shows the logged temperatures for three hot days during strategy implementation:

- Before occupation and before ceiling R4 insulation was installed,
- Before occupation and after ceiling R4 insulation was installed, and
- After occupation and after ceiling R4 insulation was installed.

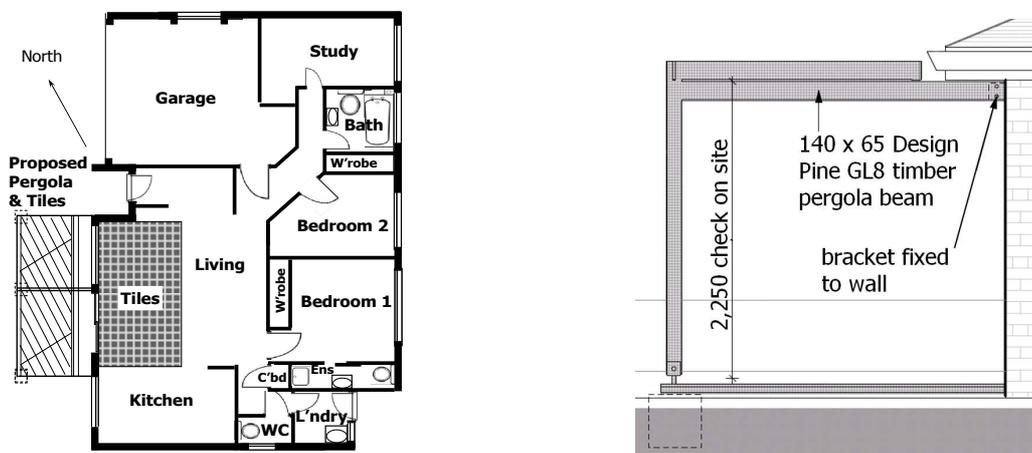


Figure 2. a) Plan of Case Study

Source: (Hunt, 2010)
b) Pergola Elevation

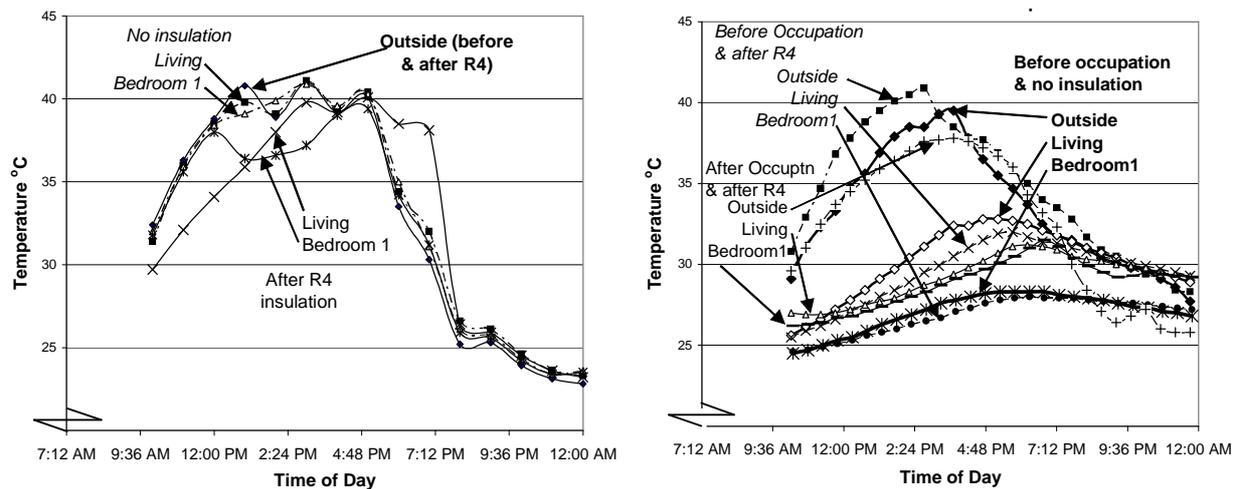


Figure 3. Effect of R4 Ceiling Insulation in Case Study.
3a (left) has AccuRate Predicted Temperatures for Hottest Day - no Heating or Cooling, and
3b (right) has actual Logged Temperatures for 3 Hot Days in Summer

Selection of Refurbishment Strategies

The AccuRate case study base case (existing house) results were a total of 240 MJ/m²/y required “comfort” energy for the house (147 MJ/m²/y heating energy and 92.9 MJ/m²/y cooling energy).

Various strategies were researched and investigated (Wrigley, 2007). Figure 4 shows the heating and cooling energy saved by the refurbishment strategies modelled. The case study uses a variation of Henriksen’s method since it relies on the AccuRate required energy to estimate emissions and choose low-cost strategies. This assumes that the AccuRate approach with its conditioning behaviour rules is acceptable.

The AccuRate design approach indicates that single strategies “draught-proofing external doors” and “R4 ceiling insulation” are effective and low cost (shown by the energy savings in MJ/m²/y and low capital cost after rebate in AU\$). The upper half of Figure 4 shows the results of R4 ceiling insulation and another strategy.

5. DISCUSSION

Comparison of Methods

The ESHRS Historical Method calculates the total operational GhG emissions as well as house ratings for energy and water. The emissions are all the previous year’s operational GhG emissions, since they are based on the actual household behaviour. The quality of the advice for refurbishment strategies depends on the skill of the Assessor.

The emissions are calculated per person, and there may be a small error in determining the occupancy in person-weeks. It is difficult to measure the GhG emissions of an actual refurbishment, since it needs a return assessment, and the GhG emissions may be affected by different occupancy and appliance patterns. It cannot compare thermal performance between houses and does not consider embodied or refurbishment emissions.

The Henriksen Predictive Method is an LCA method that uses thermal modelling to calculate GhG emissions. This method can compare specific refurbishment strategies for the particular building. These can be costed and ranked over the lifetime of the strategy, and can include simple payback periods.

Henriksen used assumptions that included 1) a 50 year building life-cycle, whereas other LCA methods use various life spans such as 70 years (Randolph et al. 2007) 50 years (EHA 2008), 100 years (Hacker et. al 2008); 2) the NatHERS climate year data used 50 times to calculate the operational CO₂-e emissions; 3) embodied emissions as well as operational emissions (which allowed investigation here of refurbishment embodied emissions); and 4) calculation of CO₂-e emissions for the energy used in NSW by air conditioning when zones were outside the comfort range. This method requires more investment in time, skills and tools to calculate refurbishment life-cycle emissions (see Figure 1). However, it allows the selection of cost-effective refurbishment strategies.

Calculation of GhG Emissions

On a CO₂-e basis in 2002, fluorinated gases made up about 20% of all energy-related CO₂-e emissions from buildings e.g. from air conditioning (Urge-Vorsatz et. al 2007), but neither approach considers these emissions.

Also, both approaches rely on the assumptions of the Factors Handbook (DCC 2008) for emissions related to fuel types, manufacturing and transmission losses which assume local state averages. This ignores the Eastern electricity transmission grid and introduces local errors e.g. Tasmania uses some electricity generated from Victoria’s brown coal generators with high factors, although the factors used in Tasmania are low (for renewable hydro-electricity).

Thermal Modelling

Thermal modelling software (TMS) calculates a house star rating; the annual heating and cooling energy required for comfort; and the temperatures of each room for every hour of the year using dynamic comfort range rules. From either of these latter two results, we can estimate GhG emissions.

The AccuRate TMS uses physics equations of thermal heat transfer, and uses standard assumptions such as average local climate; occupant and equipment heat loads; occupancy periods and thermometer settings per room type; venting of the building; house size and orientation; shading; thermal properties for materials and systems; heating and cooling behaviour; and dynamic comfort ranges. The Assessor models refurbishment strategies as variations to the plan and specification, and generates new heat requirements and temperatures.

Australia's first TMS was NatHERS, and current applications are AccuRate, BERS and FirstRate (Other House Energy Rating Software, 2010), that have more features and better capabilities. Some houses cannot be modelled or rated adequately e.g. in tropical areas if not air conditioned. Some discrepancies between modelled and measured conditioning energy are due to high-energy consuming households.

Case Study Temperatures

External temperatures for the hottest day in summer for the AccuRate temperature predictions in Part a) of Figure 3 follow on from a previous day which was also hot, and the calculations were done in the "free running" mode. So the internal temperatures remain high since the rooms have not had a chance to cool down. Other factors which may have kept the internal temperatures high are the orientation of the Living room and Bedroom 1, and that AccuRate assumes some occupant & equipment heat loads.

The effect of R4 ceiling insulation in Part a) of Figure 3 is predicted to lower the internal rooms by 2-3°C, with Bedroom 1 having comfortable temperatures by 8pm, even after consecutive hot days.

The internal zone temperatures for the logged temperatures in Part b) of Figure 3 are lower than predicted, because the climate data is different (outside temperatures on consecutive days were lower than those for AccuRate). Other trends in Part b) of Figure 3 are that ventilation behaviour had some influence on reducing the internal temperatures after the occupants moved in, and the significant influence of R4 ceiling insulation. Also, other possible reasons for the logged temperatures being different to the AccuRate ones are:

- The sensors are located near walls, which may be slightly cooler than the centre of the room, and
- The external temperature was from one shaded spot contrasted with AccuRate's location climate data.

Case Study Refurbishment Strategies

The Architect modelled the existing house base case, and twenty-four refurbishment strategy models. The energy savings and temperature graphs for the hottest and coldest weeks were compelling evidence to choose the most effective strategies, and which did not prove too costly. These changed the house rating from 1.9 to 5 or 6 stars.

The refurbishment strategies adopted were R4 ceiling insulation, weather stripping, pergola and thermal mass, lined and sealed curtains, ceiling fans and temporary double-glazing with thermal break window additions.

The complexity of the thermal modelling is shown in Figure 4 where the required energy for combined R4 ceiling and foil strategies is less than that achieved by adding these two together separately.

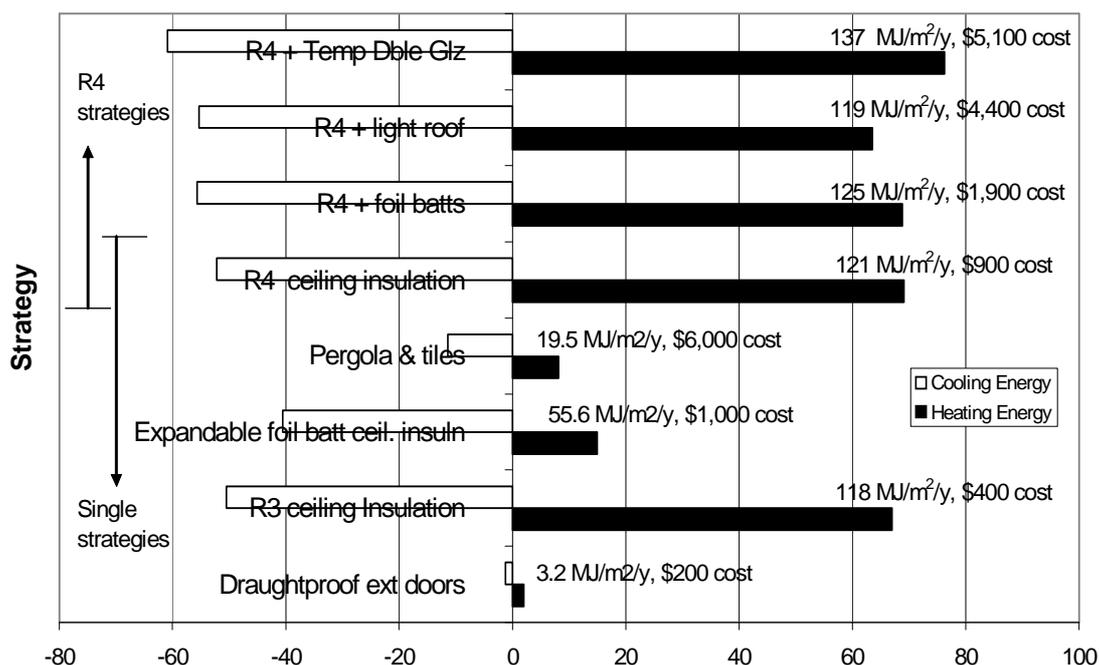


Figure 4. The Predicted AccuRate Energy Savings of Strategies for Existing House.

The capital costs assisted in the choice, although the preferred approach is to calculate the total cost of ownership over the life of the strategy. This could be a simple payback period for cost based on energy savings, with utility price rise assumptions or use the net present value (NPV) method. Also, a life-cycle emissions simple payback period can be calculated, if the embodied emissions of the refurbishment are known as well as operational emissions.

The required energy from the thermal modelling is proportional to the GhG emissions if the same fuel source is used for heating and cooling, as it was in this case. The gas emission factor would be used if gas were used for heating.

The Cross-Disciplinary Applied Research in the Case Study

The case study illustrates cross-disciplinary applied research with Scientific prediction and measurement in Architectural Science; Engineering design; and implementation according to Building practices.

An Architect used Accurate that utilises scientific heat transfer physics principles to estimate heating and cooling energy saved by refurbishment strategies, and predict internal temperatures, and the model was checked for consistency. Strategies were selected for their energy and emission savings, as well as low capital cost, and minor footing engineering details will be added to the Pergola architectural plans. The refurbishment details already built include the R4 ceiling insulation, ceiling fans, solar light tube, living room extraction fan, draught-proofing, and lined and sealed curtains. Scientific Measurement was used in monitoring the temperature and humidity with calibrated logging devices which tracked comfort levels and allowed measurement of the effectiveness of each strategy.

Further Research

Research should focus on envelope refurbishments that are the most effective for indicative samples of the existing Australian residential stock in terms of common construction types, materials and shading, and taking into account climate change scenarios.

With the current trend of accelerating Global Warming, reliable tools that are easy to update and use to use that identify practical low- and zero-GhG-emission strategies for the existing residential stock, will become particularly important for Australia's future.

6. CONCLUSION

We urgently need to upgrade the existing building stock to avoid the more extreme effects of climate change by not adding any more building GhG emissions to the stratosphere, and building refurbishments are paramount.

Answers to the specific research investigation questions are

- 1) The methods to calculate residential refurbishment GhG emissions are** grouped into **historical** and **predictive** approaches. Historical approaches are better suited to analysing GhG emissions of existing houses in arrears, whereas predictive approaches can be used to compare the GhG emissions of refurbishment strategies.
- 2) The criteria to compare the effectiveness of residential refurbishment GhG emission methods** comprise a) **what energy** is referred to e.g. all delivered energy including for all services, or just the energy required for heating and cooling the property; and b) the **assumptions** e.g. for thermal modelling – embodied refurbishment emissions and thermal appliance efficiencies, and for both methods - occupancy periods and Primary Energy conversion.
- 3) The historical ESHRS method** is effective in calculating existing household emissions in arrears, but it can only provide only general advice about refurbishments. A return visit is needed to measure the difference in full house GhG emissions, at least one year after a refurbishment. The **predictive Henriksen method** can predict a new house's embodied and operational emissions, but is effective in comparing the lowest emission-effective refurbishment strategies. A skilled Accredited Energy Assessor is required to perform the modelling, and a plan of the building and its material specifications are required. It does not take into account the actual occupant behaviour.

A residential performance upgrade case study illustrated the use of thermal modelling to select the most practical and cost-effective strategies.

7. ACKNOWLEDGEMENT

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