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Design to Thrive

Adapting to a Warmer Climate – Affordable Low-carbon Retrofits and Occupant Options for Typical Australian Houses

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Abstract: This paper describes the cost-effectiveness of adapting Australian houses and occupant behaviour to reduce room temperatures and heating and cooling requirements in a warming world. We used CSIRO's Australian Climate Futures framework and Belcher's "morphing" technique to project the 2050 climate; a novel Standard Effective Temperature (SET*) thermal comfort approach where occupants modify their behaviour and tolerate higher temperatures; a do-it-yourself (DIY) retrofit approach to find the most cost-effective retrofits simulated for typical Australian houses; and combinations of retrofits with small, medium and large simple payback periods (SPPs) to suit occupant categories. The most effective strategies were modifying occupant behaviour; partitions to reduce the conditioned volume; ceiling and roof insulation; gap sealing; and retrofits to suit the type of house construction (such as wall and under-floor insulation, and internal brick walls for added thermal mass if there was a concrete floor). The research suggests that deeper retrofits may be needed than those provided by the large SPP retrofit combinations in 2050 to adapt to high indoor temperatures, even after changing behaviour regarding higher air speeds and lighter clothing.

Keywords: cost-effective retrofits, existing houses, carbon emissions, extreme climate change, occupant adaptation

Introduction

Adapting a household for climate change means changing occupant behaviour or retrofitting the house for the projected effects of regional climate changes that may occur over the remaining life of the house (e.g. for higher house temperatures, greater wind speeds or bigger floods).

Global temperatures are rising at a potentially catastrophic rate (Nuccitelli 2016). The number of storms, floods and temperature-related natural disasters have increased from 300 to 900 over the past 35 years, with many hundreds of billions of dollars in property damage since 1980 alone (MunichRe et al., 2015, pp. 43–44). Sir Nicholas Stern has now stated that he had greatly underestimated the damages from climate change, following the poor response of global leaders (ClimateWire and Narayanan, 2013).

Australia has agreed to keep global temperature increases well below 2 °C, implying a zero-emissions economy by 2050, but has one of the world's worst-performing building stocks per capita, and where residential buildings are responsible for around 13% of all Australia's emissions. Since around 30% of the 2050 residential stock exists now and houses make up 80% of residences, it is important to retrofit existing houses for climate change (Shiel, 2017).

Improving the performance of the envelope in the housing industry is difficult due to the number of stakeholders, low energy efficiency of older houses, and a lack of relevant knowledge, of both owners and building contractors.

Since improvements are more likely if convenient, easy and affordable (Bond et al., 2011), the aim of this paper is to find cost-effective low-carbon retrofits and behaviour-change strategies to lower the effective temperatures felt by household occupants. These adaptation strategies may also mitigate climate change by lowering energy use and therefore carbon emissions.

Methodology

Climate Change

We undertook climate change modelling with the Climate Futures tool (CSIRO, 2016) to find the most appropriate general climate model (GCM) based on 1) the representativeness of the 'Maximum Consensus' case, 2) model skill and 3) availability of requisite variables (Clarke et al., 2011; J. J. Shiel et al., 2017).

Although two scenarios were examined for 2050, only one is reported here, namely the Extreme Climate Change scenario. (The Scarce Resource scenario results are reported in (J. Shiel et al., 2017)). The Extreme Climate Change scenario is a future of "business as usual" (Peters et al., 2013, p. 5) with a plentiful supply of fossil fuels, and corresponds with RCP8.5, where RCP is a Representative Concentration Pathway (RCP) (van Vuuren et al., 2011).

We generated plausible Reference Meteorological Year (RMY) Adelaide climate data for 2050 (Shiel, 2017) using:

- Belcher's "morphing" technique (Belcher et al., 2005) with the selected GCM, and
- the Adelaide 1990 RMY climate file dataset from NatHERS.

Retrofits

The characteristics of the existing houses modelled are provided in Table 1, and these were chosen to match typical Australian house constructions e.g. with external walls of weatherboard, cavity brick, and brick veneer (DEWHA, 2008; Shiel, 2017).

Table 1 – House Characteristics for the three existing houses H1 – H3

	House 1	**House 2**	**House 3**
Era	1950s	1980s	2010s
Area	112m2	187m2	223m2
Ext. Walls	Weatherboard	Cavity brick	Brick veneer
Int. Walls	Plasterboard	Single Brick	Plasterboard
Floor	Timber floor	Timber floor	Concrete slab
Garage	None	Single car	Double car
Ceiling insulation	None	None	R1 K·m²/W
Roof	Tile	Tile	Metal
Ceiling Height	2.74m	2.4m	2.4m
Eaves	450mm	600mm	600mm
Windows	Timber single-glazed windows	Aluminium single-glazed windows	Aluminium single-glazed windows

Seventy retrofits were modelled for each house including partial air-conditioning; perimeter insulation; weather-stripping; adding thermal mass; and other measures such as low-e window films and external vegetation.

We used the NatHERS AccuRate software to calculate the required energy for comfort for the retrofits; estimated their do-it-yourself (DIY) cost and carbon savings for a split-system air-conditioner in Adelaide; and ranked the retrofits by simple payback period (SPP). Retrofits were combined for three sets of costs that had small, medium and large payback periods to suit occupant categories of tenants; of owners and landlords; and of householders who would like to carry out deep retrofits (J. Shiel et al., 2017).

Occupant Behaviour Changes

For occupant behaviour change, we rely on a previous study (J. J. Shiel et al., 2017) of the effects on energy savings of an alternative Standard Effective Temperature (SET*) comfort approach, for the same warming climate scenarios for 2050. It suggested that dwelling occupants could be comfortable at higher temperatures by changing their behaviour regarding air speed and clothing.

The effective temperature felt by occupants with this alternative SET* approach depends on the six parameters: air temperature, radiant temperature, air speed, humidity, clothing and metabolic rate, with a wider comfort temperature band than used in NatHERS.

Results

The results reported here are for the Adelaide region ("Southern & SW Flatlands (East)") Extreme Climate Change scenario in 2050, with an air-conditioner and DIY costings.

Climate Change

HADGEM2-ES was found to be the most appropriate GCM and the annual average of the mean monthly increase for temperature was projected to be 1.8 K from 1995 to 2050 (CSIRO, 2016; J. Shiel et al., 2017).

House Retrofits

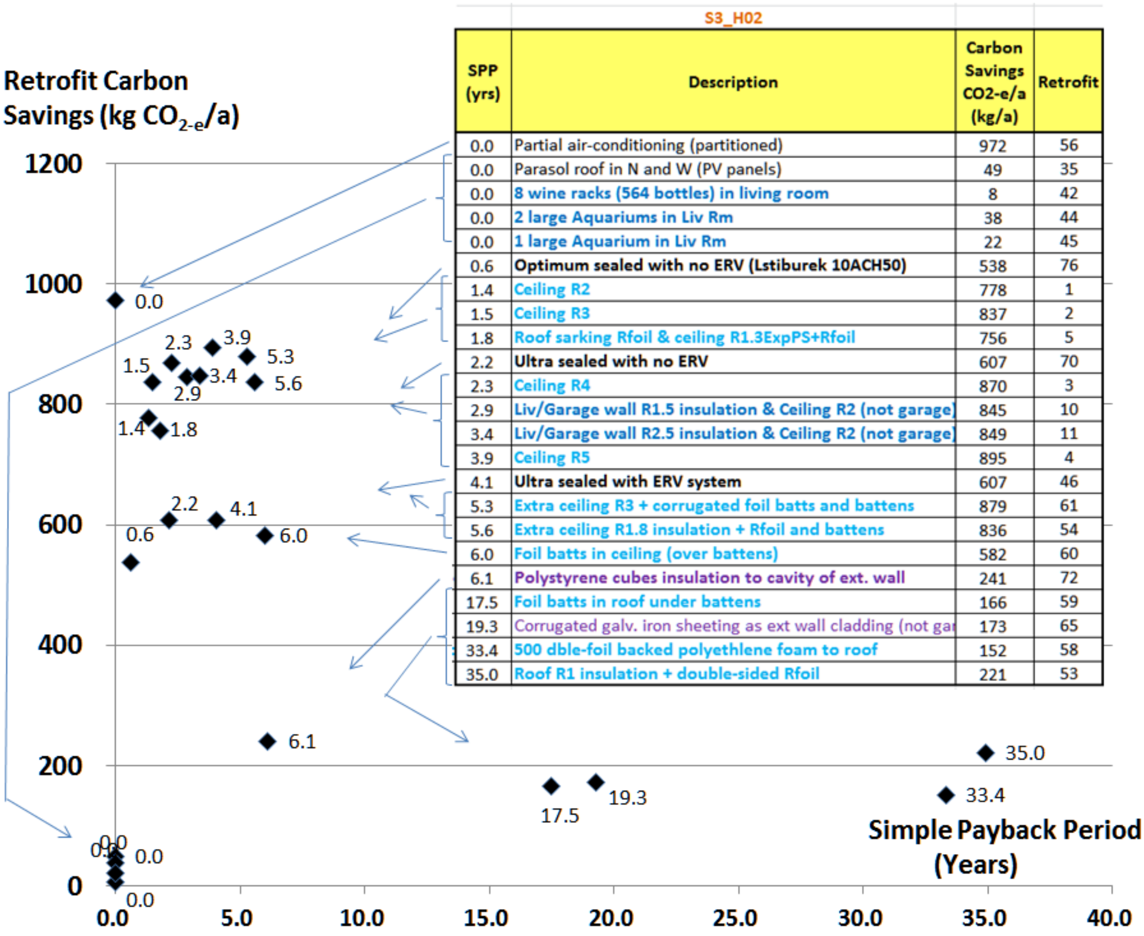
Figure 1 shows the single retrofit carbon savings by payback period for House 2, which shares characteristics of House 1 (e.g. a timber floor) and House 3 (a garage with concrete floor) and illustrates the general trend of single retrofits. It has a table that ranks the House 2 cost-effective retrofits by payback period, and similar retrofits are colour-coded as shown in Table 2. Furthermore, the size of carbon savings provide a general indication of how effective each retrofit is in keeping the temperatures of all the conditioned rooms in the NatHERS temperature comfort band.

Table 2 shows the indicative costs and carbon savings of cost-effective single retrofits for House 3, and includes only the retrofits for Houses 1 and 2 where they are in common. The older House 1 has more cost-effective retrofits than Houses 2 and 3 (Shiel, 2017).

Figure 2 shows the carbon savings and SPPs for various combinations of retrofits for each house to suit occupant categories. The retrofits that make up the large SPP combination for each house are provided in Table 3, and the small and medium SPP retrofit combinations are mostly subsets of these sets of retrofits (Shiel, 2017).

Adapting to Indoor 2050 Temperatures

Figure 3 shows the effects of the large SPP set of retrofits on the free running, or naturally conditioned temperatures of houses 1 and 3, for the living room and bedroom one, on the hottest day in 2050.



SPP (yrs)	Description	Carbon Savings CO2-e/a (kg/a)	Retrofit
0.0	Partial air-conditioning (partitioned)	972	56
0.0	Parasol roof in N and W (PV panels)	49	35
0.0	8 wine racks (564 bottles) in living room	8	42
0.0	2 large Aquariums in Liv Rm	38	44
0.0	1 large Aquarium in Liv Rm	22	45
0.6	Optimum sealed with no ERV (Lstiburek 10ACH50)	538	76
1.4	Ceiling R2	778	1
1.5	Ceiling R3	837	2
1.8	Roof sarking Rfoil & ceiling R1.3ExpPS+Rfoil	756	5
2.2	Ultra sealed with no ERV	607	70
2.3	Ceiling R4	870	3
2.9	Liv/Garage wall R1.5 insulation & Ceiling R2 (not garage)	845	10
3.4	Liv/Garage wall R2.5 insulation & Ceiling R2 (not garage)	849	11
3.9	Ceiling R5	895	4
4.1	Ultra sealed with ERV system	607	46
5.3	Extra ceiling R3 + corrugated foil batts and battens	879	61
5.6	Extra ceiling R1.8 insulation + Rfoil and battens	836	54
6.0	Foil batts in ceiling (over battens)	582	60
6.1	Polystyrene cubes insulation to cavity of ext. wall	241	72
17.5	Foil batts in roof under battens	166	59
19.3	Corrugated galv. iron sheeting as ext wall cladding (not ga	173	65
33.4	500 dble-foil backed polyethlene foam to roof	152	58
35.0	Roof R1 insulation + double-sided Rfoil	221	53

Figure 1 - The carbon savings by payback period of cost-effective do-it-yourself (DIY) retrofits for House 2, a 1980s cavity brick and timber floor house. The values are labelled with their SPPs, and the table is ranked by SPP and colour-coded as in Table 2. The other house results are in (Shiel, 2017).

Behaviour Change

The SET* comfort approach provided an extended comfort temperature band for free-running thermostat values in Adelaide of 14.2 °C to 34.8 °C based on modified air speed and clothing levels where the occupants would effectively feel like it was 16 °C to 28 °C (J. J. Shiel et al., 2017).

Discussion

Before adapting a house for climate change, a life-cycle household carbon and costing analysis should be carried out, especially with housing shortages in Australia (Iyer-Raniga, 2010).

Single Retrofits

The most cost-effective retrofits to lower Australian house temperatures are partitions to reduce the conditioned volume, ceiling and roof insulation, optimum weather-stripping e.g. by Lstiburek in (Aynsley and Shiel, 2017), and those that suit the type of house, e.g.

- wall insulation for the weatherboard and cavity wall houses with timber floors;
- under-floor insulation for the old weatherboard house; and
- added thermal mass with internal walls where there is a concrete floor.

Some retrofits with little effect were included because of the DIY costing approach, where they were assumed to be at zero cost, e.g. if part of a hobby or already part of the house such as aquariums or photovoltaic panels (Shiel, 2017).

Table 2 –Cost-effective single retrofits of House 3 and where these are shared with Houses 1 and 2. The retrofits are colour coded for roof and ceiling (light blue), walls (purple), floors (brown), thermal mass (dark blue), sealing (bolded black) and other (black).

		House 3		House 2		House 1	
Retrofit	**Description**	**SPP (yrs)**	**Carbon Savings CO_2-e/a (kg/a)**	**SPP (yrs)**	**Carbon Savings CO_2-e/a (kg/a)**	**SPP (yrs)**	**Carbon Savings CO_2-e/a (kg/a)**
35	Parasol roof in N and W (PV panels)	0.0	34	0.0	49	0.0	59
44	**2 large Aquariums in Liv Rm**	0.0	35	0.0	38	0.0	22
45	**1 large Aquarium in Liv Rm**	0.0	22	0.0	22	0.0	16
42	**8 wine racks (564 bottles) in living room**	0.0	10	0.0	8	0.0	74
76	**Optimum sealed with no ERV (Lstiburek 10ACH50)**	1.2	365	0.6	538	0.9	379
3	Ceiling R4	6.0	254	2.3	870	1.4	890
10	**Liv/Garage wall R1.5 insulation & Ceiling R2 (not garage)**	10.6	190	2.9	845		
59	Foil batts in roof under battens	49.8	66	17.5	166	4.4	364
65	Corrugated galv. iron sheeting as ext. wall cladding (not garage)	19.8	80	19.3	173	6.9	263
74	**Polystyrene cubes insulation to full 140mm cavity of ext. wall**	16.9	126				

Importance of Thermal Mass

An envelope with low diffusivity (where diffusivity is conductivity divided by thermal mass) is needed to maintain comfortable free running internal temperatures in temperate climates (Barrios et al., 2011). So having the appropriate level of thermal mass is an important retrofit to keep future energy requirements low, in addition to the right levels of radiation and insulation (Baggs and Mortensen, 2006).

Thermal mass retrofits were cost-effective for the two houses with attached concrete floor garages by adding an insulated internal garage brick wall. The brick wall retrofit was included as DIY because some householders can undertake this retrofit and it was an important retrofit while contractor costs were included for a few other retrofits, such as the ERV system (Shiel, 2017).

Combined Retrofits

For retrofit combinations, the partial air-conditioning retrofit was not used, since it does not have a temperature-lowering adaptation effect, but can be useful in lowering emissions.

Retrofit combinations with a small payback period of three years may suit tenants, those with little disposable income, those who may not be staying long in the house, or those in old houses that will only experience mild effects of climate change. Those with a higher level of disposable income could carry out the medium level of SPP retrofit combinations, whereas households keen to carry out deep retrofits could use the retrofit combination with a large SPP.

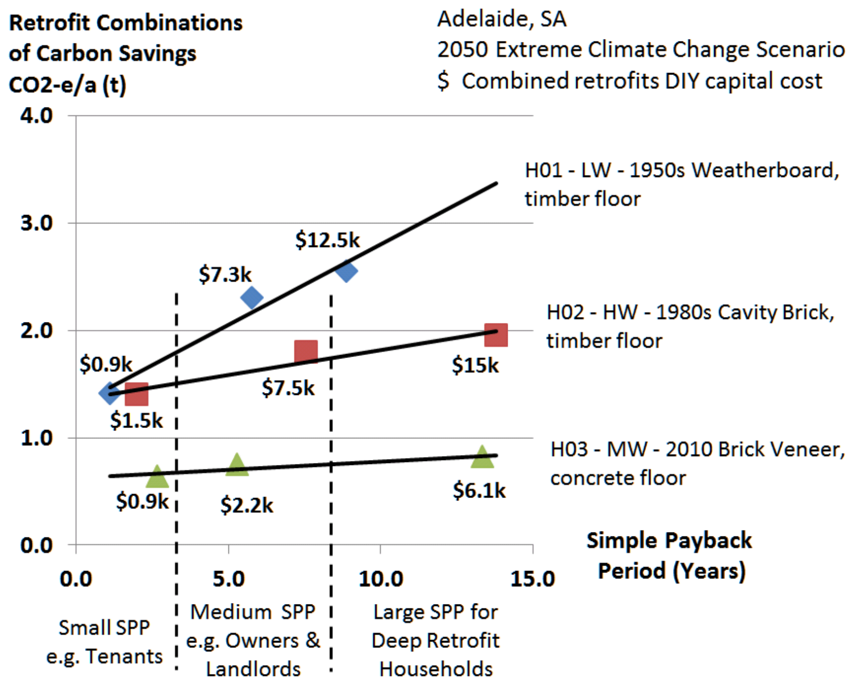


Figure 2 - Carbon savings by SPP for combinations of retrofit by house type and era (with 1950s weatherboard or light-weight walls – LW; 1980s cavity brick or heavy-weight walls – HW; and 2010 brick veneer or medium-weight walls – MW) with degree of retrofit (small, medium and large) to suit occupant categories. The dollar label refers to the DIY capital cost of the retrofit SPP combination.

Adapting Houses and Occupant Behaviour for 2050

Figure 3 indicates that the living room free running temperatures after the large retrofit combinations in Table 3 will reach 43 °C for House 1 and 41 °C for House 3, a reduction of up to 7 K and 6 K respectively.

Table 3 – The retrofits making up the combinations of the large payback periods, to suit deeper retrofit households as shown in Figure 2 (**retrofits are bolded** if in common).

House 1	House 2	House 3
3 - Ceiling R4 Insulation; 16 - Underfloor 90mm gap & 1500 bubble Insulation with dbl-sided Rfoil; 26 - 5m high deciduous trees to North windows; 32 - Low-e film applied to windows; **35 - Parasol roof in N & W roof; 42 - 8 wine racks (564 bottles); 44 & 45 - 3 large Aquariums;** 49 - 1.4m dia Ceiling fans; 53 - Roof R1 insulation; 55 - Green ivy on North & West walls; **59 - Foil batts in roof under battens;** 62 - Foil batts stapled under floor; 67 - Carpet to timber floor; **72 - Polystyrene cubes insulation to cavity of ext. wall; 76 – Optimum sealing (Lstiburek $10ACH_{50}$).**	5 - Roof sarking Rfoil & ceiling R1.3 expanded polystyrene + Rfoil; **10 – Add Liv/Garage brick wall with R1.5;** 18 - R2.5 polystyrene batts under timber floor; 34 - Low-e film tint to non-North windows; **35; 42; 44 & 45; 59;** 58 - 500 dbl-foil backed polyethylene foam to roof; 60 - Foil batts in ceiling; 62 - Foil batts underfloor; **65 – Corrugated galv. iron sheeting as ext. wall cladding; 72; 76.**	**3; 10; 35; 42; 44 & 45; 59; 65;** 74 – Poly-styrene cubes to full 140mm cavity of ext. wall; **76**

In Figure 3, for bedroom one in House 3, the maximum night temperature after retrofits is 34 °C, lowering the maximum temperature by 2 K. However, for House 1 the bedroom one temperatures are actually higher after the retrofits, due to the bedroom's location on the western side and the retrofits preventing heat escaping at night (e.g. perimeter insulation and greater sealing).

Household occupants can adapt with behaviours such as using higher air speeds and wearing lighter clothing to tolerate 34.8 °C during the day and 30.4 °C at night to feel like it is 28 °C and 26 °C respectively, with night comfort under high temperatures deserving more research (J. J. Shiel et al., 2017). However, when temperatures exceed 35 °C, there is a high risk of heat stroke as heat exchange with the environment is greatly diminished (Hanna and Tait, 2015, p. 8050), particularly for infants and elderly.

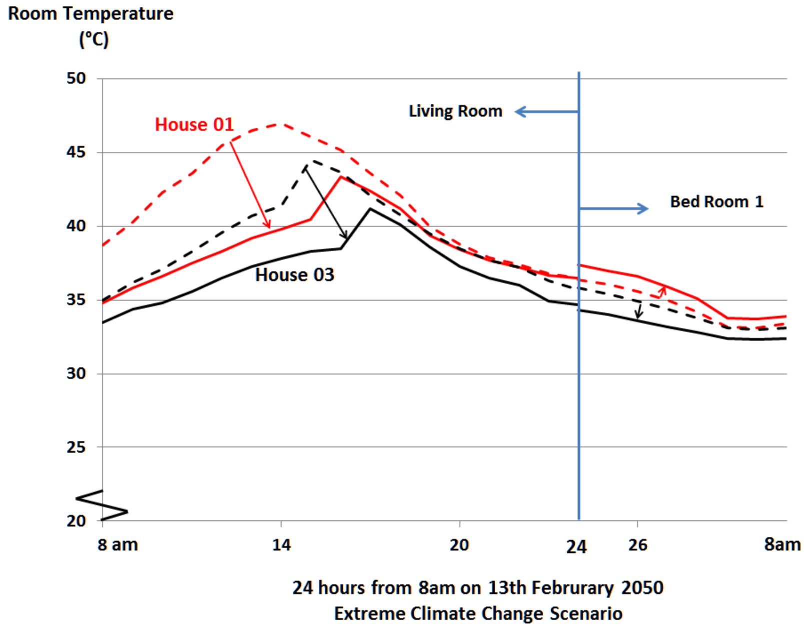


Figure 3 – The change in living and bed room free running temperatures after the combined retrofits of the largest payback period for the hottest day in 2050. These are for House 01 (1950s weatherboard) and House 03 (2010 brick-veneer), where the external maximum temperatures for day and night were 46 °C and 36 °C respectively, with maximum corresponding relative humidity levels of 20% and 38% respectively.

Cool Retreats

These results suggest that deeper retrofits are required to lower temperatures, and that there should be a greater focus on retrofitting rooms to become cool retreats. This includes changing room types and ventilation strategies e.g. moving bedrooms away from the western side, having separate living spaces for winter and summer, as well as specific retrofits and technologies to keep one room cooler (Aynsley and Shiel, 2017; Roaf et al., 2005; Saman et al., 2013).

Conclusion

The key findings are that:

- Many cost-effective retrofits can be found for older timber-floored Australian houses to adapt to a warmer future, with a fewer number identified for more modern houses with concrete floors.
- Retrofit combinations for small, medium and large payback periods were found to suit different occupant categories, with up to a 7 K reduction in room temperatures in 2050.

- Large payback period retrofit combinations as well as occupancy behaviour change may still be insufficient for Adelaide in 2050 for the Extreme Climate Change scenario, requiring deeper retrofits and special room modifications as cool retreats.

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