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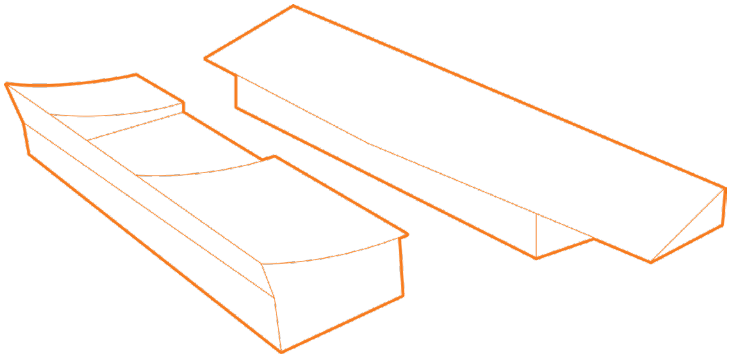

HOME RETROFITS FOR BUSHFIRE RESILIENCE AND ENERGY EFFICIENCY

FINAL REPORT

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ABOUT THIS REPORT

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Executive Summary

This report outlines contributions made by the Sustainable Buildings Research Centre (SBRC) at the University of Wollongong to a pilot project run by the Resilient Building Council (RBC). The project focused on integrating home assessments and retrofits for the dual purposes of improved energy efficiency and improved bushfire resilience.

Site inspections were undertaken at 29 case study houses of various ages and construction types. Two existing tools were used to guide separate inspections of each property: the RBC Bushfire Resilience Star Rating tool focused on bushfire resilience, and the Residential Efficiency Scorecard tool focused on home energy efficiency. Both tools automatically generate a tailored set of retrofit options for the household to consider, based on the assessment.

This report focuses on two aspects of the study:

1. It presents an assessment of potential co-benefits, conflicts, and other considerations that arose when investigating how the two separate home assessments could be integrated in the future.
2. It presents a detailed life cycle assessment of the greenhouse gas (GHG) emissions abatement potential of retrofits suggested for the 29 case study houses; this analysis included:
   a. The 'embodied' emissions associated with materials needed to undertake the retrofits;
   b. The 'operational' emissions abatement achieved through improved energy efficiency; and
   c. The emissions abatement achieved through improved bushfire resilience, caused by a decrease in the risk that the house will be destroyed by future bushfires and need to be rebuilt using new materials with their own 'embodied' emissions.

The last of these points (i.e. 2c) does not appear to have been investigated previously.

Key results from the study include the following:

- Integrated home assessment and retrofit programs for bushfire resilience and energy efficiency will need to overcome several challenges, not least of which is the need to establish a basis for the comparison and prioritisation of retrofits that is appropriate for both purposes (i.e. a method to compare benefits in life and property safety with those in improved energy efficiency).
- A range of co-benefits, potential conflicts, and other considerations have been identified for specific retrofit actions. Future projects aiming to integrate bushfire and energy-efficiency

retrofits should take such interactions into account. In many cases doing so limits the range of suitable materials or methods for the retrofit, or shifts the cost-benefit ratios of retrofits, thus mitigating the risk of adverse outcomes (e.g. the vulnerability to bushfire being increased by energy-efficiency retrofits) and maximising the efficiency and effectiveness of the retrofits (e.g. by prioritising actions that provide substantial co-benefits).

- The magnitude of net lifecycle GHG abatement calculated for combined bushfire/energy-efficiency retrofits of the 29 case study houses varied widely, from a net increase in emissions of 11.5 tonnes CO_2-e through to a net abatement of 144.5 tonnes CO_2-e. However, the impact was typically a net abatement, with an average abatement of 21.0 tonnes CO_2-e across the case study houses.
- The contribution of improved bushfire resilience to the GHG abatement (i.e. item 2c above) was significant in most cases, with an average value of 7.4 tonnes CO_2-e and maximum value of 28.6 tonnes CO_2-e within the 29 case study houses. These emissions abatements were typically smaller than, but of a similar order of magnitude to, those achieved through energy efficiency retrofits (equalling 18 % of the energy efficiency retrofit emissions abatement in the median of the cases investigated).
- The sensitivity of these results to the assumed building operational 'lifespan' and future bushfire frequency is also explored in this report.

The ongoing Disaster Resilience and Energy Efficiency Ratings project being led by the RBC will build on the findings presented here, and will develop a unified home assessment framework for energy efficiency, bushfire, cyclone, flood, and heatwave resilience.

List of Abbreviations

BRSR	Bushfire resilience star rating
BRT	Bushfire-resistant timber
BPAD	Bushfire planning and design
GHG	Greenhouse gas
HVAC	Heating, ventilation and air-conditioning
LED	Light-emitting diode
NCC	National Construction Code
NSW	New South Wales
RBC	Resilient Building Council
SBRC	Sustainable Buildings Research Centre
SHGC	Solar heat gain coefficient
U-value	Thermal transmittance

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1 Introduction

This report describes an investigation into the benefits and challenges in delivering home retrofit programs for the dual purposes of improved bushfire resilience and improved energy efficiency. Its primary focus is on greenhouse gas emissions abatement provided by such home retrofits, and the practical challenges and synergies encountered when integrating bushfire and energy efficiency assessments into coherent upgrade recommendations.

The investigation was undertaken by the Sustainable Buildings Research Centre (SBRC) at the University of Wollongong for the Resilient Building Council (RBC). Findings from this initial study will feed into a larger project led by the RBC, which is focused on home assessments and retrofits for energy efficiency and resilience against a wider range of disaster types, including bushfire, cyclone, flood, and heatwave.

1.1 BACKGROUND

Construction codes and standards for residential buildings have changed dramatically in Australia over recent decades. Efforts to mitigate global warming have included the introduction of mandatory minimum standards for home energy efficiency in certain states from 1990, introduction of such standards in the Australian National Construction Code (NCC) in 2003, and significant increases in the stringency of those standards for detached residential buildings in 2006, 2010 and 2022 [1–3].

Australian codes and standards for building in bushfire-prone areas have also changed significantly over this period. Minimum construction standards have been set in Australian Standard 3959 since 1991, that standard has been referenced in the NCC since the 1990s, and the stringency of AS 3959 was significantly increased in 1999 and 2009 [4]. An alternative standard for steel-framed houses was released by the National Association of Steel-Framed Housing (NASH) in 2014, which has since also been adopted under the NCC, and was updated in 2021 [5].

Such rapid changes in building practice have created many ‘legacy’ houses, which were built prior to the introduction of current standards and therefore typically provide a lower level of energy efficiency and bushfire resistance. This has driven initiatives to retrofit older houses (e.g. the 2008 Home Insulation Program [6]), or to provide guidance for such retrofits [7–9]. However, activities focused on retrofitting for energy efficiency and bushfire resilience (and resilience to other natural disasters) have typically been undertaken separately, with little attention paid to possible synergies between the two efforts.

The potential benefits of an integrated approach, where homes are assessed and retrofitted with the combined aims of improved energy efficiency and disaster resilience, include:

- Avoided negative impacts on one aspect of building performance when retrofitting for another purpose;
- Cost savings achieved by prescribing retrofits that offer co-benefits (e.g. when replacing windows with energy-efficient alternatives, the glass type and frame material can be selected to also offer improvements in bushfire resistance);
- Cost savings achieved by combining home assessments and other site work;
- Reduced disruption to the household; and
- Increased incentive for households to participate in retrofit programs.

While conflicts may also arise when integrating retrofit programs for energy efficiency and disaster resilience, e.g. certain insulation materials can be hazardous in bushfire-prone areas, by identifying and addressing such conflicts, a combined approach would reduce the risk of adverse outcomes (as suggested in the first point listed above).

However, such potential benefits do not appear to have received much attention previously.

Another aspect of home retrofits that appears to have not been comprehensively analysed previously is their impact on lifecycle greenhouse gas (GHG) emissions. While energy efficiency retrofits are typically justified by their impact on operational energy consumption, and the associated cost savings and/or GHG emissions abatement, the 'embodied' emissions (see Figure 1) caused by the retrofits are rarely taken into account [10]. Moreover, even in studies involving lifecycle analysis, which accounts for operational and embodied emissions, the potential GHG emissions abatement provided by retrofits for improved disaster resilience are typically not included.

When a house is damaged or destroyed in a natural disaster, any works undertaken to repair or rebuild the house consume materials and energy, and that consumption causes GHG emissions (Figure 1). Houses with a higher resilience to such disasters are less likely to be damaged, or are likely to be damaged less, than equivalent houses with lower levels of resilience. Therefore, home retrofits for improved disaster resilience not only have a GHG emissions 'cost' due to the materials and energy consumed, they also reduce the probability of future GHG emissions after natural disasters. To the best of our knowledge these factors have not been quantified prior to this work.

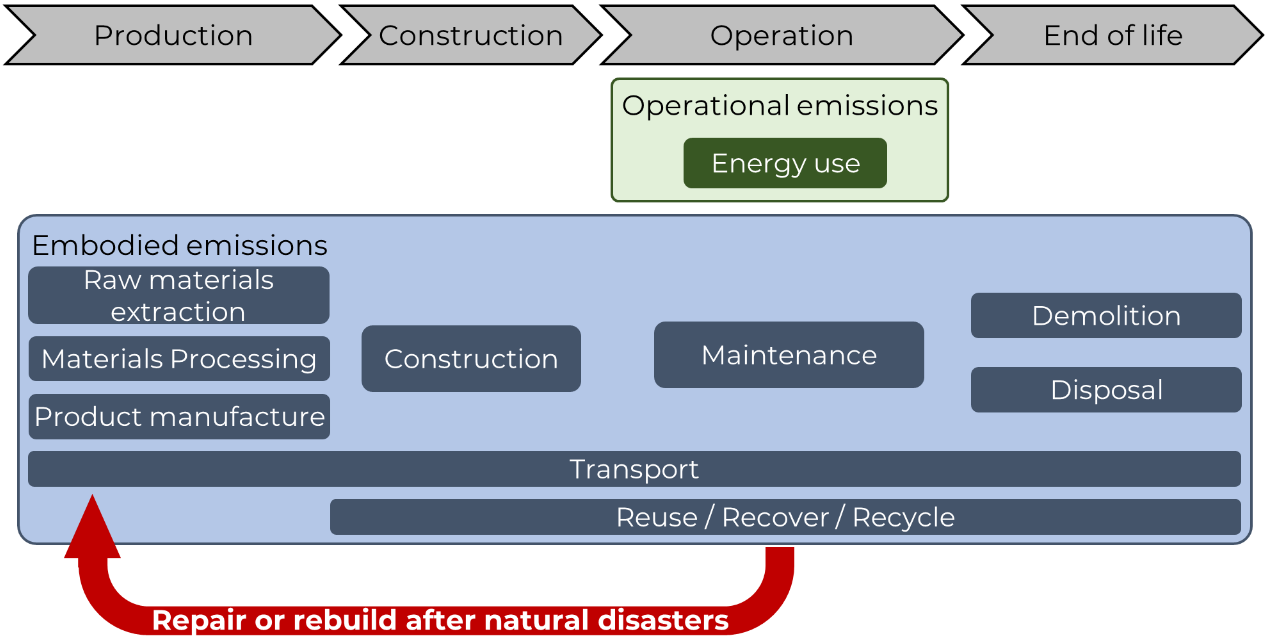

Figure 1: Schematic overview of greenhouse gas emissions associated with a building. Typical energy efficiency analysis only covers operational emissions; typical lifecycle analysis covers operational and embodied emissions; in this study we sought to also include the impact of natural disasters, as depicted by the red arrow.

The RBC has recently obtained funding to develop a home assessment platform for combined energy efficiency and multi-hazard resilience ratings (covering bushfire, flood, cyclone and heatwave resilience) during 2023 and 2024. The study presented in this report forms part of a pilot project preceding the multi-hazard home ratings project, and focused on combined home assessments and retrofits for energy efficiency and bushfire resilience only (i.e. it did not cover other types of natural disaster).

1.2 AIMS OF THIS STUDY

The aims of this study were to:

1. Analyse challenges and opportunities faced when combining home retrofit programs for energy efficiency and bushfire resilience in the Pilot Project; and
2. Quantify the net GHG emissions abatement/contribution of such home retrofit programs, taking into account:
    a. Embodied emissions of the retrofits;
    b. Emissions abatement from improved energy efficiency; and
    c. Emissions abatement from improved bushfire resilience.

2 Methodology

2.1 CASE STUDY HOUSES

Twenty nine case study households were recruited by the RBC: 15 from the Shoalhaven region of New South Wales (NSW), and 14 from various bushfire-prone regions in Victoria. Only households who owned their property and stated they were willing to undertake home retrofits within the next year were considered for inclusion in the study, and an effort was made to include houses with various:

- Wildland fuel types (e.g. forest, open woodland, grassland) nearby;
- Proximity of wildland fuels to the house;
- Density of surrounding properties (e.g. suburban, peri-urban, rural); and
- House construction types.

Construction details of each house are summarised in Table 1.

2.2 HOME ASSESSMENTS

Data were collected at each house through two separate on-site assessments: a Bushfire Resilience Star Rating (BRSR) assessment focused on bushfire resilience [11,12], and a Residential Efficiency Scorecard assessment focused on energy efficiency [13,14]. Further explanation of these two assessment methodologies is provided in Sections 2.2.1 and 2.2.2, respectively.

2.2.1 Bushfire Resilience Star Rating Assessments

The BRSR assessments were undertaken by Bushfire Planning and Design (BPAD)-accredited bushfire consultants. Information was recorded through an on-site assessment, including the following:

- Materials and design features of each house's outer 'envelope' (i.e. exterior surfaces of the walls, roof, eaves, suspended floors, etc.);
- Materials and design of attached structures, such as decks, verandahs and carports;
- The proximity of wildland fuels to the house;
- The proximity of other buildings (e.g. garages or neighbouring houses) to the house;
- The proximity of other combustible items (e.g. gardens, furniture, boats or caravans) to the house; and

- Whether items were stored in garages, roof spaces or sub-floor spaces.

Table 1: Construction details of the 29 case study houses. Houses with IDs starting with 'N' and 'V' are located in NSW and Victoria, respectively. In cases where multiple wall, roof or floor types were observed in the same house, the predominant type is entered in this table.

House ID	Construction date	Floor area [m^2]	Glazing area [m^2]	Wall type	Roof type	Floor type
N1	2001 onwards	174	47.0	Timber-clad	Steel	Lightweight unenclosed
N2	1990 - 2000	151	56.7	Brick veneer	Tile	Lightweight partially enclosed
N3	1990 - 2000	129	49.4	Brick veneer	Steel	Lightweight enclosed
N4	2001 onwards	44	24.2	Brick veneer	Steel	Lightweight enclosed
N5	1990 - 2000	137	25.3	Concrete block	Steel	Lightweight enclosed
N6	2001 onwards	183	33.5	Timber-clad	Steel	Slab on ground
N7	1961 - 1980	63	20.4	Timber-clad	Steel	Lightweight partially enclosed
N8	2001 onwards	158	67.3	Metal-clad	Steel	Suspended slab, enclosed sub-floor
N9	2001 onwards	138	30.7	Brick veneer	Tile	Slab on ground
N10	2001 onwards	221	32.8	Timber-clad	Steel	Slab on ground
N11	2001 onwards	177	59.8	Brick veneer	Steel	Lightweight enclosed
N12	2001 onwards	155	52.4	Timber-clad	Steel	Lightweight partially enclosed
N13	1981 - 1990	156	41.5	Double brick	Tile	Suspended slab, enclosed sub-floor
N14	1981 - 1990	214	56.0	Brick veneer	Steel	Slab on ground
N15	1990 - 2000	161	56.4	Brick veneer	Tile	Slab on ground
V1	2001 onwards	140	29.7	Timber-clad	Steel	Lightweight enclosed
V2	1981 - 1990	153	49.34	Double brick	Steel	Lightweight unenclosed
V3	1990 - 2000	151	46.81	Timber-clad	Steel	Lightweight unenclosed
V4	2001 onwards	232	45.25	Brick veneer	Steel	Slab on ground
V5	2001 onwards	159	41.91	Metal cladding	Steel	Lightweight unenclosed
V6	2001 onwards	178	33.57	Brick veneer	Steel	Lightweight enclosed
V7	1981 - 1990	210	47.82	Brick veneer	Steel	Slab on ground
V8	2001 onwards	366	70.49	Timber-clad	Steel	Lightweight unenclosed
V9	1981 - 1990	197	48.11	Fibre-cement-clad	Steel	Lightweight unenclosed
V10	1961 - 1980	210	44.28	Double brick	Steel	Slab on ground
V11	1961 - 1980	67	20.08	Fibre-cement-clad	Steel	Lightweight unenclosed
V12	2001 onwards	363	91.43	Fibre-cement-clad	Steel	Lightweight unenclosed
V13	1981 - 1990	194	47.29	Brick veneer	Tile	Lightweight enclosed
V14	2001 onwards	139	32.35	Rammed earth	Steel	Slab on ground

Data from the assessments were processed by the RBC, using their BRSR tool. The tool estimates the likelihood that a house would be destroyed via several different mechanisms (e.g. direct ignition of combustible doors by embers, failure of windows, etc.) if subjected to a bushfire. It then combines these values into an estimated overall probability of destruction, and assigns a Bushfire Resilience Star Rating (ranging from zero to five stars) based on this probability [12].

The RBC then used the BRSR tool to generate a set of suggested retrofits for each house. The suggestions were tailored to provide a significant reduction in the probability of destruction by bushfire, according to the BRSR tool.

Thus, the BRSR assessments produced three key outputs:

1. The estimated likelihood that each building would be destroyed if subjected to a bushfire in their current state (i.e. pre-retrofit);
2. A tailored set of retrofits for each house, to reduce the likelihood of destruction by bushfire; and
3. The estimated likelihood that each building would be destroyed by a bushfire after the suggested retrofits are undertaken.

2.2.2 Residential Efficiency Scorecard Assessments

The Residential Efficiency Scorecard assessments were undertaken by Scorecard-accredited assessors. These assessments involved a site inspection of each house. Data were collected on:

- The building fabric (i.e. materials and design);
- Indoor thermal zoning; and
- Any fixed appliances (i.e. lighting, heating and cooling equipment, hot water system and solar PV system).

These data are used to estimate the annual heating and cooling energy demands, and associated costs, using algorithms based on building performance simulations [13]. The energy use data are associated with specific fuel sources (either electricity, natural gas, liquid petroleum gas, or wood), based on the fixed equipment installed in the house.

A star rating (ranging from zero to ten stars) is automatically generated to characterise the house's energy efficiency relative to other houses in the same Australian climate zone, and separate 'hot weather' and 'cold weather' performance ratings (ranging from zero to five) are produced to characterise the house's energy consumption during summer and winter, respectively.

The Scorecard tool then suggests a set of possible retrofit actions aimed at:

a) Reducing energy used to cool the house in summer;
b) Reducing energy used to heat the house in winter; and

c) Improving the energy efficiency of fixed appliances in the house.

The suggested retrofit actions are selected based on the maximum estimated cost savings, without taking the upfront cost of retrofits into account; i.e. the suggested retrofits cause the largest possible decrease in annual energy costs, but may not provide the greatest net cost saving or benefit-cost ratio. Moreover, it is worth noting that the Scorecard tool selects retrofit actions based on the estimated cost of energy to run the house, not the magnitude of energy savings or emissions abatement.

After conducting the initial on-site assessments of each house, a desktop analysis was undertaken to quantify the impact of the suggested retrofit actions on the estimated energy consumption of each house. For each of the 29 case study houses, additional Scorecard assessments were generated: (i) including all suggested retrofits, and (ii) including each suggested retrofit individually. This typically involved between 5 and 12 additional Scorecard assessments per house.

Thus, the Scorecard assessments produced estimated annual energy consumption data for each house:

1. In the state they were assessed (i.e. pre-retrofit);
2. With all suggested retrofits implemented; and
3. With each retrofit implemented independently.

The estimated impact of each suggested retrofit action, and all suggested retrofits combined, was then quantified by subtracting the pre-retrofit estimated energy use data (1) from the post-retrofit data (2 and 3).

2.3 COMBINED RETROFIT CHALLENGES AND OPPORTUNITIES

A key objective of the study was to identify challenges and opportunities encountered when assessing houses and suggesting retrofits for the combined purposes of improved bushfire resilience and improved energy efficiency. These challenges and opportunities could relate to data collection (i.e. home assessments), data analysis (e.g. conflicts or co-benefits between retrofits), or communication of results to the household. A log of relevant observations was kept throughout the project, and after completing both assessments of all thirty houses, these observations were synthesised and reported (in Section 3.1).

2.4 LIFE CYCLE ASSESSMENT

Data from the BRSR and Scorecard assessments were used to calculate the net GHG emissions of the suggested retrofits. This life cycle analysis took into account:

- 'Embodied' emissions associated with the manufacture, transport, use and eventual disposal of materials needed to undertake the retrofits;
- 'Operational' emissions abatement caused by the reduced energy consumption of the buildings after retrofit; and
- Additional emissions abatement arising from improved bushfire resilience after retrofitting, due to a reduced likelihood that the house would be destroyed by future bushfires and need to be rebuilt using new materials (which would themselves have a embodied emissions).

These impacts on emissions were integrated over the remaining operational 'lifespan' of each house to produce a net emissions impact that could be attributed to the suggested retrofits.

The total emissions a home retrofit for energy efficiency and bushfire resilience (G) was calculated as the sum of four separate contributions:

$$G = R_B + R_O + (G_{B2} - G_{B1}) + (G_{O2} - G_{O1}) \qquad (1)$$

where R_B and R_O are the total 'embodied' emissions of materials used for bushfire and energy efficiency retrofits, respectively; G_{B1} and G_{B2} are the total emissions attributable to the risk of the house being destroyed by bushfire and then rebuilt, before and after the retrofit, respectively; and G_{O1} and G_{O2} are the operational emissions of the house, before and after the retrofit, respectively.

The methods used to evaluate each term in Equation (1) are outlined in the following sub-sections.

2.4.1 Embodied Carbon in Materials used for Retrofits

The terms R_B and R_O in Equation (1) were calculated as the total 'cradle-to-grave' embodied emissions of materials needed to undertake the suggested retrofits. Where possible, emissions intensity values for materials were taken from the EPiC database [15], since it was developed based on Australian supply chains. However, the EPiC database did not contain data on all materials of interest, so several emissions intensity values had to be sourced from manufacturer websites or the life cycle analysis software GaBi V10.6.2.9.

The EPiC data only include 'cradle to gate' emissions and therefore do not include emissions associated with transport to and from the site, or disposal. GaBi was used to calculate emissions associated with the following transportation stages:

- A 100 km trip between the manufacturer warehouse (i.e. 'gate') and the distribution store in a 34-40 tonne truck-trailer;

- A 50 km round-trip from the distribution store to the construction site in a 14-20 tonne truck; and
- A 50 km trip from the construction site to a waste depot in a 7.5-12 tonne truck.

Those transportation emissions were then added to the EPiC values per unit mass of material.

The quantity of each material needed to undertake a retrofit was estimated based on the measured floor area, roof area, glazing area, or deck area of the house (whichever was most relevant to the type of retrofit in question), as outlined in Appendix A.

2.4.2 Emissions Associated with Rebuilding Houses after Bushfires

The GHG emissions attributable to the risk that the house could be destroyed by a bushfire and need to be rebuilt (i.e. G_{B1} and G_{B2} from Equation (*1*)) was calculated as explained below.

After a house is retrofitted, such emissions can be calculated as:

$$G_{B2} = \int_0^y f_B P_{B2} W \frac{y-t}{L} dt \qquad (2)$$

where f_B is the local bushfire frequency, P_{B2} is the probability that the house will be destroyed when subjected to a bushfire given its level of resilience after being retrofitted, W is the total 'embodied' carbon in materials needed to rebuild the house, y is the number of years remaining in the operational 'lifespan' of the house, t is the time measured from $t = 0$ at the time of retrofit, and L is the assumed total 'lifespan' of a house (i.e. time from initial construction to demolition, if never destroyed by a bushfire).

The term $\left(\frac{y-t}{L}\right)$ is included in Equation (2) since only a fraction of the operational 'life' of the house remains at the time it is destroyed by bushfire, and after being rebuilt it will remain in service for time L unless destroyed by another bushfire (i.e. its 'lifespan' is assumed to restart when it is rebuilt).

Calculation of the corresponding emissions for scenarios where a retrofit is not undertaken (i.e. G_{B1}) is more complicated, because it is assumed that if a house is destroyed and rebuilt, it will be rebuilt to current bushfire safety standards. In calculations for this report, we have assumed that such standards match the level of resilience of the same house if it had been retrofitted; i.e. we have assumed that if a house is destroyed and rebuilt, the probability that it would be destroyed by bushfires is thereafter equal to P_{B2}. Based on this assumption, G_{B1} is given by:

$$G_{B1} = \int_0^y \left[P_s f_B P_{B1} W \frac{y-t}{L} + (1 - P_s) f_B P_{B2} W \frac{y-t}{L} \right] dt$$

$$G_{B1} = \frac{f_B W}{L} \int_0^y [(P_{B1}P_s - P_{B2}P_s + P_{B2})(y - t)]dt \quad (3)$$

where P_s is the probability that the house has not yet been destroyed by any bushfires at time t. P_s is therefore a function of t:

$$P_s(t) = (1 - P_{B1})^{(f_B t)}. \quad (4)$$

The bushfire frequency, f_B, was estimated for the location of each of the 29 case study houses based on the number of recorded historical bushfires that burnt land within a 1 km radius of the house. Spatial data outlining the extent of historical bushfires were obtained from the NSW and Victorian State Government records [16,17]. Within NSW, only data from fires during the period 1957–2019 were used, since it has been reported that record keeping prior to 1957 was not comprehensive [18]. For the Victorian properties, only data from the period 1940–2022 were included.

It was recognised that the historical bushfire records may not be complete; especially data from earlier periods when records were not digital. Moreover, historical bushfire frequencies will not necessarily continue unchanged into the future, especially given the impacts of global warming and changes in land use. To quantify the potential impacts of this uncertainty in future bushfire frequency, the sensitivity of results to f_B was also explored.

The probability of destruction before and after retrofit (i.e. P_{B1} and P_{B2}, respectively) were estimated by the RBC using the Bushfire Resilience Star Rating tool, and provided to the SBRC. This tool is based on a fault tree analysis of building component ignition via 22 different mechanisms [11,12]

The total embodied energy of materials needed to rebuild each house, W, was estimated based on the floor area, glazing area, and construction type (i.e. predominant materials) of the existing house. Emissions intensity values were established for each material using the EPiC database and GaBi software, as described in Section 2.3.1. The total embodied emissions in materials required to build an archetypal detached residential house were then calculated for a range of construction types (e.g. external walls of brick veneer, steel frame with fibre-cement cladding, etc.; steel-clad and tiled roofs; suspended floors and concrete slab on ground; etc.). Embodied emissions calculated for the archetypal house were then scaled to suit each of the 29 case study houses, based on floor area or glazing area, as outlined in Appendix B. Appendix C includes details of the archetypal house used for these calculations.

The total 'lifespan' of a house, L, is a critical assumption in most lifecycle analysis. It can have a large impact on results and tends to vary widely from house to house (e.g. some houses can be demolished as soon as 30 years after construction, whereas other houses remain in operation for hundreds of years). For the majority of calculations in this report, we assumed L equals 75 years, and the impact of this assumption was then explored through a sensitivity analysis.

The Scorecard assessments included an estimate of the age of each building at the time of inspection, within a set of categories (Table 2). The value y in Equations (*2*) and (*3*) (i.e. the number of years remaining in the operational 'lifespan' of the house) was then estimated by assuming the exact age of the house was equal to the average value from the relevant category (see Table 2).

Table 2: Assumed age of houses based on the estimated construction date recorded during Scorecard assessments.

Construction date category from Scorecard assessment	Assumed age [years]
1961–1980	52
1981–1990	37
1991–2000	27
2001 onwards	12

2.4.3 Operational Emissions from Energy Use

For houses that are retrofitted, the total operational emissions over the remaining operational 'life' of the house is given by:

$$G_{O2} = \int_0^y (O_2)dt \quad (5)$$

where O_2 is the operational emissions per year of the house in its retrofitted state, and y is the number of operational years remaining before the house is eventually demolished.

Calculation of the total operational emissions of houses that are not retrofitted is more complicated, because if such houses are destroyed by a bushfire they will be rebuilt to modern energy efficiency standards, and thenceforth require less energy to operate. In our analysis, we have assumed that the operational energy consumption of a house after being destroyed and rebuilt to modern standards is equal to the operational energy consumption of the same house if it had been retrofitted. Therefore, the total operational emissions of houses that are not retrofitted, over the remaining 'life' of the house (y), is given by:

$$G_{O1} = \int_0^y [P_s O_1 + (1 - P_s) O_2]dt \quad (6)$$

where O_1 is the operational emissions per year of the house in its un-retrofitted state, and P_s is the probability that the house has not yet been destroyed by any bushfires at time *t*, given by Equation (4).

O_1 is given by:

$$O_1 = (E_{e1} - E_{PV})C_e + E_{g1}C_g + E_{l1}C_l + E_{w1}C_w \quad (7)$$

where subscripts e, g, l and w denote electricity, natural gas, liquid petroleum gas (LPG) and wood, respectively, and symbols E and C represent the estimated annual consumption of each fuel type by the house and the emissions factors for each fuel type, respectively. E_{PV} represents the estimated annual electricity generation from on-site solar photovoltaic (PV) panels. The subscript 1 is included to indicate values calculated for the house without any retrofits.

Likewise, O_2 is given by:

$$O_2 = (E_{e2} - E_{PV})C_e + E_{g2}C_g + E_{l2}C_l + E_{w2}C_w \quad (8)$$

where the subscript 2 is included to indicate values calculated for a retrofitted house.

The Scorecard tool was used to estimate the values E_{e1}, E_{e2}, E_{g1}, E_{g2}, E_{l1}, E_{l2}, E_{w1} and E_{w2}. It uses algorithms based on a parametric set of building performance simulations performed by Isaacs [13].

Emissions factors for natural gas, liquid petroleum gas and wood were assumed to be constant over time, as summarised in Table 3.

Table 3: Emissions factors for household consumption of gas and solid fuels.

Fuel type	Symbol	Emissions factor [kg CO_2-e per MJ]	Notes
Natural gas	C_g	0.05963	Scope 1 and national average Scope 3
LPG	C_l	0.08080	Scope 1 and Scope 3
Wood	C_w	0.00120	Scope 1

The emissions factor for mains electricity, C_e, is a function of time due to the projected decarbonisation of the Australian electricity grid over the coming decades [19]. In this study, C_e was calculated using a model fitted to the 2022 Australian Government emissions projections [19] in the near-term, and a constant value representing 100 % renewable generation in the long-term. The emissions factor for 100 % renewables was estimated by calculating the average Scope 1 and 2 emissions intensity of wind, solar and hydro generation reported to the Australian Government Clean Energy Regulator during the 2021–2022 reporting period [20]. This model is illustrated in Figure 2 and given by the following expression:

$$C_e(t) = \begin{cases} 0.006 + 8 \times 10^{-6}(30 - t)^3 & t < 30 \\ 0.006 & t \geq 30 \end{cases} \quad (9)$$

Here, t is the number of years after 2022 (i.e. after the date of retrofit in this study), and C_e is given in units of kg CO_2-e per MJ of electricity delivered.

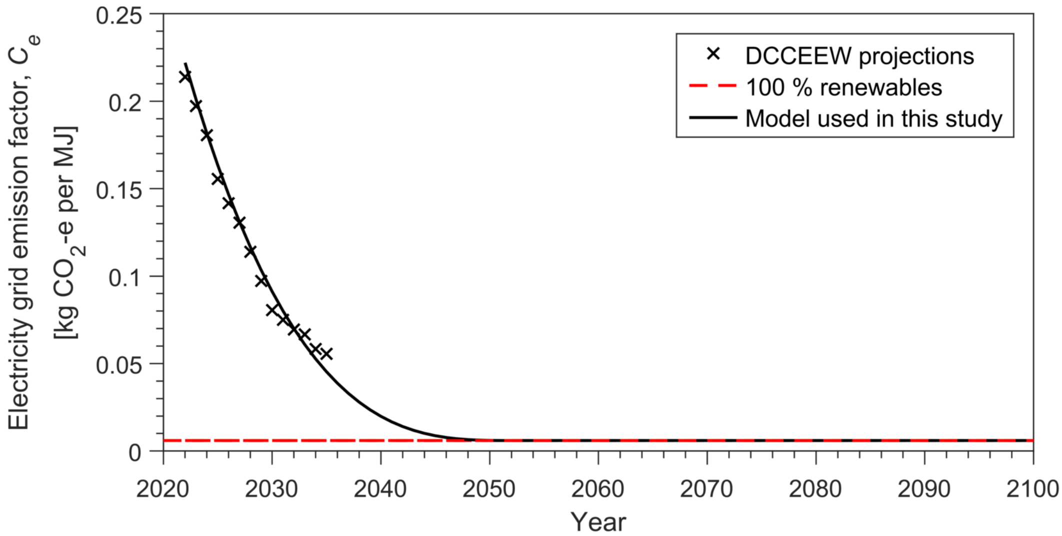

Figure 2: Projected future emissions factors of the Australian electricity grid, including projections published by the Department of Climate Change, Energy, the Environment and Water (DCCEEW) [19]*, the average value reported by renewable energy generators to the Clean Energy Regulator during the 2021–2022 period* [20]*, and the model developed for calculations in this report.*

Electricity generation by solar PV panels, E_{PV}, was calculated as the product of the nominal power rating of any solar PV system installed at the property (expressed in kW) and the average annual PV power potential of 5,400 MJ per year per kW capacity (based on data for south-eastern Australia from the Global Solar Atlas 2.0 [21]).

2.4.4 Solution Procedure

Equations (2), (3), (8) and (9) were solved numerically using the forward-Euler method, with discrete timesteps of 0.001 years. It is also possible to solve these equations analytically; however, they become very cumbersome, so a numerical approach was adopted for this study.

The calculated values of G_{B1}, G_{B2}, G_{O1} and G_{O2} were then combined with the estimated embodied carbon in materials needed to retrofit each house, R_B and R_O, using Equation (1).

3 Results and Discussion

This section presents findings on the potential synergies and conflicts encountered when combining home retrofit programs for energy efficiency and bushfire resilience (in Section 3.1), and from the life cycle assessment of such combined retrofits for the 29 case study houses (in Sections 3.2–3.5).

3.1 SYNERGIES AND CONFLICTS IN COMBINED ASSESSMENTS

The task of inspecting a home, and then analysing home inspection data and prescribing retrofits, becomes significantly more complicated when attempting to integrate the dual aims of improved energy efficiency and bushfire resilience. However, that added complexity is potentially unavoidable if adverse outcomes are to be avoided and the potential efficiencies of combined home assessments are to be achieved.

3.1.1 Home Inspections

The potential benefits of undertaking home inspections for both energy efficiency and bushfire resilience in one visit appear to primarily be:

- Logistical time/cost savings during the planning of inspections and travel to/from site; and
- Reduced disruption to households.

The potential saving of time/cost due to overlap in the data needing to be collected for each type of assessment appears to be minor, since the BRSR assessment focuses primarily on outdoor features of the house and surrounding property whereas the Scorecard assessment is primarily undertaken indoors. While there is some overlap in the data collected for the two assessments, there are nuanced differences in some of those common items, which may not be immediately obvious. For example, both assessments require data on the roof and external wall construction type, but while the Scorecard tool is concerned with the predominant construction type relevant to each indoor thermal zone, BRSR assessments are focused on identifying the weakest features to bushfire attack, even if they are not the predominant type of construction found on the building.

A purpose-built home assessment tool that covered both types of assessment could maximise the time/cost savings from such overlaps in the data collection, but without such a tool it is likely that assessors would choose to undertake inspections for each purpose separately (whether it be during the same site visit, or separate visits), to ensure that the correct data is collected for each one.

3.1.2 Prescription of Retrofits

One major challenge in designing a framework for the prescription of integrated bushfire and energy efficiency retrofits is in establishing a quantitative metric that is appropriate for both purposes.

Even when prescribing retrofits only for energy efficiency, a range of metrics could be used, including:

- Total annual operational energy savings;
- Total annual operational energy cost savings;
- Net cost savings (i.e. including the upfront cost of retrofits and ongoing energy cost savings);
- Total GHG emissions abatement from reduced operational energy use; and
- Net GHG emissions abatement (i.e. including the embodied emissions of retrofit materials and ongoing emissions abatement from operational energy savings).

Each of these metrics is likely to give different outcomes. Moreover, a range of other considerations should also be taken into consideration when prescribing retrofits, such as:

- The needs and preferences of the household with regard to their home's amenity, aesthetics, etc.;
- How disruptive the retrofit works would be to the household (e.g. removing internal wall linings to install insulation is much more disruptive than installing weather stripping); and
- The availability of funding for the retrofit works.

When the aim of improved bushfire resilience is added to this already complex task, it increases the complexity substantially. The motivations to retrofit for bushfire resilience are typically the safety of property and life. Therefore, developing a quantitative basis to rank bushfire and energy efficiency retrofits against each other is not straight-forward.

Furthermore, when prescribing retrofits for multiple aims, such as energy efficiency and bushfire resilience, retrofit actions intended to address one aim can have unintended impacts on the other. Table 2 outlines the interactions that we identified for each of the specific retrofits suggested by the Scorecard and BRSR tools. We found that these interactions could be grouped into three categories, as follows:

1. *Direct co-benefits* for aim B when retrofitting for aim A.
2. Cases where additional *considerations* need to be taken into account; these cases took one of three different forms:

a. By selecting certain methods or materials when retrofitting for aim A, co-benefits for aim B can also be achieved.
b. When considering both aims A and B, the choice of retrofit type/method/material is different to what it may have been when considering the aims independently, e.g. due to a shift in the cost-benefit ratio, or since retrofitting for A provides easy access to also retrofit for B.
c. There is a potential conflict, but by selecting certain methods and materials the conflicts can be avoided.

3. *Direct conflict*; i.e. retrofitting for aim A has an unavoidable negative impact on aim B.

The majority of interactions (41 of the 45 total) fell under the second category (i.e. 'considerations'), while only 4 retrofits had direct co-benefits, and no direct conflicts were identified.

These results illustrate the potential benefits of combined retrofit programs, as compared to separate assessments for energy efficiency and bushfire resilience. Many of the 'considerations' we identified represent opportunities to either improve the retrofit effectiveness, improve efficiency, or avoid unintended adverse outcomes from the retrofits. Separate home assessments would miss such opportunities. Moreover, the fact that no 'direct conflicts' were identified indicates that even where the two aims might seem to conflict (e.g. timber window frames are typically beneficial for energy efficiency and detrimental to bushfire resilience), an approach informed by both aims can overcome those challenges.

*Table 4: Summary of potential co-benefits, conflicts and considerations between home retrofits intended for energy efficiency (labelled with *) and bushfire resilience (labelled with †). (The table continues over several pages.)*

Building feature	Retrofit	Co-benefits, Conflicts, Considerations
Roof	Upgrade ceiling insulation *	*Consideration:* Non-combustible insulation (e.g. mineral wool) is preferred to mitigate risk from embers during bushfires.
	Paint roof lighter colour, or replace with lighter colour materials *	*Consideration*: Possible cost savings if also replacing or repairing roof for bushfire resistance.
	Install roof ventilation *	*Consideration*: Ventilation openings larger than 2 mm should be screened with appropriate ember mesh. *Consideration:* Vent materials should be non-combustible. *Consideration:* If roof is designed to match a tested Bushfire Attack Level Flame Zone (BAL FZ) compliant design, check whether ventilation upsets that compliance.

Building feature	Retrofit	Co-benefits, Conflicts, Considerations
	Install sarking †	*Co-benefit*: Reflective sarking material can improve the thermal resistance of a roof space. *Consideration*: Mineral wool roof blankets (bonded to sarking-like material) can offer superior thermal performance to standard sarking. *Consideration*: When removing roof cladding, consider replacing with a more suitable colour for the local climate. *Consideration*: Ensure that sarking does not impede ventilation of the roof space (this typically means leaving openings at the ridge and gutters of the roof—such openings can be protected using ember screens).
	Remove stored combustible items from roof space †	None identified.
	Install ventilation products with ember screens at ridge and hip capping †	*Consideration*: Ventilation is likely to improve the thermal performance, and mitigate the risk of condensation and mould risk, in most Australian residential roofs, in which case, this retrofit has co-benefits. However, a small proportion of roof spaces (known as 'warm roofs') are designed to be maintained at indoor conditions, with the primary insulation layer installed directly under the roof rather than on top of the ceiling and no designed ventilation openings. Adding ventilation to 'warm roofs' is typically not advisable.
	Install screens over roof vents †	*Consideration*: It is not advisable to completely block roof ventilation openings (i.e. with material other than screens), as this could reduce the effective thermal resistance of the roof, and increase the risk of condensation and mould.
	Install metal fascia and gutters †	None identified.
	Install screens over skylights †	None identified.
	Replace skylights with toughened glass alternative †	*Consideration*: Possible co-benefits if an energy-efficient skylight is installed (e.g. double- or triple-glazed with thermally broken frames).
	Remove debris from near skylights †	None identified.
	Install gutter guard †	None identified.
Walls	Upgrade wall insulation *	*Consideration*: Non-combustible insulation (e.g. mineral wool) is preferred to mitigate risk from embers during bushfires.
	Paint walls lighter colour *	*Consideration*: Possible cost savings if also replacing or repairing cladding for bushfire resistance.

Building feature	Retrofit	Co-benefits, Conflicts, Considerations
	Seal gaps with flashing/ caulk/moulding/etc. †	*Consideration*: Potential co-benefits if the building envelope is made significantly more airtight. However, the internal lining (typically plasterboard) is usually the primary air barrier in Australian houses, so sealing gaps in the cladding may have a minimal impact on overall air-tightness.
	Remove fuels near wall †	None identified.
	Replace combustible cladding with non-combustible alternative †	*Consideration*: Consider taking the opportunity to install/upgrade wall insulation while the cladding is removed. *Consideration*: If removing external insulation (e.g. expanded polystyrene boards), it should be replaced with an alternative, non-combustible insulation material (e.g. mineral wool board).
	Install flashing over horizontal ledges †	*Consideration*: To avoid watertightness issues, rot and mould, flashings should lap over/under adjacent materials appropriately (e.g. tuck under cladding above and lay over cladding below).
Windows	Weather strip windows *	*Co-benefit*: Weather strips can mitigate the risk of ember entry into the indoor space during bushfires. *Consideration*: Draft seals should be composed of a material resistant to bushfire attack (e.g. silicone)—refer to product BAL rating.
	Replace high-performance windows *	*Consideration*: Potential co-benefits if bushfire-resistant glazing and frame material are selected—refer to product BAL rating. *Consideration*: Consider the thermal performance of the window frame as well as the glazing. Aluminium frames without thermal breaks are not advisable given their poor thermal performance.
	Install lined curtains with pelmets *	*Consideration*: Consider installing external, bushfire-rated shutters rather than internal window treatments.
	Install flashing over combustible sills †	*Consideration*: To avoid watertightness issues, rot and mould, flashings should lap over/under adjacent materials appropriately (e.g. tuck under cladding above and lay over cladding below).
	Replace with metal-framed, toughened 5/6 mm †	*Consideration*: Potential co-benefits if energy-efficient window products are selected.
	Install bushfire shutters †	*Co-benefit*: External shutters, when operated at appropriate times, can significantly improve the thermal performance of buildings.
	Clear fuels, mulch from below windows †	None identified.
	Replace window with wall †	*Consideration*: Potential co-benefit, since replacement of windows with opaque sections of wall will typically improve the overall thermal performance of the building envelope. *Consideration*: The removal of windows could degrade occupants' ability to effectively ventilate and/or light the indoor space.
Doors	Weather strip doors *	*Co-benefit*: Weather strips can mitigate the risk of ember entry into the indoor space during bushfires.

Building feature	Retrofit	Co-benefits, Conflicts, Considerations
		Consideration: Draft seals should be composed of a material resistant to bushfire attack (e.g. silicone)—refer to product BAL rating.
	Install steel kickplate †	None identified.
	Install ember screen door †	*Consideration*: Potential co-benefit, since screen doors can increase the options for natural ventilation available to occupants.
	Replace with fire-rated door system †	*Consideration*: Potential conflict, if door system includes metal components (e.g. jambs) that form 'thermal bridges' between the indoor and outdoor spaces. Bushfire-rated timber components could be an alternative, or designs in which the thermal bridge is 'thermally broken' by insulating materials.
	Seal around garage doors (e.g. brush seals) †	*Consideration*: While the overall air-tightness of the building envelope could be improved by seals around garage doors, in many houses garage doors do not form part of the primary air control layer, in which case the potential co-benefits are minor.
Subfloor	Upgrade floor insulation *	*Consideration*: Non-combustible insulation (e.g. mineral wool) is preferred, especially if subfloor is unenclosed.
	Remove combustible materials from under deck †	None identified.
	Enclose subfloor/subdeck with mesh †	*Consideration*: Adequate openings should be maintained to allow subfloor ventilation, which reduces the risk of condensation and mould in the building—refer to the National Construction Code (NCC) for minimum open area requirements.
Pergola/ carport/ verandah	Install guard/flashing around verandah posts †	*Consideration*: The long-term durability and weathertightness of the flashing should be considered. Measures may need to be taken to prevent moisture from accumulating behind the flashing where it could cause rot.
	Replace combustible verandah posts †	None identified.
	Replace combustible verandah rafters †	None identified.
	Replace fibreglass verandah roof with steel or polycarbonate †	None identified.
	Remove fuel/shrubs near verandah supports †	None identified.
	Replace decking with bushfire-resistant timber (BRT) or non-combustible alternative †	None identified.
	Replace/modify balustrade to eliminate vertical timber †	None identified.

Building feature	Retrofit	Co-benefits, Conflicts, Considerations
Services	Install dampers in exhaust ducts *	*Consideration*: Any vents exiting outdoors should also have ember mesh installed, if not already installed.
	New reverse-cycle heating *	*Consideration*: The hazard posed by any combustible outdoor equipment (e.g. outdoor unit and conduit) should considered, as well as the potential for outdoor equipment to promote the accumulation of leaf litter and other debris, including embers.
	New reverse-cycle ducted cooling *	*Consideration*: The hazard posed by any combustible outdoor equipment (e.g. outdoor unit and conduit) should considered, as well as the potential for outdoor equipment to promote the accumulation of leaf litter and other debris, including embers. *Consideration*: Any make-up air and exhaust vents opening to the outdoors should be covered by ember mesh.
	New ducted evaporative cooler *	*Consideration*: The outdoor unit may require an ember guard.
	Shower head with 3 star WELS rating *	None identified.
	Replace hot water system with a heat pump or solar hot water system *	*Consideration*: The hazard posed by any combustible outdoor equipment (e.g. outdoor unit and conduit) should be considered, as well as the potential for outdoor equipment to promote the accumulation of leaf litter and other debris, including embers.
	Replace halogen downlights with LEDs *	None identified.
	Install ember guard over evaporative cooler †	None identified.
	Install ember guard over air conditioner outdoor unit †	None identified.
	Install bushfire sprinklers †	*Consideration*: Rainwater collected and stored by the system could be used for other purposes, to reduce the consumption of potable water. However, measures should be in place to ensure enough water is available during bushfires.
Garden	Trim or remove overhanging trees †	*Consideration*: Loss of shading can impact the thermal performance of a house.
	Remove combustible items stored in garage †	None identified.
	Install non-combustible path around house †	*Consideration*: Consider using materials with low embodied carbon, such as low-carbon concrete pavers or gravel.
	Move combustible items away from home †	None identified.
	Clear vegetation from around items in yard †	None identified.

3.2 EMBODIED CARBON IN RETROFIT MATERIALS

Figure 4 and Figure 5 present the 'embodied' GHG emissions calculated for retrofits suggested by the BRSR and Scorecard assessments, respectively. Many retrofits were predicted to create very little embodied emissions, as they only require small quantities of materials (e.g. ember screen or sheet steel flashings). Replacement of roofs, windows, cladding and balustrades, as well as the installation of new heat pumps, evaporative coolers or hot water systems, created the most embodied emissions.

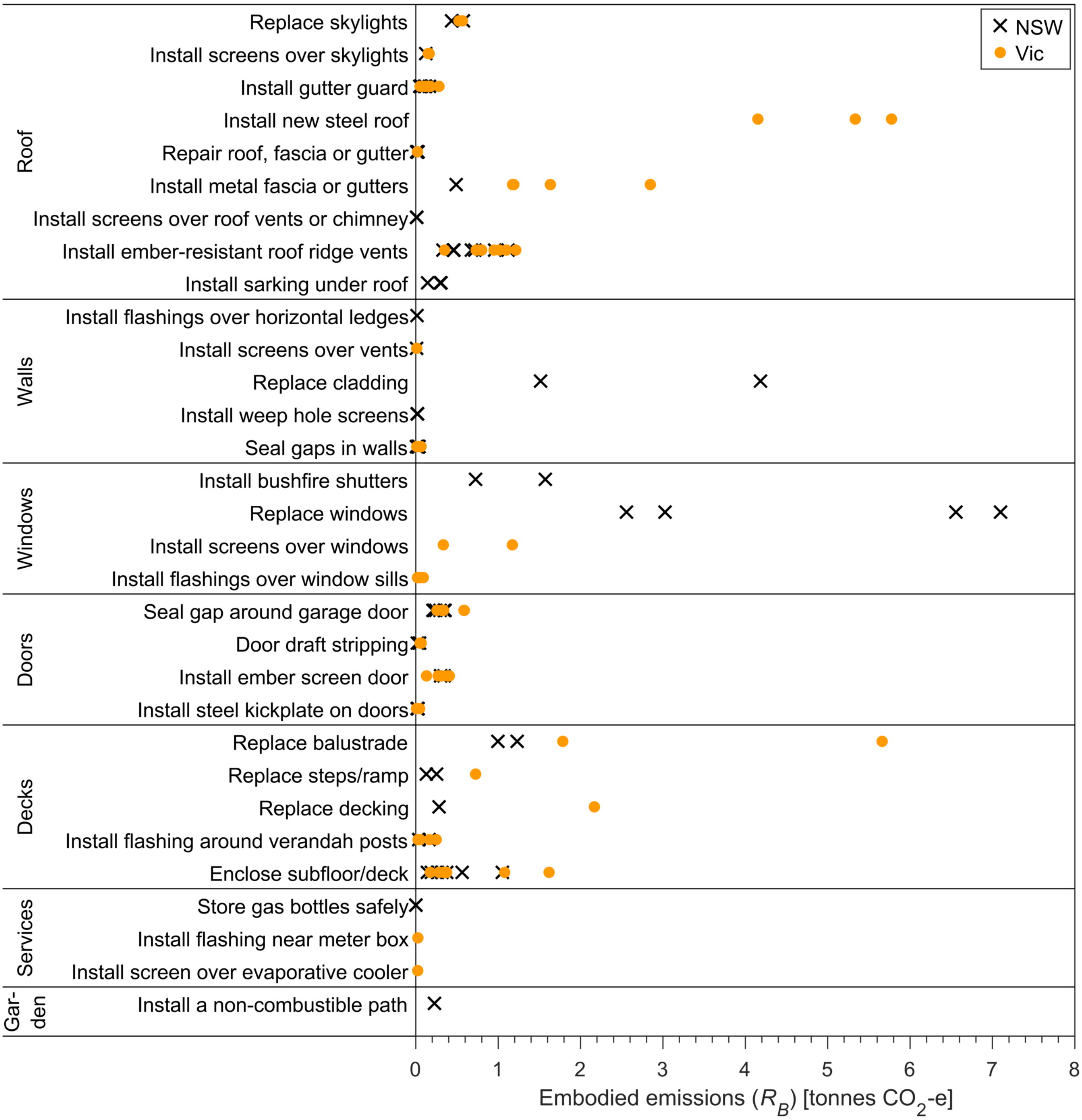

Figure 3: Embodied carbon in the materials needed to undertake retrofits suggested based on Bushfire Resilience Star Ratings.

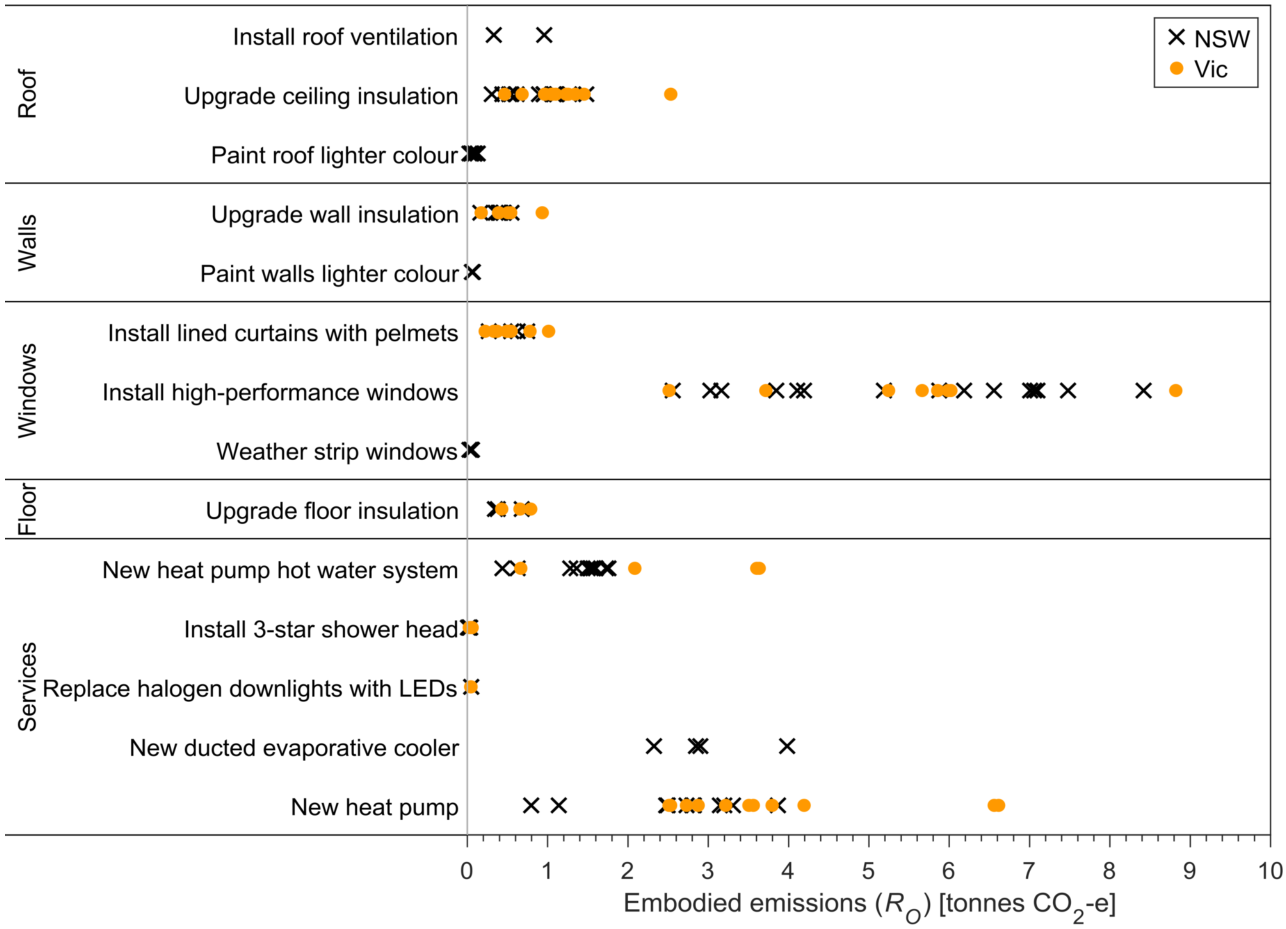

Figure 4: Embodied carbon in the materials needed to undertake energy efficiency retrofits suggested by Scorecard tool.

The total embodied emissions associated with all retrofits suggested for each of the 29 houses ranged from 3.5 to 29.2 tonnes CO_2-e, with an average value of 12.6 tonnes CO_2-e.

3.3 OPERATIONAL EMISSIONS ABATEMENT

Figure 6 presents the operational emissions abatement achieved by undertaking each energy efficiency retrofit suggested by the Scorecard tool, where each retrofit was modelled independently. The Scorecard tool suggests retrofits based on the estimated reduction in energy costs, not the emissions abatement, and therefore some suggested retrofits can provide negligible emissions abatement, or even increase emissions. However, several of the suggested retrofits were calculated to have a significant positive impact; reducing the operational emissions of houses by tens of tonnes CO_2-e over their remaining operational 'lifespan'.

The retrofits predicted to provide the greatest GHG emissions abatement were the installation of a new heat pump hot water system, 3-star high-efficiency shower heads, and lined curtains with pelmets, with (13.1, 3.9, and 3.2 tonnes CO_2-e median abatement, respectively).

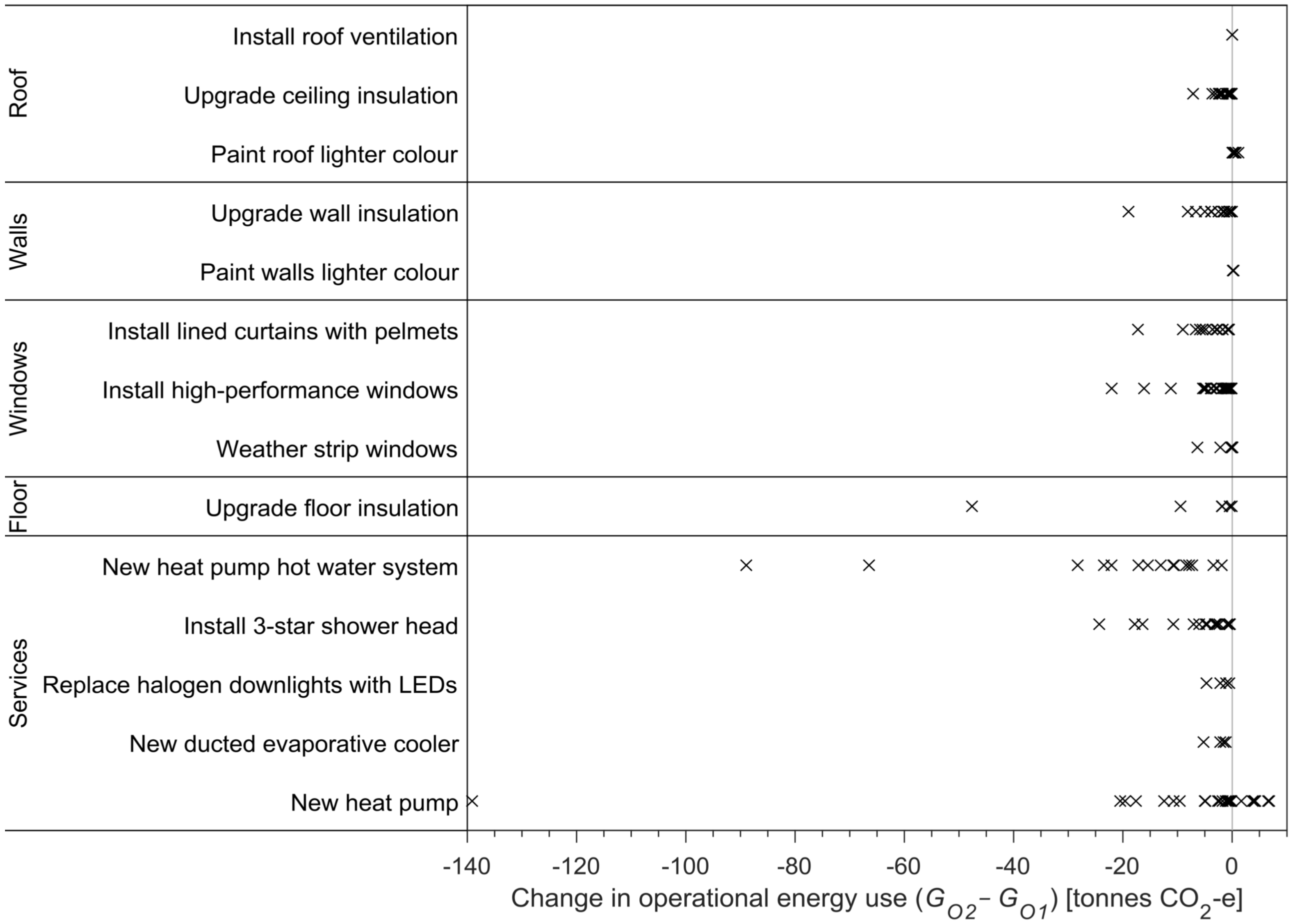

Figure 5: Operational emissions abatement caused by energy efficiency retrofits prescribed by the Scorecard tool, based on energy consumed for heating, cooling and hot water production over the remaining operational 'lifespan' of each house.

The retrofits predicted to have negative impacts (i.e. increase operational GHG emissions), included the installation of a new heat pump (minimum abatement of 6.8 tonnes CO_2-e), and painting the roof or walls a lighter colour (minimum abatement of 1.1 and 0.05 tonnes CO_2-e, respectively). In the case of new heat pumps, these increases in emissions were caused by a switch from wood-burning stoves to electrical equipment for heating—the emissions intensity of wood being significantly lower than that of electricity until the grid is decarbonised. Retrofitting the houses with lighter coloured roofs or walls was predicted to increase operational emissions in all cases; these retrofits were suggested by the Scorecard tool to improve hot-weather thermal performance, rather than total annual energy consumption.

The total operational GHG emissions abatement from all retrofits suggested by the Scorecard tool for each of the 29 houses ranged from –4.1 to 156.9 tonnes CO_2-e (i.e. from an increase in operational emissions of 4.1 tonnes, to a decrease of 156.9 tonnes), with an average value of 26.2 tonnes CO_2-e.

3.4 EMISSIONS ABATEMENT THROUGH BUSHFIRE RESILIENCE

One of the primary areas of focus in this study was the potential GHG emissions abatement offered by retrofitting for improved bushfire resilience, as described in Sections 1.1 and 2.4.2. To our knowledge, these aspects of life cycle assessment had not been investigated previously.

Figure 7 presents the calculated GHG emissions that can be attributed to the risk that each house may need to be rebuilt after being destroyed by a future bushfire. The calculations span the remaining operational 'lifespan' of each house. The orange circles show the calculated emissions for each house if it isn't retrofitted for improved bushfire resilience, and the blue triangles show the reduced emissions calculated for the retrofitted houses.

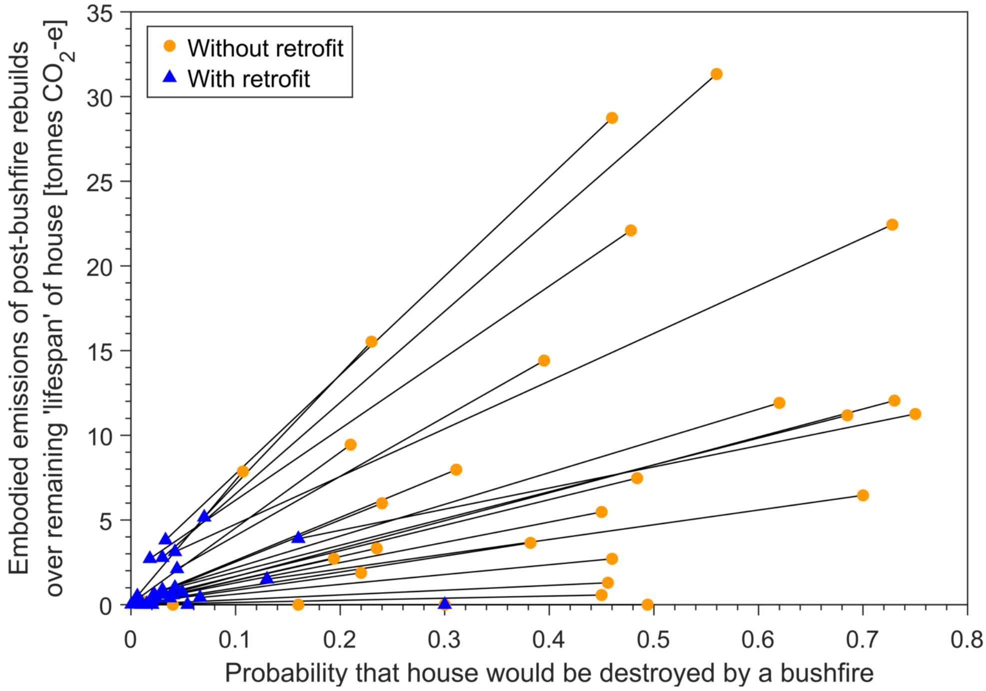

Figure 6: Impact of bushfire retrofits on the probability each house would be destroyed by a hypothetical future bushfire and greenhouse gas emissions associated with rebuilding after future bushfires, calculated over the remaining operational 'lifespan' of each house.

There is a wide variation in the magnitude of such emissions between individual houses. For un-retrofitted houses it ranged from 0.0 to 31.3 tonnes CO_2-e with an average value of 8.5 tonnes CO_2-e, and for retrofitted houses it ranged from 0.0 to 5.2 tonnes CO_2-e with an average value of 1.1 tonnes CO_2-e. The estimated GHG emissions abatement caused by the bushfire resilience retrofits ranged from 0.0 to 28.6 tonnes CO_2-e with an average value of 7.4 tonnes CO_2-e.

3.5 NET IMPACT OF RETROFITS ON EMISSIONS

By combining the contributions to GHG emissions presented in Sections 3.2, 3.3, and 3.4, the overall (net) impact of energy efficiency and bushfire resilience retrofits on emissions was calculated, as illustrated in Figure 8.

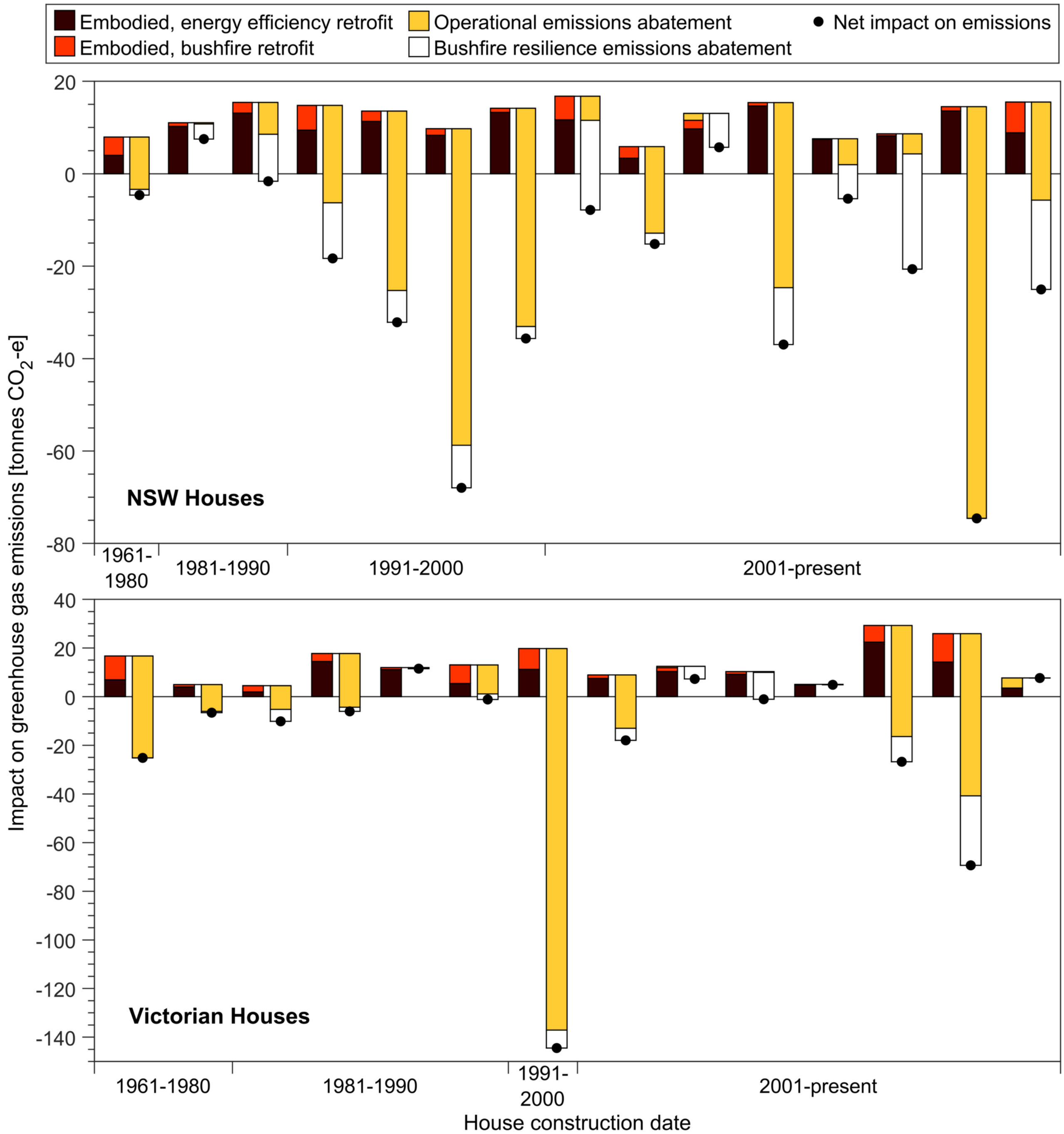

Figure 7: Net impact of retrofits for energy efficiency and bushfire resilience on greenhouse gas emissions, calculated for each of the 15 NSW houses (top), and 14 Victorian houses (bottom).

Thirteen of the fifteen NSW houses, and ten of the fourteen Victorian houses, would provide a negative net GWP value (i.e. a net abatement) if they were retrofitted. The magnitude of net emissions abatement ranged from –11.5 to 144.5 tonnes CO_2-e with an average value of 21.0 tonnes CO_2-e.

The relative magnitude of the white bars and orange bars in Figure 8 illustrates the significance of bushfire resilience retrofits as compared to energy efficiency retrofits in terms of GHG emissions abatement. In most cases the operational emissions abatement from improved energy efficiency is larger, but the emissions abatement from improved bushfire resilience is of a comparable order of magnitude. The median ratio of bushfire resilience emissions abatement to energy efficiency emissions abatement across the 29 case study houses was 18 %.

Importantly, these emissions abatements are essentially co-benefits arising from the suggested retrofits, since the primary aim of the BRSR tool is to improve life and home safety, and the primary aim of the Scorecard tool is to reduce energy costs for households.

There is considerable uncertainty in several of the inputs to the analysis presented in this report, most notably in the estimated future bushfire frequency, and total building operational 'lifespan' assumed. Figure 9 illustrates the sensitivity of results presented in Figure 8 to these two key input assumptions.

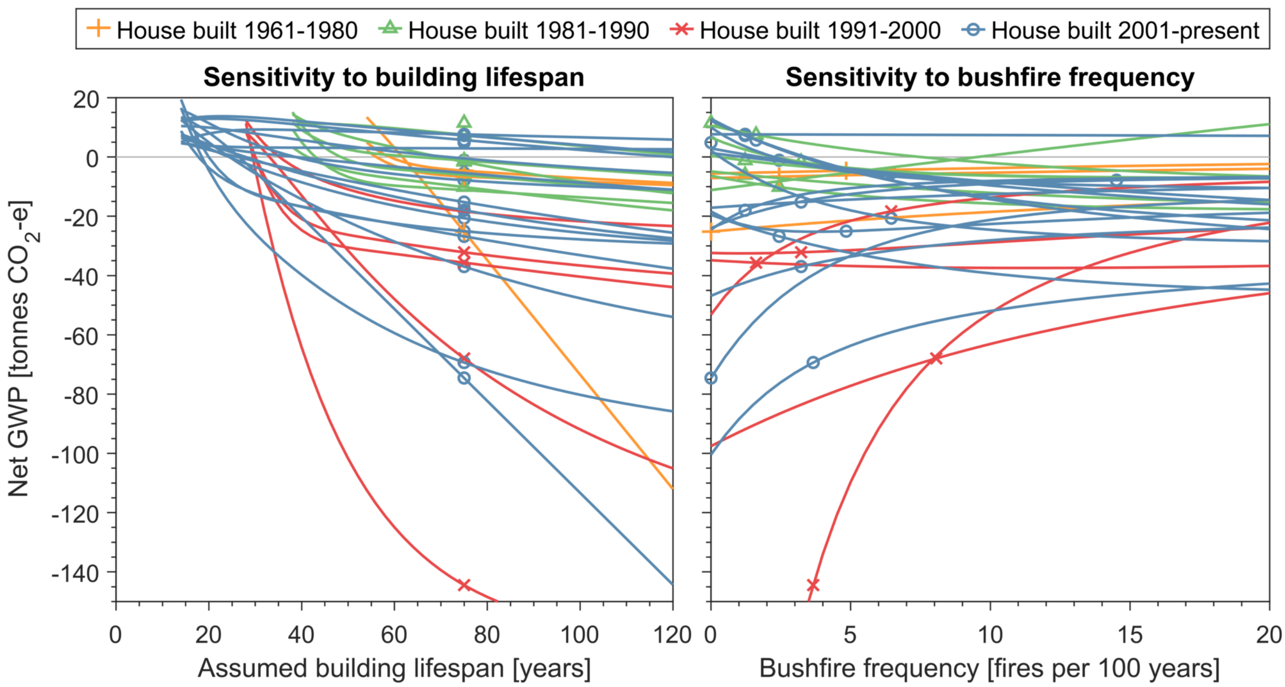

Figure 8: Sensitivity of the calculated impact of retrofits on greenhouse gas emissions to the assumed building operational 'lifespan', and the local frequency of bushfires.

For the primary set of calculations, we assumed the operational 'lifespan' of each house was 75 years in total, so the remaining 'lifespan' was 75 years minus the current age of the house. This assumption has a large impact on the results (as shown by the slope of lines in the left-hand graph in Figure 9); if the houses are operated for more than 75 years, the net emissions abatement from retrofitting the house will be greater.

For the primary set of calculations, we also assumed that the recorded historic bushfire frequency at the location of each house would continue into the future. These bushfire frequency values were based on the number of recorded bushfires that had come within a 1 km radius of each house. The right-hand graph in Figure 9 shows how the calculated net impact of retrofitting on emissions would change if the future bushfire frequency is different to the historic bushfire frequency. In locations where there are fewer than 5 bushfires per 100 years, the bushfire frequency can have a significant effect on emissions abatement, but as the bushfire frequency becomes higher this sensitivity declines.

4 Conclusion

The analysis of retrofits suggested by the BRSR and Scorecard tools in this report provides insights into two important aspects of retrofit programs aiming to integrate efforts to improve the bushfire resilience and energy efficiency of houses:

1. The potential synergies and conflicts encountered when undertaking such a combined retrofit program; and
2. The potential impact of such retrofits on GHG emissions.

In regard to the first of these points, a detailed table of co-benefits, considerations and conflicts have been included in this report, covering the range of retrofits suggested by the BRSR and Scorecard home assessment tools. These additional considerations represent an added layer of complexity for those wishing to undertake a combined bushfire/energy-efficiency retrofit program. However, the benefits of including such considerations are potentially very significant. Unintentional adverse impacts can be avoided, co-benefits can be maximised, and a more accurate understanding of the costs and benefits associated with each potential retrofit action can be obtained.

Calculations of the potential GHG emissions abatement provided by bushfire-resilience and energy-efficiency retrofits for 29 case study houses revealed the following:

- The magnitude of net lifecycle GHG abatement can vary widely between houses (from –11.5 to 144.5 tonnes CO_2-e in the set of case study houses), but typically represents a net reduction in emissions (with an average value of 21.0 tonnes CO_2-e across the case study houses).
- The emissions abatement achieved through bushfire resilience retrofits is typically smaller than, but of a similar order of magnitude to, those achieved through energy efficiency retrofits (equalling 18 % of the energy efficiency retrofit emissions abatement in the median of the cases investigated).
- The sensitivity of these results to the assumed building operational 'lifespan' and future bushfire frequency is significant in some cases:
    - If buildings are operated for longer than the assumed 75 years, larger net emissions abatements would be achieved; and
    - If bushfires occur more frequently at each location than suggested by historical records, the net GHG emissions provided by retrofitting can increase or decrease,

depending on the case, but tends to become less sensitive to this assumption when the bushfire frequency exceeds approximately 5 fires per 100 years.

Thus, this pilot study has demonstrated a range of potential benefits that could be realised if efforts to retrofit buildings for energy efficiency and bushfire resilience were integrated.

Such retrofit programs would need to overcome several challenges, such as establishing a quantitative basis to compare and prioritise retrofits for bushfire and energy efficiency, which are not typically measured by the same type of performance metric (i.e. bushfire retrofits are focused on improving life and property safety, whereas energy efficiency retrofits are typically focused on energy, cost, or emissions savings). However, these challenges do not appear to be insurmountable.

The ongoing Disaster Resilience and Energy Efficiency Ratings project will build on the findings presented here, and will develop a unified home assessment framework for energy efficiency, bushfire, cyclone, flood, and heatwave resilience.

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Appendices

APPENDIX A: EMBODIED EMISSIONS OF RETROFITS

Table 4 and Table 5, below, present the unit embodied emissions calculated for each retrofit action recommended by the Scorecard and Bushfire Resilience Star Rating tools, respectively. These values are expressed in terms of kg CO_2-e per unit roof area, floor area, glazing area, deck area, or per house, as indicated in the tables. The values were determined using emissions factors for all materials and products consumed by the retrofits, and the quantities of materials needed to undertake the retrofit on the archetypal house presented in Appendix C.

These unit values were then applied to the 29 case study buildings by multiplying by the relevant building property (e.g. roof area, floor area, etc.).

Table 5: Unit embodied emissions of energy efficiency retrofits.

Retrofit	Unit embodied emissions	Units
Lighter roof colour	0.587	kg CO_2-e per m^2 roof area
Lighter wall colour	0.437	kg CO_2-e per m^2 floor area
Upgrade ceiling insulation	6.920	kg CO_2-e per m^2 roof area
Upgrade wall insulation	2.569	kg CO_2-e per m^2 floor area
Upgrade floor insulation	4.345	kg CO_2-e per m^2 roof area
Weather strip windows	0.855	kg CO_2-e per m^2 glazing area
Weather strip doors	0.199	kg CO_2-e per m^2 floor area
Replace windows with low-SHGC, low U-value	125.125	kg CO_2-e per m^2 glazing area
Lined curtains w pelmets	11.062	kg CO_2-e per m^2 glazing area
Install roof ventilation	5.232	kg CO_2-e per m^2 roof area
Install dampers in exhaust ducts	0.256	kg CO_2-e per m^2 floor area
New heat pump	18.071	kg CO_2-e per m^2 floor area
New ducted evaporative cooler	18.017	kg CO_2-e per m^2 floor area
Replace halogen downlights w LEDs	0.302	kg CO_2-e per m^2 floor area
Shower head with 3 star WELS rating	0.162	kg CO_2-e per m^2 floor area
Heat pump or solar hot water system	9.928	kg CO_2-e per m^2 floor area

Table 6: Unit embodied emissions of bushfire resilience retrofits.

Retrofit	Unit embodied emissions	Units
Install sarking under roof	1.903	kg CO_2-e per m^2 roof area
Remove stored items from roof space	0	kg CO_2-e per m^2 roof area
Install ember-resistant roof ridge vents	5.232	kg CO_2-e per m^2 roof area
Install screens over roof vents or chimney	0.062	kg CO_2-e per m^2 roof area
Install metal fascia or gutters	7.779	kg CO_2-e per m^2 roof area
Repair roof, fascia or gutter	0.133	kg CO_2-e per m^2 roof area
Install new steel roof	27.500	kg CO_2-e per m^2 roof area
Install gutter guard	0.770	kg CO_2-e per m^2 roof area

Retrofit	Unit embodied emissions	Units
Install screens over skylights	0.778	kg CO_2-e per m^2 roof area
Replace skylights	2.699	kg CO_2-e per m^2 roof area
Remove fuels near skylights	0	kg CO_2-e per m^2 roof area
Seal gaps in walls	0.176	kg CO_2-e per m^2 floor area
Install weep hole screens	0.125	kg CO_2-e per m^2 floor area
Remove fuels from near wall	0	kg CO_2-e per m^2 floor area
Replace cladding	24.048	kg CO_2-e per m^2 floor area
Install screens over vents	0.062	kg CO_2-e per m^2 floor area
Install flashings over horizontal ledges	0.234	kg CO_2-e per m^2 floor area
Install flashings over window sills	1.001	kg CO_2-e per m^2 glazing area
Install screens over windows	16.629	kg CO_2-e per m^2 glazing area
Replace windows	125.125	kg CO_2-e per m^2 glazing area
Install bushfire shutters	30.000	kg CO_2-e per m^2 glazing area
Clear fuels from below window	0	kg CO_2-e per m^2 glazing area
Replace window with wall	2.747	kg CO_2-e per m^2 glazing area
Install steel kickplate on doors	0.126	kg CO_2-e per m^2 floor area
Install ember screen door	1.940	kg CO_2-e per m^2 floor area
Replace door with fire-rated door	1.152	kg CO_2-e per m^2 floor area
Door draft stripping	0.286	kg CO_2-e per m^2 floor area
Seal gap around garage door	1.610	kg CO_2-e per m^2 floor area
Remove items from under deck	0	kg CO_2-e per m^2 deck area
Enclose subfloor/deck	11.725	kg CO_2-e per m^2 deck area
Install flashing around verandah posts	1.800	kg CO_2-e per m^2 deck area
Replace verandah posts	10.007	kg CO_2-e per m^2 deck area
Replace verandah rafters	31.708	kg CO_2-e per m^2 deck area
Replace fibreglass verandah roof	25.000	kg CO_2-e per m^2 deck area
Replace decking	23.560	kg CO_2-e per m^2 deck area
Replace steps/ramp	7.892	kg CO_2-e per m^2 deck area
Replace balustrade	61.530	kg CO_2-e per m^2 deck area
Install screen over evaporative cooler	23.449	kg CO_2-e per house
Install screen over AC outdoor unit	23.449	kg CO_2-e per house
Install flashing near meter box	25.569	kg CO_2-e per house
Store gas bottles safely	0.593	kg CO_2-e per house
Trim/remove overhanging trees	0	kg CO_2-e per house
Clear vegetation from near home	0	kg CO_2-e per house
Move items away from home	0	kg CO_2-e per house
Remove items stored in garage	0	kg CO_2-e per house
Install a non-combustible path	226.560	kg CO_2-e per house
Install bushfire sprinkler system	11.456	kg CO_2-e per house

APPENDIX B: EMBODIED EMISSIONS OF HOME REBUILDS

Table 6 presents the unit embodied emissions calculated for rebuilding a house. The values are expressed in terms of kg CO_2-e per unit roof area, floor area, glazing area or deck area, as indicated in the table. The values were determined using emissions factors for all materials and products consumed by the retrofits, and the quantities of materials required to construct the archetypal house presented in Appendix C.

These unit values were then applied to the 29 case study buildings by multiplying by the relevant building property (e.g. roof area, floor area, etc.) and adding the relevant components (e.g. by adding values for the base structure, relevant external wall type, relevant roof type, relevant floor type, any decking, and any glazing, where each value was first multiplied by the appropriate floor/roof/deck/glazing area).

Table 7: Unit embodied emissions associated with rebuilding.

Building element	Construction type	Embodied emissions	Units
Base structure	Common to all houses	78.267	kg CO_2-e per m^2 floor area
External walls	Brick veneer	66.053	kg CO_2-e per m^2 floor area
	Lightweight cladding	13.079	kg CO_2-e per m^2 floor area
	Concrete block	101.303	kg CO_2-e per m^2 floor area
Roof	Steel-clad	58.977	kg CO_2-e per m^2 roof area
	Tiled	60.049	kg CO_2-e per m^2 roof area
Floor	Concrete slab	126.152	kg CO_2-e per m^2 roof area
	Suspended floor	44.746	kg CO_2-e per m^2 roof area
Verandah/deck	All types	217.632	kg CO_2-e per m^2 deck area
Glazing	All types	125.125	kg CO_2-e per m^2 glazing area

APPENDIX C: DETAILS OF THE ARCHETYPAL HOUSE

To facilitate the calculation of unit embodied emissions for retrofits and rebuilds (see Appendices A and B, respectively), an archetypal Australian house design was used as the basis of assumed 'typical' internal wall lengths per unit floor area, external wall lengths per unit floor area, quantities of frame members per unit roof/floor area, window perimeter per unit glazing area, etc.

For this purpose, we adopted a design originally developed by Isaacs [22] for energy efficiency analyses, which has been used as a detached housing archetype in multiple housing stock modelling studies previously, e.g. by Bannister et al. [23]. The archetypal house is shown in Figure 10, and its floorplan and key dimensions are provided in Figure 11.

Figure 9: 3D sketch of the archetypal house; reproduced from [22].

Figure 10: Floor plans of the archetypal house showing room dimensions (top), and glazing dimensions (bottom); adapted from [22].