Building a healthy, zero-carbon ecovillage: innovative homes meeting a high-performance building standard

John J. Shiel [1, 2, 3]
[1] *EnviroSustain, Gosford, Australia*
jafshiel@outlook.com, *Orc-ID: 0000-0002-3233-6284*[1]
[2] *Narara Ecovillage, Gosford, Australia*
[3] *University of Newcastle, Newcastle, Australia*

ERRATA: Please note there is now an errata section on pages 11 and 12, with values in red corrected in Table 3b to replace Table3, and an additional graph of the carbon LCA of 5 homes.

Abstract: The Council of Australian Governments (COAG) have set a trajectory towards net zero carbon buildings by 2050. This paper describes the design, materials and construction technologies of low carbon homes of members of a low environmental footprint ecovillage. Fifty homes in Stage 1 of Narara Ecovillage Co-operative (NEV) in NSW, have met a flexible, high-performance building standard, which required homes to have 1) a 2017 NatHERS rating of at least 7 stars, 2) solar power to meet their annual energy needs, and 3) sufficient reward points for items such as resource efficiency, good indoor environmental quality and low embodied carbon. The methods used included surveys of members and case studies comparing innovative buildings including an earthship home; a kit home with reverse-timber-veneer walls; an earthquake-resistant super-adobe walled art studio; homes with straw panel and strawbale walls; and those with CO_2-absorbing hempcrete wall infill. The paper describes the lessons learnt in Stage 1 that have improved the Stage 2 building standards, and considers the carbon life cycle for five homes. NEV has created a healthy, high-performance residential precinct with affordable, low embodied carbon homes, some built on difficult sites. This study provides a glimpse into the future of housing to 1) lower its impact on the electricity grid, 2) mitigate home operational and embodied carbon emissions for the climate emergency, 3) adapt homes for heatwaves, and 4) provide home energy storage as bi-directional charging becomes available for electric vehicles and they are charged from renewable energy.

Keywords: Zero energy ecovillage; innovative homes; construction technologies; life-cycle carbon analysis

1. Introduction

Greenhouse gas (GHG) emissions globally need to come down quickly and to reduce the impacts of extreme events related to climate change.

The recent dangerous weather of intense heat and devastating rainfall in the Northern Hemisphere summer has been attributed to human-induced climate change (WMO 2023). It has caused heatwaves, wildfires and floods with significant impacts on human health, agriculture, energy, water supplies, ecosystems and economies, including many thousands of excess heatwave deaths (Dickie, Abnett, and Dickie 2023).

Of Australia's total carbon emissions, residential buildings contribute around 13% of operational emissions from using appliances in the home (ASBEC, 2016, 26), and around 2.5% of embodied emissions, which are related to the home construction and manufacture of its materials (GBCA and thinkstep-anz 2021, 5).

The Council of Australian Governments (COAG) is aiming for net-zero operational carbon buildings by 2050 with more energy-efficient buildings and appliances, with new homes having renewable energy (Prasad et al., 2022). Existing homes can be operationally energy neutral since the cost of solar photovoltaic panels is falling.

To reduce their operational carbon footprint homes require more components for energy-efficiency and for solar power, increasing their embodied energy and emissions which are expected to dominate operational emissions in the building sector in 2050 (GBCA and thinkstep-anz 2021, 4). Therefore, the emphasis for new construction should be on creating low embodied carbon homes with net zero operational carbon.

1.1. Narara Ecovillage

This study describes homes in Narara Ecovillage (NEV), a community located at Narara in the NSW Central Coast aiming to live in healthy homes that have a low environmental footprint, by minimising energy, water and waste, while having strong social and financial sustainability values. The study compares seven innovative low carbon homes in detail and considers the carbon life-cycle of five homes.

NEV is a unique owner-developer of land co-operative, with 100 memberships and owing a 63-hectare (ha) site consisting of eleven hectares for residential development; a 45 ML irrigation dam with a freshwater river; a conservation forest of around 30 ha; and having 50 homes completed in Stage 1.

Sustainable precincts were reviewed to create the by-laws and the building standards, and these included Cape Paterson in Victoria for its renewable and embodied energy policy; Lochiel Park and Aldinga Arts Eco Village in South Australia for their proven home energy reduction and artistic, permaculture and environmental sustainability approaches; the NSW BEND Neighbourhood Association for community and management guidance; the Qld Ecovillage at Currumbin regarding reducing the number of managed precincts; and the Mullum Creek Development near Melbourne, Victoria for its sustainable materials.

1.1.1. Building standard and smart grid

NEV has been cited as an exemplar precinct for achieving net energy positive status since:

> "…Its building standards incorporate requirements for demand reduction, energy efficiency and on-site renewables... Each house is required to install sufficient PV energy on the roof to meet [its] needs [and is] connected to a Smart Grid that manages excess power and integration with the grid." (Prasad et al. 2022, 186)

NEV initially won a NSW government Growing Community Energy Grant of $70,000 for a feasibility study that showed that a smart grid concept could work, where an embedded network balances its own internal loads and generation. This paved the way to win a $1.38m Advancing Renewables Program grant from the federal Australian Renewable Energy Agency (ARENA 2016) to help build it.

NEV members created their own building standard which had high energy efficiency and sustainability standards. It required homes to 1) gain at least 7/10 stars in the 2017 version of the Nationwide House Energy Rating Scheme (NatHERS) for home design, when the minimum was 6 stars and there were no limits on heating and cooling loads; 2) generate the solar power to meet annual needs; 3) achieve 70/100 points in an evaluation similar to Greenstar for small house size, reducing the use of water, energy, waste and their embodied carbon, and improving the indoor environmental quality (IEQ) for healthy homes.

NEV members updated the building standards in 2022 for Stage 2 that expanded the scope to also include member education and the review of the building stages from lessons learned in building Stage 1. This standard prepares homes for heatwaves by increasing the minimum NatHERS rating to 7.5 stars, while lowering the maximum BASIX cooling load by 50%. It also rewards Owners for undertaking an As-Built assessment to ensure important environmental design features other than in BASIX are checked during construction, and to record the As-Built NatHERS rating (or any Passive House blower door test result). The Stage 2 building standard rewards good ventilation and sealing as described in the 2023 National Construction Code (NCC) for better mould and other pathogen management, with extra points to achieve the minimum 70 points.

The Stage 1 members of the co-op also developed their own sustainable by-laws for the community association to minimise the use of energy, carbon emissions, water and waste, and encourage using electricity and renewable energy, and aspire to obtain the:

> "…target of purchasing, or generating, excess renewable energy, over a period of thirty (30) years, than the amount of embodied energy in the inhabited homes on the Lot." (NEV 2017, 44)

2. Method

The 55 home owners were surveyed about their home and family characteristics, appliance behaviour, special heating and cooling features, comfort levels and electric vehicle usage (ARENA 2016). The energy imported and exported to the grid by the village was recorded for the 2022/23 financial year.

Seven homes were selected for their innovative design and form, their materials or their construction method. The case study method was used to compare them for 1) materials used, 2) construction technologies, 3) energy assets, 4) thermal performance, and 5) health and amenity. This required a more detailed survey and analysis of the homes, owner appliances and behaviour, and detailed reviews of their construction methods.

An operational and embodied carbon analysis was conducted on five homes for which the appropriate data for energy and materials was available, and a projected life-cycle analysis (LCA) of their carbon footprint was performed.

3. Results & Discussion

3.1. Stage 1 homes

Figure 1 shows the construction types of the 55 stage 1 homes showing 22 had innovative designs or materials, and the remaining 33 are traditional lightweight homes with either timber or concrete floors, or both.

Figure 1 - Construction types of the 55 stage 1 homes (Source: Author)

3.2. The design of innovative homes

The relative sizes, shapes and Northerly aspects are compared for the seven innovative homes in Figure 2.

The features of the innovative homes are compiled in Table 1 which describes the home characteristics for: 1) an Earthship home; 2) & 3) two hempcrete homes 4) a reverse-timber-veneer kit home; 5) a family home with many biogenic (i.e. natural) and second-hand materials; 6) a super-adobe (walls made of earth bags with barbed wire between layers for earthquake-resistance) art studio with earthen floors; and 7) a home with strawbale walls and a reciprocal roof made from bamboo. Table 1 also shows the cost ranges per square metre, the type of heating and cooling systems installed, and the NatHERS rating.

3.2.1. Discussion

Table 1 shows these homes comply with the building standards maximum size of 180m2, and have areas about half the average Australian detached home of around 245m2 (ABC 2015; ABS 2010). This greatly contributes to their affordability, and results from removing extra bedrooms, with other village accommodation available.

All homes have good thermal mass, with most having a concrete floor charged with direct sunlight in winter, while others have dense external walls: home 5 has a solid timber inner wall; homes 6 and 7 have compressed earth bricks CEB and earth floors (see Table 1). All have good insulation for their external walls.

Cold-bridging for the window frames was reduced by using timber, thermally broken aluminium or uPVC.

The home designs ensure good cross-ventilation in rooms; most having decks for outdoor living; and good ventilation features including utilising the convective stack effect (e.g. homes 1, 2, 3, 6 and 7 have openable upper windows and doors) aided by ceiling fans. While the costs per square meter are above average, the smaller village home sizes than average mean that the home costs are quite affordable and cost-effective, except for the homes which are particularly innovative.

3.3. The construction technologies of innovative homes

Details of construction materials, technologies and methods are shown in Table 2. All of the innovative homes use biogenic wall materials e.g. earth-filled tyres, strawbales, cob (earth, straw, lime and water), hempcrete (hemp husks, sand, a lime binder and water), a solid timber inner wall leaf, prefabricated strawbale panels, rammed earth, CEB, super-adobe, and light straw.

Figure 3 shows the construction technologies of homes 1 to 4 It shows the earth-filling of home 1 tyre walls; a comparison of an Owner Builder hempcrete wall workshop and one built by a builder and the highly unusual Home 4 2-bedroom kit home with computer numerically controlled (CNC) laser solid timber wall being formed. The roof of the Octagon is an unusual reciprocal bamboo roof, and 3 of these homes have green roofs.

Figure 2 - Thumbnail sketches of relative plan sizes, shapes and orientations of the 7 innovative homes, numbered 1 to 7 from left to right (Source: Author)

Table 1: Design Features, Heating and Cooling Appliances and NatHERS ratings of Selected Innovative Homes (Source: Author)

Home	1	2	3	4	5	6	7
Description	Earthship	Hempcrete powerhouse	Sustainable hempcrete home	Reverse timber veneer modular kit	Natural family home	Hobbit style art studio	Bamboo & strawbale octagon
Drawings or Designer	Dr Martin Freney	Earlx2 Architecture	*	Mark Cassidy**	Kenney LeMire of IBD***	IBD's Will Eastlake	IBD's Will Eastlake
Gross Floor Area (m2)	82	143	113	79	83.6	53	104
Completed (year)	2019	2020	2020	2023 (expected)	2023 (upstairs)	2023 (expected)	2023 (expected)
Cost/area (AUD$/m2)	$4500 - $5000	$3,000 - $3,500	$5,000 - $5,500	$3,000 - $3,500	$4,300 - $4,800 (upstairs)	> 5,000	
No. bedrooms	2	3 and WIR	1	2	3 and study	1	1
Storeys	1	1 plus mezzanine	1 plus mezzanine	1	2	1	3
Ceiling insulation****	R5	R3	R5	R4	R6.5	R2.5	R4
Windows	Timber single and double glaze	Timber double-glazed	Thermally-broken, dble-glzd aluminium	Double glazed PVC	Local timber double glazed	Timber single-glazed	Timber single-glazed
Ext. Walls	Earth-filled tyres	Hempcrete	Hempcrete	Rvrs timber veneer	Prefab. strawbale	Super-adobe	Strawbale
Ext. wall insulation[#]	> R5	R4; R2.5 upper	R4; R2 upper	R2	> R7	> R5	> R7
Floor type(s)[##]	Concrete SOG	Concrete SOG	Concrete SOG	Steel-frame timber	Concrete part-suspended	Multiple	Multiple
Roof	Metal	Metal	Metal	Metal	Metal & green (plant) roof	Green roof	Metal & green roof
Eaves (m)[###]	0.47	0.6 N&S, 1 E&W	0.3	0.1 N&S, 0.3 E&W	0.78	N/A	0.86
Ceiling Height (m)	2 to 3.6	2.7; 2.8 to 6.1	2.5 to 4.9	2.5 to 4.0	2.5	2 to 4	3 to 4.5 (3 levels)
NatHERS (design)	7.6	8.8	7.3	7.2	7	7.1	7.1
Heating and cooling systems[####]	Cooling tubes; inter-room fans; internal greenhouse	4 Laros Lunos e2 MHRV units	Air-conditioner; clerestory windows	Air-conditioner	Hydronic bathroom floor heating system	Openable cupola windows	Upper storey door for stack ventilation

*Not for publication; **Adapted a kit design; ***Integrated Biotecture (IBD); ****K.m2/W; [#](Acosta et al. 2010; Ahmed et al. 2022; Downton 2023); [##] Slab on ground (SOG); Multiple (Earth, timber & concrete floors); [###]North (N), South (S), East (E), West (W); [####] Mechanical heat recovery ventilation system (MHRV).

Figure 3 - Building technologies of homes 1 to 4. a. Compacting earth in tyres -earthship home 1 (Source: S. Bozkewycz); b. Home 2 volunteer hempcrete wall workshop (Source: G. Cameron): c. Home 3 hemp walls by builders (Source: M. Ong): d. Home 4 builders hammering together the solid timber wall (Source: P. Atkins)

Figure 4 shows the construction technologies of homes 5 to 7. It shows the prefabricated straw panels; the art studio rock walls and arched doors; the art studio internal wall clay rendering of the super-adobe walls; installing the internal straw bale walls of the octagon home.

Figure 4 - Building technologies of homes 5 to 7. a. Prefabricated straw panel external wall for home 5 (Source: M. Lloyd); b. Home 6 art studio (Source: L. Scott); c. Home 6 art studio internal wall clay rendering onto super-adobe earth bags (Source: Will Eason); d. Straw baling the internal walls of the octagonal-shaped home 7, with the bamboo reciprocal roof at the top left blue cupola (Source: C. Oosthuizen)

3.3.1. Discussion

Except for homes 3 and 4, all were Owner-built with the help of the community, friends, relatives and others interested in learning during workshops, as well as professionals where needed. These workshops imparted valuable biogenic building skills on walls of hempcrete, earth-filled tyres, super-adobe, strawbale and rammed earth; and earthen floors; as well as for landscaping.

The kit home was sourced from Germany and manufactured in Lithuania, and had several delays resulting in late completion, including during the corona virus lockdown.

3.4. The health and amenity of innovative homes

Table 2 shows the building materials are low in toxins, which should provide a healthy indoor environment. It also shows that the external walls of two of the homes were made of hempcrete, two had 450mm strawbale and one had a reverse timber veneer wall where the inner leaf was solid timber and the outer was colorbond. The internal walls of some homes included straw bales, straw panel and rammed earth.

For health and amenity two homes have hempcrete walls which have good environmental properties, and 4 have clay render while all have low VOC finishes and most have 2nd hand materials. The art studio and octagon homes have earth floors.

3.4.1. Discussion

The home air quality is high because owners used products with low volatile organic compounds (VOCs) or natural finishes e.g. earth floors had six oil coats taking many weeks to dry out. No carpets were used on floors, and the use of many second-hand materials and furniture items reduced fluorocarbon off-gassing effects.

Good natural ventilation was ensured as well as having active systems such as ceiling fans, mechanical heat recovery ventilation (MHRV) systems, buried cooling tubes activated with fans, and air conditioners to regulate temperature and humidity. These ventilation systems also reduce the risks of mould and can help reduce air-borne bacteria and viruses such as corona especially if using high-efficiency particulate air (HEPA) filters.

3.5. Village energy and carbon

Figure 5 shows the Smart Grid's net annual export values, the grid connection via a 1MVA tap transformer regulating the voltage and frequency, and typical annual energy flows for homes with and without batteries.

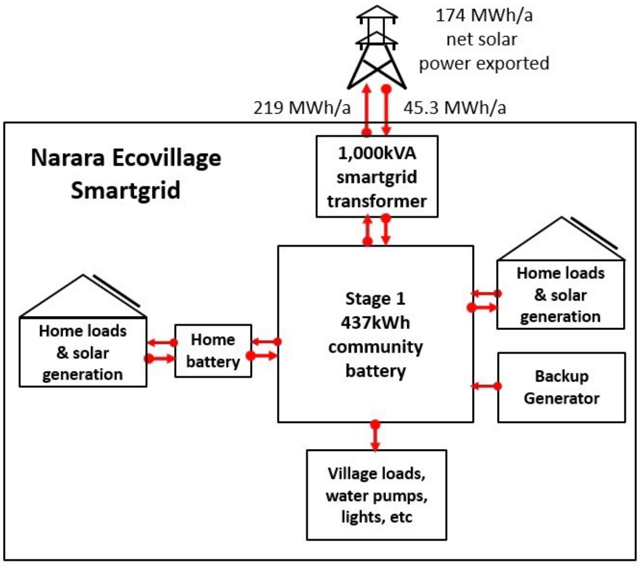

Figure 5 - Village and typical home energy assets, and annual exports and imports (Source: author)

The large community battery of 437kWh is charged by the village solar power with some homes having their own batteries, while there are village loads and an emergency diesel generator.

3.5.1. Discussion

The village is energy positive with the net energy exported in Figure 5 of 174 MWh/a which is equivalent to an offset of around 135 t CO_2-e/a and is a significant renewable contribution to the grid from 50 homes. This is

Table 2: Material details, construction methods and health and amenity of Innovative homes (Source: Author)

Home	1	2	3	4	5	6	7
Description	Earthship	Hempcrete powerhouse	Sustainable hempcrete home	Reverse timber veneer	Natural family home	Hobbit style art studio	Bamboo & strawbale octagon
Ext. Walls	Earth-filled-tyres; glass bottles; 450mm Strawbale; rammed earth; cob	Lower - 250mm hempcrete; Upper – lightweight wall	Lower – 300mm Hempcrete; Upper – lightweight wall	Reverse 80mm Nordic spruce veneer with colorbond	Lower – concrete, rammed earth, CEB & CEB veneer; Upper - Prefabricated 350mm strawbale panel; glass bottles	Double super-adobe with int. clay render & ext. lime render; glass bottles; cob	450mm strawbale; Light straw; cob; glass bottles
Int. walls	Rammed earth; cob walls	Timber frame with plasterboard	Timber frame & plaster-board	50mm solid timber	Straw-panel; Rammed Earth	Cob; double super-adobe with int. clay render	450mm strawbale; light straw; cob
Floor details	Concrete SOG with glass aggregate, polished 7 times	Concrete SOG	Burnished concrete SOG	Steel framed timber floor	Coloured low carbon concrete partly suspended	Mainly earthen with oil finish; timber; and concrete bathroom	Mainly earthen with oil finish; timber loft and concrete bathroom
Roof details	Light-coloured colorbond	Light-coloured colorbond	Light-coloured colorbond	Light-coloured colorbond	Light-coloured colorbond & green roof with plants	Green roof with plants	Bamboo reciprocal roof; Light-coloured colorbond & green roof with plants
Construction methods	Owner assisted in workshops with family & volunteers; local materials; skilled workers where required.	Owner build, with Local materials, workshops with volunteers; & skilled workers	Employed a local builder experienced in hempcrete building	Kit purchased from Germany, built in Lithuania, assembled by local organisation	Owner assisted by a local builder friend; volunteer workshops; skilled workers where required	Owner assisted by designers & builders for foundations & super-adobe workshops; skilled workers where required	Owner assisted by designers & builders for foundations & strawbale workshops; skilled workers where required
Health & amenity - avoiding toxins, and improving indoor environmental quality (IEQ)	Clay render on strawbale & low-toxic spray on rammed earth; low VOC paints in greenhouse; lime render on bathroom ceiling and bamboo ceilings elsewhere; air cooled in buried tubes for cooling; good ventilation incl. inter-room reversible fans; many 2nd hand materials and furniture.	Breathable hempcrete home; low VOC paints; double glazed fire-resistant timber framed windows; good cross-ventilation; slow combustion heater; 4 small MHRV units	Breathable hempcrete home; thermally broken windows; good ventilation including stack effect; small air conditioner	Reverse timber veneer with solid Nordic spruce and colorbond mini-orb; low-VOC aquaclear paint; good cross-ventilation; small air conditioner.	Natural wall materials and clay render finish including rammed earth, strawbale panels, cob walls with bottles; good cross-ventilation; many 2nd hand materials; low VOC paints	Natural wall materials & clay render finish for the strawbale walls; good cross-ventilation; earth, timber and concrete floors; low VOC finishes; 2nd hand materials.	Natural wall materials & clay render finish (cob, strawbale & light straw); good cross-ventilation; earth, timber and concrete floors; low VOC finishes; 2nd hand materials.

due to 1) the holistic approach to building standards, 2) energy generation and community battery storage, 3) peak power minimization and 4) other load demand management (ARENA 2016). The grid connection prevents the village from being operational zero carbon until it is decarbonised.

A few homes have electric vehicles (EVs) which can supply some power to the home. As EVs become more popular, NEV will encourage charging them with renewable energy and is looking forward to the imminent arrival of bi-directional charging where the EV can contribute as energy storage for the home (Teague 2023).

3.6. Home operational energy and carbon

Table 3 shows the home details; the operational and embodied energy; and the carbon for five village homes where the full year of energy data were available. Three homes were from the above seven innovative homes and there are two additional ones. It shows the net operational energy exported and the carbon offset for supplying renewable energy into the grid for each home per year.

Table 3 also shows the NatHERS star ratings, the solar panel size, any home battery, the 2 major home loads of 1) hot water system with their co-efficient of performance (COP) efficiencies and that use timers to use renewable energy and 2) the major heating and cooling systems. It also has the net energy exported and corresponding carbon offset, the home embodied carbon adjusted for the carbon-absorbing hempcrete.

3.6.1. Discussion

For thermal comfort Table 3 shows that three of the five homes have air-conditioning installed. The village homes have 50% with air-conditioning due to higher NatHERS ratings or alternative approaches for heating or cooling (see Table 1), which eliminate temperature extremes. Two homes described in this section have MHRV systems to ensure proper ventilation, and assist with temperature and humidity stabilisation: home 2 having four small wall-inserted units that operated synchronously for a few hours per day; and home 8 having a large ducted system like that of a Passive House.

All homes have good thermal mass, but home 8 has an internal brick wall and a phase-change material called bio-PCM which releases and absorbs energy during the phase transition to assist with temperature control for the lightweight upper floor.

3.7. Home embodied energy and carbon

Table 3 shows the embodied carbon using 1) NEV's embodied calculator in the Stage 1 building Standards and 2) using a current best practice value from Prasad et. al (NEV 2017, 24–25; Prasad et al. 2022, 130).

Table 3 also shows the recurrent embodied carbon of the PV system (assuming that the renovation carbon is small in comparison), the total home embodied carbon after 90 years and the carbon capture calculations for the volume of hempcrete in two of the homes, with different wall thicknesses and perimeters. The table shows the calculations for offsetting due to solar panels and to hempcrete carbon capture, leading to an estimate of how many years each home would take to pay back its total embodied carbon (row 12 divided by row 14).

3.7.1. Discussion

NEV's embodied calculator in the Stage 1 building Standards was based on older overseas data, and only had the scopes of A1, A2 and A3 (raw materials supply, transport, and manufacturing, respectively), although it did include the solar panel and inverter embodied carbon and was a useful comparative measure. The best practice low value of Prasad et al (2022, p. 130) uses current Australian data and average values for the additional scopes of transport to site (A4) and construction carbon (A5), although it was assumed there was no solar panel embodied carbon calculation included, so the embodied carbon of the actual solar panel of each home was added when calculating the total embodied carbon for the five homes over 90 years.

The greatest challenge facing new housing is building homes with low embodied carbon. This is very difficult to achieve but successful strategies adopted by NEV members include 1) building smaller homes; 2) using biogenic materials like earth, timber, straw or hemp; and 3) using recycled and waste materials e.g. bricks, timber and cementitious materials for low carbon concrete.

All biogenic materials absorb carbon as they grow, but hemp grows particularly fast, and hempcrete captures carbon after setting since it reacts with lime to form limestone ($CaCO_3$), and so it has negative embodied carbon over its lifecycle. Hemp also has many other environmental features such as breathability, termite resistance, excellent insulation, good air-tightness and wastage recyclability. (Ahmed et al. 2022; Clarke 2018; Hempcrete Australia 2014). However, it has poor compressive strength, and so requires a frame.

Table 3: Energy and carbon features of five NEV homes, with hempcrete carbon calculations (Source: Author)

Home	Details	1	2	3	8	9
Description		Earthship	**Hempcrete** powerhouse	Sustainable **hempcrete** home	Lightweight tightly sealed	Pre-fabricated 2 storey
NatHERS*	Stars	7.6	8.8	7.3	8.3	7.2
Solar panel size	kW	6.3	11.0	9.0	5.0	5.0
Battery	kWh	10.0	N/A	20.0	N/A	N/A
Hot water system	COP	5.0	5.0	5.0	4.0	17.0
Heating and cooling systems		Cooling tubes; inter-room fans; int. greenhouse	4 Laros Lunos e2 MHRV units	Air-conditioner; clerestory windows	Ducted MHRV system; air-conditioner	Air-condit-ioner
Net energy exports	kWh/a	4,567	12,013	7,692	4,674	3,325
PV carbon offset**	t CO_2-e/a	3.6	9.5	6.1	3.0	2.6
Home embodied carbon***	NEV (2017)	62.9	74.0	61.0	50.8	58.6
	Prasad et. al. (2022)	62.5	109.0	86.1	87.6	114.3
PV system recurrent embodied carbon	t CO_2-e every 30 years	18.9	33	27	19.8	15.6
Total home embodied carbon Prasad et al. (2022)	After 90 years (PV plus)	119	208	167	147	161
Hempcrete[#]	width (m)		0.25	0.30		
	area (m^2)		50.0	80.0		
	Volume (m^3)		12.5	24.0		
	Carbon capture (t CO_2-e/a)		0.0119	0.0228		
Carbon offsets for PV & hempcrete[##]	t CO_2-e/a	3.6	10.7	8.4	3.0	2.6
Total embodied carbon payback[###]	years	33.0	19.5	20.0	48.9	61.3

*Design NatHERS rating (2017 version) except for Home 8 (As-Built – NatHERS version 2019)

** Based on energy exported and the NSW electricity carbon intensity from National Greenhouse Accounts Factors (DCCEEW 2022)

*** (NEV 2017, 24–25; Prasad et al. 2022, 130)

[#] Hempcrete has a net sequestration range from 48.4 kg CO_2 per m3 to 137 kg CO_2 per m3 over 100 years (Jami, Karade, and Singh 2022, 229–30). So, the average of this range (95 kg CO_2/m3) was used to estimate the carbon capture per year.

[##] PV carbon offset from home PV net energy exported plus any hempcrete carbon capture

[###] Total home embodied carbon divided by carbon offset from home PV and any hempcrete carbon capture

The NEV by-laws have an aspiration to payback the for the home embodied carbon within 30 years, and there are three owners (homes 1, 2 and 3) who may achieve this (see Table 3). These homes use large solar systems, or moderate amounts of solar power with a battery, or have low energy consumption.

Home 3 has monitored its energy and carbon, and has abated 8.3t CO_2 in around 2 years, by using excess energy returned to the grid, without considering their hempcrete carbon capture. At this rate in 30 years, home 2 would only pay back around 120 tonnes of CO_2-e not the 167 tonnes estimated. However, this is a very interesting question for any future home carbon LCA and sustainability research, especially for hempcrete.

4. Conclusion

Members of Narara Ecovillage in the Central Coast of NSW have created high-performance, healthy, energy-positive homes with low embodied carbon, and the village is known as an exemplar global precinct for achieving nearly net zero carbon.

Seven homes were compared for performance, construction technologies and health and amenity, and five others were compared for carbon imported and exported, embodied and their lifecycle carbon (LCA).

This study provides a glimpse into the future of housing to 1) improve home building with additional builder checks; 2) lower housing impacts on the electricity grid, 3) mitigate operational and embodied carbon emissions for the climate emergency, 4) adapt homes for heatwaves, and 5) prepare to rebalance home loads as a) the National Construction Code (NCC) increases its stringency for thermal performance, and b) electric vehicles replace home batteries as bi-directional charging arrives but require charging from renewable energy.

5. Acknowledgements

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6. References

ABC. 2015. "Fact File: 9 Million Homes with 2.6 Occupants - This Is the Australian Housing Market - Fact Check - ABC News (Australian Broadcasting Corporation)." 2015. http://www.abc.net.au/news/2015-05-06/fact-file-housing-in-australia/6442650.

ABS. 2010. *Building Approvals - 8731.0*. Canberra A.C.T., Australia.: Australian Bureau of Statistics, Commonwealth of Australia. www.abs.gov.au/AUSSTATS/subscriber.nsf/LookupAttach/1301.0Publication24.05.121/$file/13010_2012.pdf.

Acosta, J. D. Revuelta-, A. Garcia- Diaz, G. M. Soto- Zarazua, and E. Rico- Garcia. 2010. "Adobe as a Sustainable Material: A Thermal Performance." *Journal of Applied Sciences* 10 (19): 2211–16. https://doi.org/10.3923/jas.2010.2211.2216.

Ahmed, A. T. M. Faiz, Md Zahidul Islam, Md Sultan Mahmud, Md Emdad Sarker, and Md Reajul Islam. 2022. "Hemp as a Potential Raw Material toward a Sustainable World: A Review." *Heliyon* 8 (1). https://doi.org/10.1016/j.heliyon.2022.e08753.

ARENA. 2016. "Narara Ecovillage Smart Grid." Australian Renewable Energy Agency. 2016. https://arena.gov.au/projects/narara-ecovillage-smart-grid/.

ASBEC. 2016. "Low Carbon, High Performance - How Buildings Can Make a Major Contribution to Australia's Emissions and Productivity Goals." Surry Hills, NSW, Australia: Australian Sustainable Built Environment Council. http://www.asbec.asn.au/research/.

Clarke, D. 2018. "Hemp, Hemp Masonry and Hempcrete - Sanctuary Magazine." *Sanctuary Magazine*, July 16, 2018. https://renew.org.au/sanctuary-magazine/building-materials/hemp-hemp-masonry-and-hempcrete/.

DCCEEW. 2022. "National Greenhouse Accounts Factors." Australia: Department of Climate Change, Energy, the Environment and Water, Commonwealth of Australia. https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-factors-2022.

Dickie, Gloria, Kate Abnett, and Gloria Dickie. 2023. "61,000 Europeans May Have Died in Last Summer's Heatwaves, Experts Say." *Reuters*, July 11, 2023, sec. Europe. https://www.reuters.com/world/europe/61000-europeans-may-have-died-last-summers-heatwaves-experts-say-2023-07-10/.

Downton, Paul. 2023. "Straw Bale | Your Home - Materials." *Your Home - Australia's Guide to Environmentally Sustainable Homes* (blog). July 14, 2023. https://www.yourhome.gov.au/materials/straw-bale.

GBCA and thinkstep-anz. 2021. "Embodied Carbon & Embodied Energy in Australia's Buildings." Sydney N.S.W.: Green Building Council of Australia. https://gbca-web.s3.amazonaws.com/media/documents/embodied-carbon--embodied-energy-in-australias-buildings-2021-07-22-final-public.pdf.

Hempcrete Australia. 2014. "Sustainability." 2014. https://www.hempcrete.com.au/index.php?option=com_content&view=article&id=24&Itemid=25.

Jami, Tarun, Sukhdeo R. Karade, and Lok Pratap Singh. 2022. "Current Trends in Applications of Cannabis/Hemp in Construction." In *Cannabis/Hemp for Sustainable Agriculture and Materials*, edited by Dinesh Chandra Agrawal, Rajiv Kumar, and Muralikrishnan Dhanasekaran, 203–37. Singapore: Springer. https://doi.org/10.1007/978-981-16-8778-5_8.

NEV. 2017. "Community Association DP270882, Narara Ecovillage, Narara, Community Management Statement." Narara Ecovillage Co-operative Ltd (NEV).

Prasad, Deo, Aysu Kuru, Philip Oldfield, Lan Ding, Malay Dave, Caroline Noller, and Baojie He. 2022. *Delivering on the Climate Emergency: Towards a Net Zero Carbon Built Environment*. Singapore: Springer Nature. https://doi.org/10.1007/978-981-19-6371-1.

Teague, Chris. 2023. "GM's EVs Will Offer Bi-Directional Charging by 2026." Thetruthaboutcars.Com. August 8, 2023. https://www.thetruthaboutcars.com/cars/news-blog/gm-s-evs-will-offer-bi-directional-charging-by-2026-44502265.

WMO. 2023. "Exceptional Heat and Rain, Wildfires and Floods Mark Summer of Extremes." July 13, 2023. https://public.wmo.int/en/media/news/exceptional-heat-and-rain-wildfires-and-floods-mark-summer-of-extremes.

7. Errata

7.1 Data Correction

Please find the updated:

- Table 3 (Table 3b below), with corrections in red for the Carbon offsets for PV & hempcrete (t CO2-e/a).
- An LCA graph for the 5 homes in Table 3b

NB: the embodied carbon for the hempcrete homes may be conservative because it uses the lower range of the typical home embodied carbon, with only a small reduction for the hempcrete absorbing carbon over its life.

Table3b: Energy and carbon features of five NEV homes, with hempcrete carbon calculations (Source: Author)

Home	Details	1	2	3	8	9
Description		Earthship	**Hempcrete** powerhouse	Sustainable **hempcrete** home	Lightweight tightly sealed	Pre-fabricated 2 storey
NatHERS*	Stars	7.6	8.8	7.3	8.3	7.2
Solar panel size	kW	6.3	11.0	9.0	5.0	5.0
Battery	kWh	10.0	N/A	20.0	N/A	N/A
Hot water system	COP	5.0	5.0	5.0	4.0	17.0
Heating and cooling systems		Cooling tubes; inter-room fans; int. greenhouse	4 Laros Lunos e2 MHRV units	Air-conditioner; clerestory windows	Ducted MHRV system; air-conditioner	Air-condit-ioner
Net energy exports	kWh/a	4,567	12,013	7,692	4,674	3,325
PV carbon offset**	t CO_2-e/a	3.6	9.5	6.1	3.0	2.6
Home embodied carbon***	NEV (2017)	62.9	74.0	61.0	50.8	58.6
	Prasad et. al. (2022)	62.5	109.0	86.1	87.6	114.3
PV system recurrent embodied carbon	t CO_2-e every 30 years	18.9	33	27	19.8	15.6
Total home embodied carbon Prasad et al. (2022)	After 90 years (PV plus)	119	208	167	147	161
Hempcrete[#]	Wall width (m)		0.25	0.30		
	Wall area (m^2)		50.0	80.0		
	Wall volume (m^3)		12.5	24.0		
	Carbon capture (t CO_2-e/a)		0.0119	0.0228		
Carbon offsets for PV & hempcrete[##]	t CO_2-e/a	3.6	9.5	6.1	3.0	2.6
Total embodied carbon payback[###]	years	33.0	21.9	27.4	48.9	61.3

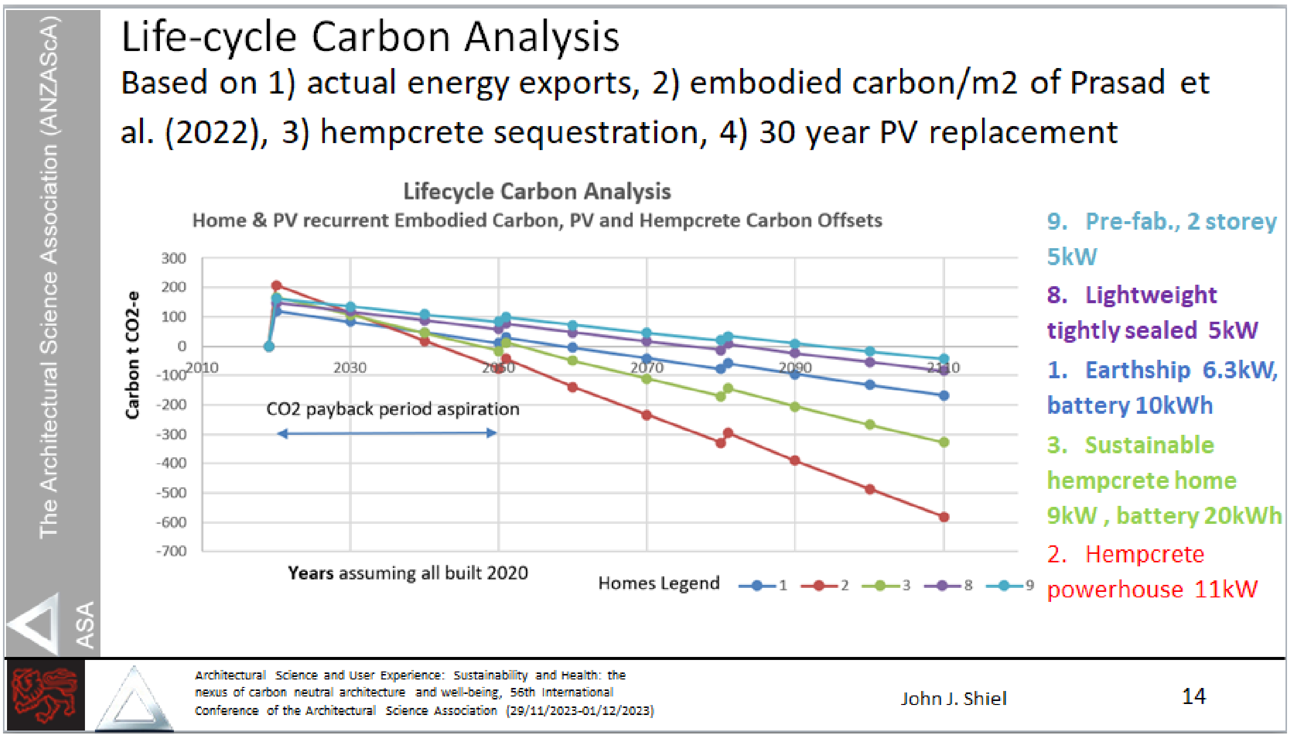
(superscripts are the same as in Table 3 above)

These figures in red are the estimated carbon offset per year and the number of years to payback the embodied carbon of the 2 hempcrete homes.

7.2 **Life Cycle Carbon Analysis Graph**

Figure 6 shows the Life-cycle Carbon Analysis of 5 homes in Table 3b, with the assumptions:

- The actual energy exports for the first year would continue at the same rate (and the NSW grid carbon/kWh ratio was used to convert the exported energy for each home to carbon)
- The homes had the lower range of Prasad et al. (2022)'s embodied carbon
- The hempcrete homes had a small amount of overal sequestration,
- Only the solar PV and inverters were recurrenlty replaced each 30 years



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Life-cycle Carbon Analysis

Based on 1) actual energy exports, 2) embodied carbon/m2 of Prasad et al. (2022), 3) hempcrete sequestration, 4) 30 year PV replacement

9. Pre-fab., 2 storey 5kW

8. Lightweight tightly sealed 5kW

1. Earthship 6.3kW, battery 10kWh

3. Sustainable hempcrete home 9kW , battery 20kWh

2. Hempcrete powerhouse 11kW

Architectural Science and User Experience: Sustainability and Health: the nexus of carbon neutral architecture and well-being, 56th International Conference of the Architectural Science Association (29/11/2023-01/12/2023)

John J. Shiel

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Figure 6 - Life Cycle Carbon Analyses of 5 Ecovillage homes