Fleetwood Challenge Cup 2022

Concept Design Validation Report: Achieving Net Zero begins at home

1. Executive Summary

This report aims to showcase a net-zero prefabricated multi-storey apartment design emphasising the growing need for sustainability in residential applications.

Energy analysis using NatHERS rating of the proposed building design yields a 7.9/10 star building system, supporting the potential for factory construction of the module design as a scalable solution to net-zero housing. This is facilitated by the module and apartment design.

The module design uses external, load-bearing cross-laminated timber (CLT) with foldable module features aiming to both improve building floor space while reducing risks during module transport. Consequently, prefabrication processes aim to reduce construction build time and increase uniformity between projects.

Construction processes seek to reduce costs and increase quality of build during on-site assembly. In addition, it aims to incentivise reusability/recyclability of building materials through limiting volume of materials processed on-site.

2. Key considerations and challenges

This module and construction design aims to serve the following purposes:

- Energy efficient across building lifecycle and generates excess energy
- Configurable module arrangements for use in a variety of building environments
- Ease of construction with avenues for cost-effective module recycling

These key factors aim to create an adaptive net-zero building design that responds to challenges related to sustainable development.

3. Energy

This section addresses energy and prefabrication of the design meeting the needs of a net-zero building.

3.1 Meeting net zero

Prefabricated constructions offer various environmental benefits, such as reduced construction waste (Lawson & Ogden, 2010), less energy consumption during construction (Abey & Anand, 2019), and alleviated end-of-life impacts since they can be disassembled and relocated to other sites for reuse rather than being disposed (Navaratnam et al., 2019a). In recent years, the building industry has experienced a transition towards low-carbon energy systems (Navaratnam et al., 2019a), making prefabrication a prospective element to realise such goal. To date, main efforts to achieve decarbonisation in the building sector has been to minimise energy impacts in the use stage provided it accounts for 80%-85% of the total energy consumption (Tumminia et al., 2018). However, improvement in building performance cannot be guaranteed when focusing only on the use phase. In other words, the assessment of building performance should be extended to all stages of life cycle.

The life cycle of a building has several major components, including manufacturing, transportation, on-site construction, use, and end-of-life stages (Faludi et al., 2012). The designed modular building has applied various sustainable techniques corresponding to each of the stages.

3.1.1 Operational energy efficiency – design choices and impacts

As the operational phase contributes more than 80% of the total life cycle impacts (Tumminia et al., 2018), the following measures aim to respond to this issue, improving energy efficiency.

- Increased thermal insulation of building envelopes
- Optimised window size and position
- Enhanced energy production from renewable (solar) energy

The proposed modular building employs cross-laminated timber (CLT) wall material. This material has high thermal insulation property and therefore reduces heating energy requirement (Pei et al., 2016) – see Section 4.3. The arrangement uses an external air-pocket configuration for maintenance benefits (Radhi, 2010).

The position of window is kept in the middle of the wall, and window-to-wall ratio (WWR) is maintained between 10% to 20%. According to research by Kim et al. (2016), these two inputs will lead to the least annual energy load. Additionally, photovoltaic (PV) panels are installed on the roof to generate energy for internal building use.

3.2 Embodied energy efficiency – optimising CLT timber

Once a building reaches the net zero energy target, the largest life cycle impact relies on construction material choices (Faludi et al., 2012). Using CLT, in addition to good insulation properties leading to reduced heating requirement, CLT has relatively lower embodied energy compared to the conventional Reinforced Concrete (RC) framed buildings (Chen, 2012). To illustrate, a CLT solution for a multi-level residential building consume around 80% less energy during the manufacturing stage. It may also reduce 61% of greenhouse gas emissions (GHG) across the building's life span (Dong et al., 2019) – see Section 4.3 for additional detail.

3.3 Butterfly module form

Since modular homes are framed with larger studs and requires additional structural elements to accommodate transportation load, 8% more materials are placed in them compared to conventional construction method (Kim, 2008). To improve sustainable design aspects, a butterfly module form is employed, with the ceiling panel folded down to the side of the wall during transportation. Once the modules are unloaded and positioned at planned locations on-site, ceiling panels will be lifted horizontally and connected with adjacent modules. The reduced modular size during transportation will greatly improve transportation efficiency, and hence reduce energy consumption and GHG during the construction-transportation stage. Additionally, prefabricated building produce 2.5 times less construction waste compared to an equivalent traditional home (Quale et al., 2012). This will compensate for the increased need of material in prefabricated buildings – see Section 4.1.

3.4 Connection between modules

A bolted connection is used in this design which offers extensive flexibility to connect various modules both vertically and horizontally. It also serves as a simple way to disassemble the modular building into various modules, which can then be transported to other sites for either recycling or reuse instead of being disposed – see Section 5.5 and 5.6. To join between rotated panels, a lap joint will be used to connect both panels together with steel reinforcement – see Section 4.2.

3.5 Module Energy Usage and Generation

3.5.1 Energy usage

An energy assessment was performed on a 2-bedroom 2-bathroom unit, shown in Figure 3.2.1A.

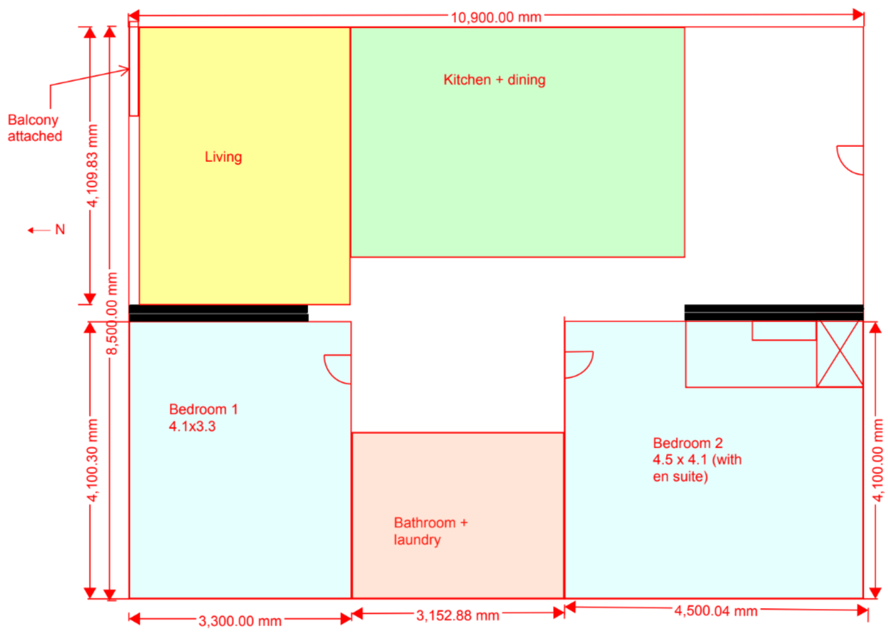


Figure 3.2.1A: Floor plan of a 2-bedroom 2-bathroom apartment unit

The unit has a length and width of 10.9m and 8.5m, respectively, equalling a total area of around 93m^2. To ensure WWR ranges between 10-20%, the following window schedule was adopted. Based on this, a WWR ratio of approximately 13% was expected.

Table 3.2.1A: Window schedule of a 2-bedroom 2-bathroom unit.

					Width		Height	
Room	Category	Number	Position	AS Code	Stud Opening	Window size	Stud Opening	Window Size
Living and Dining	Sliding Door	1	Bottom Aligned	ASD2124 SF	2150	2100	2460	2410
	Fixed Window	1	Middle of wall	AS1806	660	610	1860	1800
Master Bedroom	Sliding Window	1	Middle of wall	AS1224	2460	2410	1260	1200
	Sliding Window	1	Middle of wall	AS1006	660	610	1090	1030
Single Bedroom	Sliding Window	1	Middle of wall	AS1812	1260	1210	1860	1800

The Nationwide House Energy Rating Scheme (NatHERS) was employed to assess the building's energy efficiency, reflected by star ratings (Berry & Marker, 2015). A higher star rating indicates less heating, or cooling is required to maintain a comfortable room temperature. To demonstrate compliance with the National Construction Code energy efficiency requirements, a minimum start rating of 6 was required (Daniel et al., 2015).

Heating and cooling are two main sources for the majority of the average Australian household's energy use and GHG (NatHERS, 2022). FirstRate5 is used to perform accredited energy simulation, estimating the heating and cooling energy requirement for new homes and apartments in Australia (FirstRate5, 2022). The input floor plan for modelling was shown in Figure 3.2.1B and building specifications as input data in Table 3.2.1B.

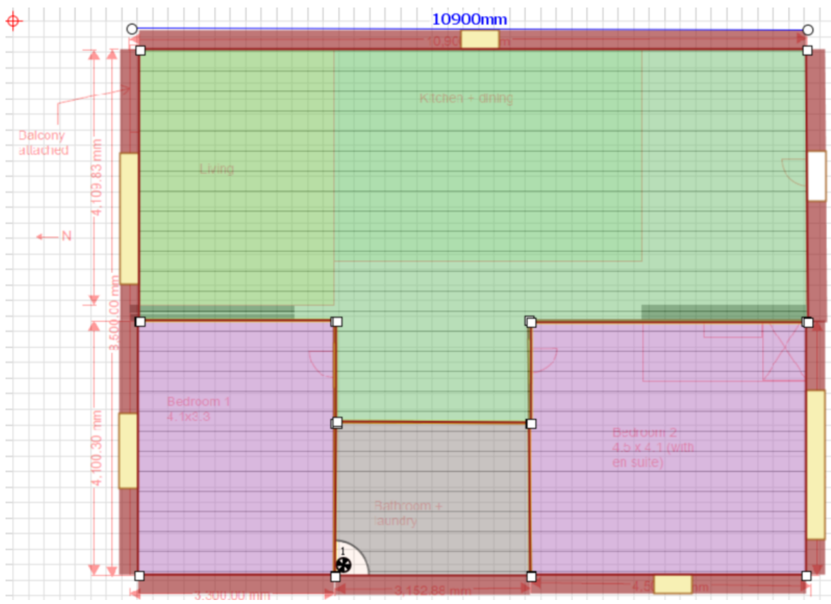


Figure 3.2.1B: Floor Plan Modelling in First Rate 5.

Main Assumptions	Other Inputs
• R 2.5 Wall Insulation • R 6 Ceiling Insulation • R 4.0 Ceiling • Sub Floor with R 2.0 • Double-glazed high-performance windows with PVC frames • No eaves	• Climate: 21 Melbourne RO • Mode: New Home • Site Exposure: Suburban • Construction Type: Timber Material

Table 3.2.1B: Main assumptions for energy assessment

Based on the information above, the energy analysis result is shown below:

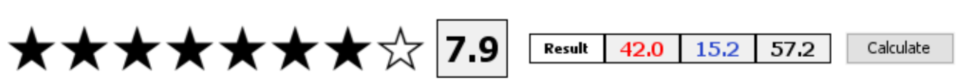
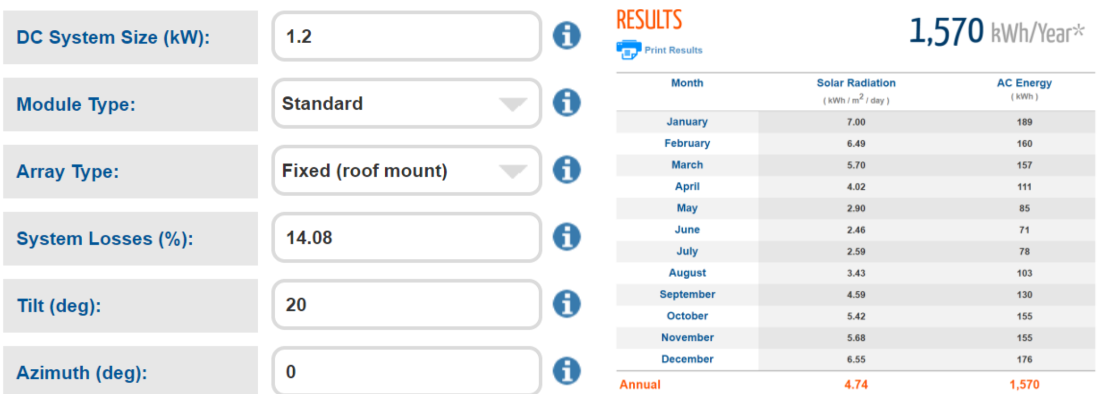


Figure 3.2.1C: A model apartment yields an energy rating of 7.9 stars from FirstRate5

This unit can achieve an energy star rating of 7.9, exceeding the 6-star rating threshold. This represents excellent energy performance, where building energy consumption is around half of required by a 6-star home. The annual heating and cooling energy usage were calculated as 42.0 MJ/m^2 and 15.2 MJ/m^2, respectively, leading to a total annual energy usage of 57.2 MJ/m^2 (see Appendix A for full report).

3.5.2 Energy generation

The total annual energy usage of 57.2 MJ/m^2 was converted to an annual energy load of around 1473 kWh. To achieve net zero energy building, PV panels are required to be installed on the roof to generate energy off-grid. Utilising PVWatts Calculator (Laboratory, 2022), the area of PV panels required to generate at least 1473 kWh energy annually was defined in Figure 3.2.2A.



(a) System Input (b) Result

Figure 3.2.2A: Inputs required to generate at least 1473 kWh annually

As shown above, the DC System Size should be kept above 1.2 kW, which is equivalent to an area of 8.1 m^2 – see Appendix B.

3.5.3 Energy usage and generation for the whole building

The chosen 2-bedroom 2-bathroom requires 4 modules while the proposed 3-level building has 48 modules. Based on this, the total energy usage and PV panel areas required to achieve net zero energy building are summarised in the Table 3.2.3A below - additionally see Appendix B.

Indication	Value
Annual heating energy usage (kWh/year)	12971
Annual cooling energy usage (kWh/year)	4695
Annual total energy usage (kWh/year)	17666
PV panel area (m^2)	97.2
Annual total energy generation (kWh/year)	18840

Table 3.2.3A: Energy assessment results for the whole building

4. Module

This section aims to detail the module design and connection system.

4.1 Materials and form timber design

To produce a liveable design for this module to be used in a variety of residential applications, the module specifications were to meet the minimum floor to ceiling height of 2700mm as per the Victorian Apartment Design guides. In addition, the volumetric modules proposed will have W/L/H dimensions of 3000mm x 4500mm x 3000mm. These dimensions have been chosen to comply with VicRoads specifications to not require any restrictions in the delivery of the modules to site (e.g., escort, time, and spaces constraints) (VicRoads, 2018). A nominal height of 3000mm of the module was adopted to meet this criterion – with the fold-out mechanic of our design, we will achieve a floor to ceiling height of 2725mm; which is the height when considering the thickness of the CLT wall panels.

The fold-out butterfly mechanic of the modules was to foster and create more possibilities for flexibility for the consumers with more habitable area. These modules have been designed to be used in pairs, creating this open area in Figure 4.1A.

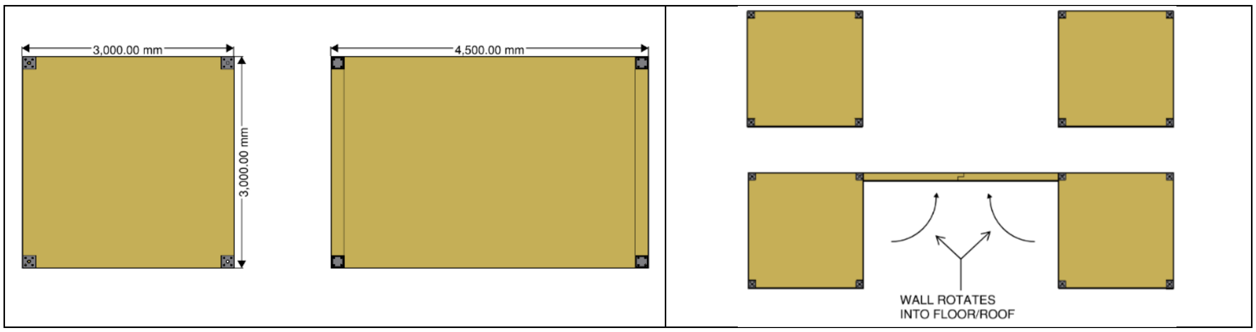


Figure 4.1A - Module dimensions and folding mechanism

Interior width of the module is 2450mm, which is the nominal width, subtracted by two wall thicknesses. Similarly, the interior liveable length of a single module is 3950mm. Hence, the liveable interior area of a single module before it is expanded 9.68m^2. The area of two, expanded modules is evidentially much greater than two unopened modules. The extension of the module is governed by the height of the module, where a maximum of 2450mm extension is possible due to the rotation mechanic of the module. Inhabitable area in the pair of joined opened modules will now be 38.72m^2. Understanding the liveable area of created by the modules was necessary to allocate a necessary number of modules to create a liveable space that abided by apartment design regulations (NSW Design guide followed as minimum areas are quoted, NSW Gov., 2022). Table 4.1 below shows that 48 modules are required to fulfill the requirements of the design brief denoting the necessary number of units, and the corresponding bedroom and bathroom demands.

Table 4.1A - Summary of necessary modules required

Apartment Type	Count	Minimum Internal Area (m^2)	Modules Needed	Total
1 Bed 1 Bath	4	50	3	12
2 Bed 1 Bath	4	70	4	16
2 Bed 2 Bath	2	80	5	10
3 Bed 2 Bath	2	95	5	10
Sum	12			**48**

With 48 modules required, this generated the layout of our apartment complex. Because the modules must be used in pairs, a 4x4 block of modules is chosen, and hence the building will be three storeys tall (see section 5.5 for details).

4.2 Connection design and steel reinforcement design

There are connectors at all corners of all modules and are used for reasons below.

- Connectors fasten the module together, connecting to the CLT panels.
- Connectors are used to connect modules together adjacently, but also vertically.
- Connectors are used for the rotation mechanism of the wall panel.

The connectors are cube shaped and made of steel in Figure 4.2A. There is one open face on each of the connectors, and this is to allow for the interior of the connector to be accessed for easier on-site installation. Figure 4.2A illustrates the connectors that are used for the corners that are involved with the rotation. If the connector is at a corner that does not require any rotation, a cylindrical section would not be used.

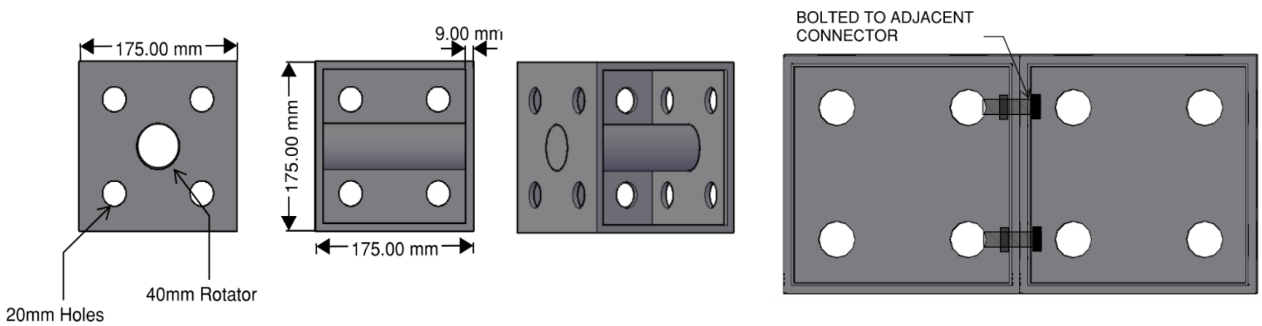


Figure 4.2A - Connector design

Where the connector is used to connect to CLT panels, screws can be used to join both together. When joining connector to connector, a bolted connection can be used to go through connectors and join them together, this is for both adjacent and vertical connections. When the connector is used for the rotation of the CLT wall panel, the 40mm hollow cylindrical steel section will extend into the floor panel, hence allowing it to rotate about the centre of the connector. This rotation component will not be relied on for structural purposes, as after the wall panel has been rotated, screws will be used to fasten the two together.

Due to the extended section that we create with the fold out being very long in length (about 11 meters), we expected that the bending strength at the midspan would be the most critical aspect to analyse. With the moment being proportionate with the square of the length (assuming a simply supported beam setup), the moment becomes large. Hence, we have designed a reinforcement system to add over the rotations to reinforce the modules and change the moment distribution. The reinforcement includes rebating steel strips into the surface of the floor. The reinforcement is 3000mm long, 40mm wide and 20mm deep as seen in Figure 4.2B.

By implementing restraint over the rotation of the wall panel, it will change the bending moment of the system – massively reducing the moment at the mid-span of the extended connection (see figure 4.2B). The maximum moment is now in tension at the location of the reinforcement.

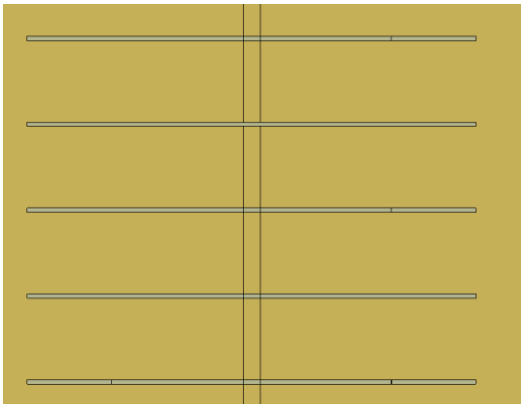


Figure 4.2B - Reinforcement Design

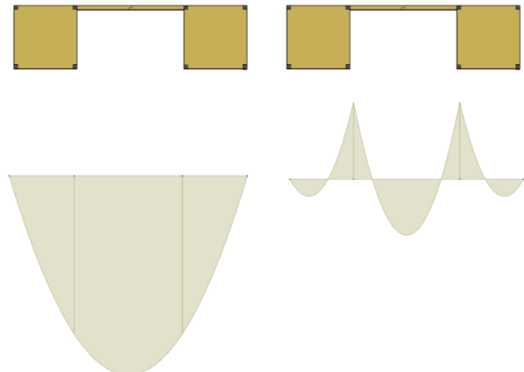


Figure 4.2C - Bending Moment of Base Module (Left) and Reinforced Module (Right)

Once the panels have been rotated, a lap joint will be used to connect them together in the middle. Additional screws will be provided either side of the join for shear support

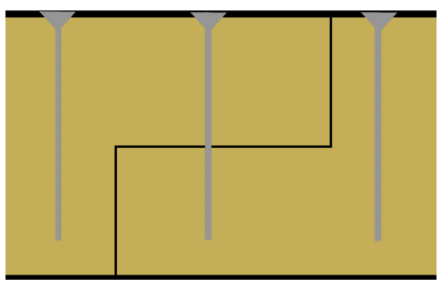


Figure 4.2D – Lap Joint

4.3 Wall panel composition

As discussed previously, our building is to be comprised of almost all timber, and this effects the need for external cladding and interior insulation. The cladding that we have suggested here is ColorBond Steel, chosen because of its sustainable characteristics of durability and its ability to be recycled (ColorBond Steel, 2022). However, there is flexibility in that this module will be able to accommodate for other cladding types, such that the ColorBond we suggest will be screwed in and can easily be replaced by new types of cladding depending on site environment and wants of the builder.

EPS has been used considering its main benefits of:

- Scale with wide availability and cost-effectiveness (Pavel & Blagoeva, 2018)
- Flexibility of installation
- High thermal resistance (Kumar et al., 2020)

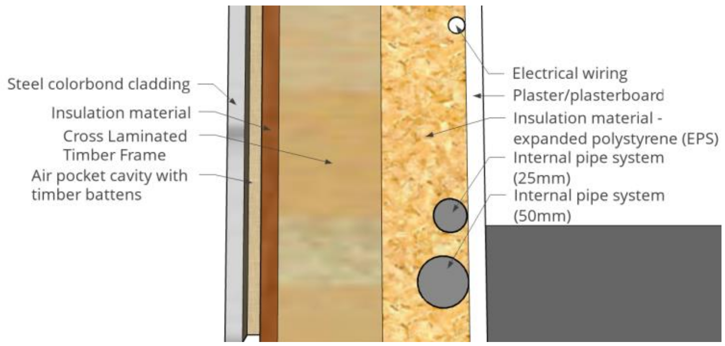


Figure 4.3 – Widened image of CLT wall panel external (left) to internal (right) sides

5. Construction methodology

This section aims to demonstrate concept building construction processes during build-up and end-of-life. It will discuss how a fully functional building using proposed modularised units will be constructed. This proposed schedule assumes flat foundations however may be adjusted for sloping land using additional excavation techniques or raising of foundation on piles.

5.1 Construction methodology

This section will discuss how a fully functional building using proposed modularised units will be constructed. This proposed schedule assumes flat foundations however may be adjusted for sloping land using additional excavation techniques or raising of foundation on piles.

5.2 Design, planning and site preparation

Excavation of ground for laying of foundation and placement of concrete slab will occur during design, planning and factory building stages. Design of whole building structure should involve duplication of unit modules arranged into unique building forms of varying levels, with room for flexible external façades aided by building information modelling (BIM). Any BIM should use the base module, with design adjustments made depending on site characteristics and expected locations of services (Song et al., 2012). During this period, local utilities will be configured to serve planned apartment. Each module will be constructed off-site to the detail prescribed as shown in Section 3 with interior build-up during the building finishes phase.

5.3 Site transport

Transportation of module units to the site assume the module dimensions in Section 3 against a base case W/L/H of 4500/6000/3000 units in millimetres.

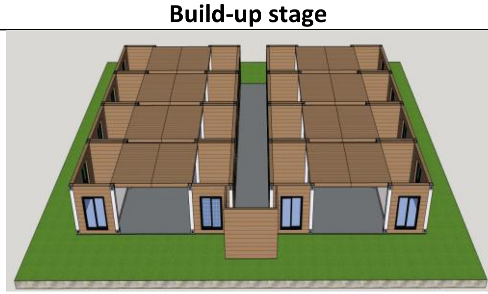
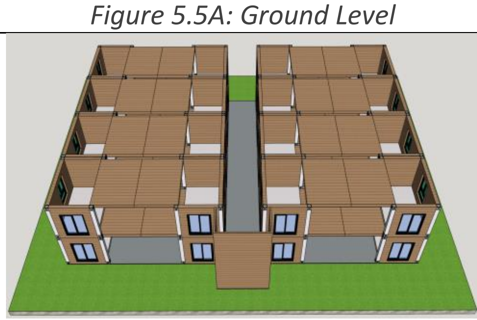
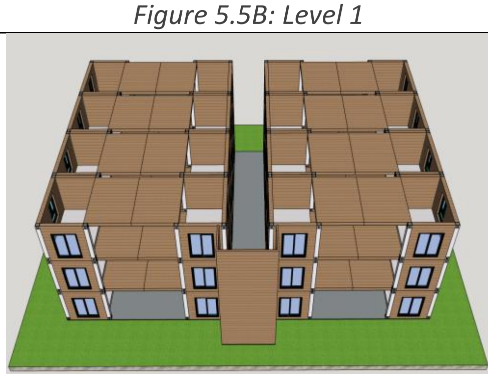
By reducing the volume transported, module foldability saves useful space during transport on trucks and can be carried throughout the day in Melbourne metropolitan cities to the site (VicRoads, 2018) to a truck floor dimension of 21m by 3m. Due to the compactness of the module, the critical dimension (width) of the module is 3m in the module case, versus 4.5m in the base case. This compactible design reduces the risk of regulations and special traffic control (*Loading*, 2018) in transportation planning (Navaratnam et al., 2019b) important for a travel distance of 50-250km from factory to site.

Table 5.4: Module transport savings

	Base case	Module case	Units
Critical width	4.5	3	Meters
Length	6	4.5	Meters
Modules per truck	3	5	Modules
Trips needed	16	10	Trips
Floor area per truck	81	135	Meters^2

5.4 Construction

A <150 tonne crane will be used to lift modules from truck units from the main road directly onto the site foundation. The sequence of the load should begin from central towards outer units.

Build-up stage	**Floor and construction**
 *Figure 5.5A: Ground Level*	• Construction of slab foundation or raised foundation. • Transport modules from factory. • Place and connect modules into site with <150 tonne crane from main access road. • Install temporary scaffolding and stairs. • Install Ground Level floor and ceiling. • Install Ground Level prefabricated wall panels and seal floor interior.
 *Figure 5.5B: Level 1*	• Begin installation of building services installation including water and electricals from Ground Level to Level 1. • Construct Level 1 floor and ceiling fit-out. • Extension of temporary scaffolding to Level 1. • Install Level 1 prefabricated wall panels and seal interior.
 *Figure 5.5C: Level 2*	• Construct Level 2 floor and 1/2000 inclined colorbond steel permanent roof. • Install permanent staircase at hallway ends for travel between floors and staircase/lift system • Complete building services installation. • Install plasterboard interior frame. • Install Level 2 prefabricated wall panels and seal interior. • Conduct landscape finishes.

5.5 Building end-of-life

At end of building life cycle, the module connection system allows dismantling of units that can be moved to factory and processed for recycling. Alternatively, depending on building creep and serviceability requirements, modules or their components such as insulation and cladding will be re-used or recycled (Vefago & Avellaneda, 2013). The simple connection system discussed in this design allows for a re-thinking of how building materials are re-used at their end-of-life, paving the way for a net-zero future.

6. Appendix

Appendix A: Full Report of Energy Assessment generated from FirstRate5

FirstRate® Provisional Diagnostic Information

Project Information

Mode	New Home
Climate	21 Melbourne RO
Site Exposure	suburban
Client Name	
Rated Address	1 CBD
Accredited Rater	
Date	
Reference	

Energy Usage

Type	Energy MJ/m²
Total	57.2
Heating	42.0
Cooling	15.2

Areas

Area	Size (m²)
Net Conditioned Floor Area (NCFA)	83.4
Unconditioned Room Area	7.7
Garage Area	0.0
Basement Car Park Area	0.0
Glazed Common Area	0.0

Zones

Zone	Area (m²)	Conditioning Type	Conditioned
Bedroom 2	18.2	bedroom	Y
Bedroom 1	12.9	bedroom	Y
Bathroom+Laundry	7.7	unconditioned	N
Living	52.2	kitchen	Y

Walls

Type	Bulk Insulation (R)	Num Reflective Airgaps	Area (m²)
Custom wall	2.8	0	92.2
Internal Plasterboard Stud Wall	0.0	0	45.5

Floors

Type	Bulk Insulation (R)	Slab edge insulation (R)	Ventilation	Area (m²)
Timber	2.0	0.0	encl	91.1

Roofs/Ceilings

Type	Bulk Ceiling Insulation (R)	Bulk Roof Insulation (R)	Area (m²)
Disc:Attic-Discontinuous	4.0	0.0	91.1

Windows

Type	U-Value	SHGC	Area (m²)
PVC-006-03 W uPVC B DG Argon Fill High Solar Gain low-E -Clear	2.00	0.31	11.84

Window Directions

Direction	Area (m²)
S	0.6
E	2.9
W	7.2
N	1.1

Air leakage

Item	Sealed	Unsealed
Generic Vent	-	0
Unflued Gas Heater	-	0
Exhaust Fan	1	0
Downlight	0	0
Chimney	0	0
Heater Flue	-	0

Zone Energy Loads

Zone	Heating (MJ/m2)	Total Heating (MJ)	Cooling (MJ/m2)	Total Cooling (MJ)
Bedroom 1 (Z004)	35.4	457.1	10.3	132.9
Living (Z002)	66.7	3480.2	25.9	1352.5
Bedroom 2 (Z001)	32.1	585.3	8.1	147.5

Provisional Diagnostic Information 25-06-2022 13:09:30 Ver:5.3.2a (3.21) Engine Ver:3.21 Accredited Rater: Assessor's Accreditation Number:

Appendix B: PV panel area required

6/25/22, 7:19 PM PVWatts Calculator

NREL

Caution: Photovoltaic system performance predictions calculated by PVWatts® include many inherent assumptions and uncertainties and do not reflect variations between PV technologies nor site-specific characteristics except as represented by PVWatts® inputs. For example, PV modules with better performance are not differentiated within PVWatts® from lesser performing modules. Both NREL and private companies provide more sophisticated PV modeling tools (such as the System Advisor Model at https://sam.nrel.gov) that allow for more precise and complex modeling of PV systems.

The expected range is based on 30 years of actual weather data at the given location and is intended to provide an indication of the variation you might see. For more information, please refer to this NREL report: The Error Report.

The energy output range is based on analysis of 30 years of historical weather data, and is intended to provide an indication of the possible interannual variability in generation for a Fixed (open rack) PV system at this location.

RESULTS

1,570 kWh/Year*

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)
January	7.00	189
February	6.49	160
March	5.70	157
April	4.02	111
May	2.90	85
June	2.46	71
July	2.59	78
August	3.43	103
September	4.59	130
October	5.42	155
November	5.68	155
December	6.55	176
Annual	**4.74**	**1,570**

Location and Station Identification

Requested Location	338 Gore Street, Fitzroy
Weather Data Source	Lat, Lng: -37.79, 144.98 0.4 mi
Latitude	37.79° S
Longitude	144.98° E

PV System Specifications

DC System Size	1.2 kW
Module Type	Standard
Array Type	Fixed (roof mount)
Array Tilt	20°
Array Azimuth	0°
System Losses	14.08%
Inverter Efficiency	96%
DC to AC Size Ratio	1.2

Performance Metrics

Capacity Factor	14.9%

For a 2-bedroom 2-bathroom unit:

As shown in Section 3.2.2, this power generation rate corresponds to a DC System Size of 1.2kW.

The PV panel array area can be determined based on the below equation:

$$Size\ (kW) = Array\ Area\ (m^2) \times 1kW/m^2 \times Module\ Efficiency\ (\%)$$

$$Array\ Area\ (m^2) = \frac{1.2kW}{1kW/m^2 \times 14.9\%} = 8.05m^2 \approx 8.1m^2$$

Based upon the result obtained from First Rate 5,

$$Annual\ Energy\ Load = \frac{57.2MJ}{m^2} = 15.89kWh/m^2$$

Hence, the total annual energy usage can be calculated as:

$$Annual\ Energy\ Usage = \frac{15.89kWh}{m^2} \times 10.9m \times 8.5m = 1473kWh/year < 1570kWh/year$$

For the whole apartment:

A 2-bedroom 2-bathroom apartment requires 4 modules while the whole apartment takes up 48 modules. Thus, the total energy usage for the whole apartment can be determined as below:

$$Annual\ heating\ energy\ usage = \left(\frac{42MJ}{m^2} \div \frac{3.6kWh}{MJ}\right) \times 10.9m \times 8.5m \times \frac{48}{4} = 12971kWh/year$$

$$Annual\ cooling\ energy\ usage = \left(\frac{15.2MJ}{m^2} \div \frac{3.6kWh}{MJ}\right) \times 10.9m \times 8.5m \times \frac{48}{4} = 4695kWh/year$$

$$Annual\ energy\ usage = 12971 + 4695 = 17666kWh/year$$

The total PV panel array area can be calculated as:

$$Total\ PV\ Array\ Area\ (m^2) = 8.1 \times \frac{48}{4} = 97.2m^2$$

The total energy generation rate then becomes as follows:

$$Total\ energy\ generation\ rate = \frac{1570kWh}{year} \times \frac{48}{4} = 18840kWh/year > 17666kWh/year$$

7. References

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