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Development of an in-home energy rating tool for existing housing

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Abstract: In 2019, energy ministers agreed the Trajectory for Low Energy Buildings (the Trajectory). It aims to improve Australia's energy productivity by 40% between 2015 and 2030. One of the key aspects in the Trajectory for residential buildings is to expand the Nationwide House Energy Rating Scheme (NatHERS) to offer nationally accredited whole-of-home (WoH) tools to enable compliance requirements in the National Construction Code (NCC). CSIRO was commissioned by the NatHERS Administrator to develop a benchmark WoH tool for existing housing. For this purpose the WoH tool was developed by implementing new modules for space heating and cooling, water heating, lighting, swimming pool, other appliances, and solar PV into the modified version of AusZEH design tool. The initial version of the tool was released in May 2022 for evaluation. After receiving feedback from stakeholders, the WoH tool was recently updated with the extensive input from the NatHERS Technical Advisory Committee (TAC) and other industry experts.

The whole-of-home framework builds on the existing NatHERS framework and technology. Energy requirements for space heating and cooling are simulated by the Chenath engine developed by CSIRO. Considering energy efficiency of heating ventilation and air conditioning (HVAC) systems and the related system losses, hourly energy consumption is calculated over a period of one year. Energy consumption modules for other appliances, including lighting, water heating, plug-in load, cooking, pool pump, are also developed based on previous monitoring and survey studies and related standards.

To demonstrate the tool's capability for calculations of whole-of-home energy consumption, and energy value and rating, a case study was conducted for capital cities of Australia states and territories using a detached house built in 1990 with a gross floor area of 293 m^2. As expected, a large amount of energy is required for space heating in Hobart and Canberra (heating dominated regions), and for space cooling in Darwin (tropical regions). To operate the house, when only electricity supply is available, Darwin is the most expensive city (near A$7000). It is the cheapest in Brisbane. The energy rating scale is 0 in Canberra, Darwin, Hobart and Melbourne. That means the energy performance of the house in these cities is under the worst energy performance condition.

With the house being updated with high energy performance building envelop and high energy efficient equipment and appliances, more than half energy was saved in all the eight cities. To achieve zero energy (carbon) housing, installation of 5 kW solar PV is required in Darwin and Hobart, 4 kW in Melbourne and Canberra, 3.5 kW in Adelaide and Sydney, and 3 kW in Brisbane and Perth. Even it was achieved zero energy, it needs several hundred Australia dollars to operate the retrofitted house (except in Darwin) as the difference in tariffs for electricity imported and exported.

Keywords: *Whole-of-home energy consumption, benchmark tool, societal cost, energy rating scale*

1. INTRODUCTION

In February 2019 the Council of Australian Governments (COAG) Energy Council agreed on the Trajectory for Low Energy Buildings, which aims to improve Australia's energy productivity by 40% between 2015 and 2030. The Trajectory identified cost effective opportunities for energy efficiency improvements through the building system, from building envelope thermal performance to appliance energy usage and renewable energy generation.

One of the key aspects in the Trajectory for residential buildings is to expand Nationwide House Energy Rating Scheme (NatHERS) to offer nationally accredited whole-of-home tools for new and existing houses to enable compliance requirements in the National Construction Code (NCC). Since February 2019 the NatHERS Administrator has held discussions with NSW Planning and Environment, the Victorian Department of Environment, Water, Land and Planning, Sustainability Victoria and CSIRO regarding tool harmonisation opportunities. After these discussions, the consensus was that a Whole of Home (WoH) Benchmark tool under the NatHERS framework should be ready before the end of 2019 for new dwellings and the end of June 2022 for existing dwellings. CSIRO was commissioned to deliver the benchmark WoH tools in the required timeframe.

A Technical Expert Panel (TEP) and workshops were organised by NatHERS Administrator to seek recommendations from the TEP to inform the policy agreement on assumptions/settings behind whole of house modules for tools. With inputs from the TEP the Whole of Home National Calculations Method (WHNCM 2022) was developed. For existing dwellings, with the major assumptions/settings adopted from NatHERS Whole of Home National Calculations Method (WHNCM 2022) and the Scorecard (Scorecard 2022), a whole-of-home tool, the AccuRate Benchmark Tool, was developed by implementing new modules for water heating, lighting, swimming pool, other appliances, and solar PV into the modified version of the AusZEH design tool (Ren et al. 2013, Ren et al. 2018). This report details the development of the in-home benchmark tool.

2. IMPLEMENTING MODULES INTO THE AUSZEH DESIGN TOOL

The Whole of Home framework builds on the existing NatHERS framework and technology. The CSIRO Chenath engine (Walsh et al. 1983, Ren et al. 2010) is applied to calculate energy requirements for space heating and cooling with hourly data over a period of one year. In collaboration with the NatHERS TAC and other industry experts, methods were developed for calculating the energy demand of a home (WHNCM 2022), including space heating and cooling appliances, hot water system, lighting, pool and spa pumps, on-site solar PV system, plug in appliances, and energy scale rating.

2.1. Space heating and cooling

Considering delivery efficiency and energy efficiency of HVAC systems, energy consumption for space heating /cooling (H/C) can be calculated as

Hourly energy use for a zone is calculated using Equation 1:

$$E_{z.hr} = \frac{L_{z.hr}}{(1-LS)\times COP_A} \quad (1)$$

where

$E_{z.hr}$ = Hourly energy use for the zone (MJ)
$L_{z.hr}$ = Hourly energy load for the zone (MJ) calculated using the Chenath engine
COP_A = Coefficient of performance for the specified appliance, detailed in (WHNCM 2022)
LS = The system loss specified for the system type (e.g., ductwork), default losses for specified equipment losses are defined in (WHNCM 2022).

To obtain a single combined WoH assessment result for a parameter of interest (e.g., energy consumption for space heating/cooling), the values obtained for each of the separate performance assessments (All-Day and Work-Day) must be weighted using Equation 2:

$$P_{WoH} = 0.6 \times P_{All-Day} + 0.4 \times P_{Work-Day} \quad (2)$$

where

P_{WoH} = The weighted value of the subject parameter
$P_{All-Day}$ = The value of the subject parameter as assessed using the All-Day occupancy profile
$P_{Work-Day}$ = The value of the subject parameter as assessed using the Work-Day occupancy profile
The weighting factors of 0.6 and 0.4 were selected to align with the NCC 2022 settings (ABCB 2019).

2.2. Water heating

Hot water energy consumption

The methodology of Scorecard (Scorecard 2022) is adopted for this study. Energy consumption for water heating can be expressed as:

$$E_W = HWSL \times T_{adj} + \frac{E_{water}}{HWF} \times T_{adj} \quad (3)$$

where

E_w = The annual energy consumption for water heating (MJ/annual)
$HWSL$ = The standard losses of the hot water system (MJ/annual) (refer to (Scorecard 2022))
HWF = The marginal efficiency of energy conversion for the particular hot water system (refer to (Scorecard 2022))
T_{adj} = Corrects usage for variations in inlet water temperature and average ambient temperature, depending on location (detailed in (Scorecard 2022))
E_{water} = The annual energy requirements (MJ/annual) for hot water for dishwashing (E_{dw}), clothes washing (E_{cw}) and shower (E_{sh}), which are detailed in (Scorecard 2022)

With solar radiations 'G_s'(Scorecard 2022), solar fraction for water heating if present can be estimated as:

$$F_s = \frac{\left(0.4736 - 0.0562 \times \frac{60 - \frac{18.2}{T_{adj}}}{E_{water}} \times 365\right) \times 4 \times G_s - 0.1564 \times (60 - 18.2/T_{adj})}{E_{water}} \times 365 \quad (4)$$

Note that F_s should be in range 0-0.95, i.e, if $F_s \leq 0$, then $F_s=0$, and if $F_s \geq 0.95$, then $F_s=0.95$.

Considering solar hot water fraction and T_{adj}, the hot water energy efficiency is adjusted as

$$HWF_{adj} = HWF \times T_{adj}/(1 - F_s) \quad (5)$$

HWF_{adj} = The adjusted energy efficiency of the hot water system

With solar hot water system, the energy consumption can be estimated using Eq.3 by replacing HWF with HWF_{adj}.
The change in COP of heat pump hot water systems is caused by the different ambient temperatures in each location, which is detailed in (Scorecard 2022).

Calculation of hourly hot water energy consumption

The variation of water heating energy use with regions and seasons is described in AS/NZS4234 (AS/NZS 2008). AS/NZS4234 allocates four climate zones in Australia for solar thermal systems and five climate zones for heat pump water heaters. For the 69 climate zones in AccuRate, the corresponding climate regions for hot water module are defined in (Scorecard 2022). The monthly hot water use for each climate zone is also defined in (Scorecard 2022).

With the requirement for the WoH tools to provide hourly energy usage, the annual energy consumption by Eq. 3 needs to be broken down to daily and hourly usage, which is described in (Scorecard 2022).

2.3. Lighting module

When there are no halogens installed in the house, the annual energy consumption for lighting is calculated using Equation 15:

$$E_{tot} = \frac{365 \times P_L \times H_{avg} \times A_{tot} \times 3.6}{1000} \quad (6)$$

where

E_{tot} = Total annual energy consumption for lighting (MJ)
P_L = Light power density (W/m^2), 5 W/m^2 is used as default in this development
H_{avg} = Average hours for lighting use per day (hours), 1.6 hours are used for this development, which is adopted from ABCB NCC 2022 analysis (ABCB 2019).
A_{tot} = The total floor area (m^2), excluding garage zone, subfloor, roofspace, glazed common area and basement car park zones
365 is days per year, 3.6 converts kWh to MJ, and 1000 converts Wh to kWh.

The annual energy consumption for halogens is calculated as:

$$E_H \frac{365 \times H_{avg} \times N_H \times 60 \times 3.6}{1000} \quad (7)$$

where

E_H = Annual energy consumption for halogen lighting (MJ)

H_{avg} = Average hours for lighting use per day (hours), 1.6 hours are used for this development, which is adopted from ABCB NCC 2022 analysis (ABCB 2019).

N_H = The number of halogens

Hourly energy consumption for lighting is calculated using Equation 8:

$$E_{m,hr} = E_{tot} \times F_{L,hr} \quad (8)$$

where

$E_{m,hr}$ = Hourly energy consumption for lighting (MJ/hour)

E_{tot} = Total annual energy consumption for lighting (MJ), calculated by Equations 6 and 7

$F_{L,hr}$ = Lighting hourly factor, defined by Table 62 of (WHNCM 2022).

2.4. Pool and spa equipment

Pool energy consumption for pump and cleaning

For existing housing, pool volume is estimated roughly to be four levels, very small (2000L, representing a spa), small (10,000L), medium (25,000L) and large (50,000L). Energy consumption (kWh/annual) for pool pump and salt cleaning is adopted from Scorecard (Scorecard 2022).

Hourly energy consumption for pool pumping

Pool pumps are assumed to run for longer during swimming seasons than non-swimming seasons. Most people use outdoor swimming pools during warm and mild weather. The swimming season is defined (Scorecard 2022), from October to April. For swimming season swimming pool pump will run 4.5 hours a day and 3 hours for non-swimming day. So pump will run 1413 hours a year. Hourly energy consumption for pool pumping can be estimated as

$$Power_{pump} = E_{pump}/1413 \quad (9)$$

E_{pump}=Annual energy consumption for pool pumping (kWh/year)

$Power_{pump}$ = Hourly energy consumption (kWh) for pool pumping

2.5. Plug and cooking loads

This section will address energy consumption for other equipment, such as whitegoods, audio visual, small appliances, computers and peripherals, other electronic and standby power, and cooking.

The assumed annual plug loads in this study are based on work undertaken previously for Sustainability Victoria (SV 2022) and the Australian Building Codes Board (ABCB, 2019). From this work annual average total plug loads per number of occupants were derived, which are calculated as (WHNCM 2022)

$$E_{Plug} = 7022.4 + N_{Occ} \times 441.65 \quad (10)$$

where

E_{Plug} = Total annual plug energy load (MJ/year)

N_{Occ} = Number of occupants in the home, defined in (WHNCM 2022)

Annual cooktop and oven loads are calculated as (WHNCM 2022)

$$E_x = C_x + N_{Occ} \times F_x \quad (11)$$

where

E_x = Total annual cooktop/oven energy load in MJ/year

N_{Occ} = Number of occupants in the home

C_x = Cooktop/oven constant (MJ/year), defined in (WHNCM 2022)

F_x = Cooktop/oven factor, defined in (WHNCM 2022)

Plug and cooking loads are not evenly distributed across the day or cross the seasons. The annual plug and cooking load value is broken down into hourly loads across the year based on the expected distribution of those loads across the year. Hourly loads are calculated as

$$E_{x.hr=}E_x \times F_{x.hr} \quad (12)$$

where

$E_{x.hr}$ = hourly energy load for hour of day in each month (MJ/hour)
E_x = total annual plug energy load (MJ)
$F_{x.hr}$ = hourly load factor for hour of day in month (1/hour), which was generated by Energy Efficient Strategies based on monitoring study as defined in (WHNCM 2022)

2.6. Solar PV module

Electricity generation from onsite solar PV

The power output from a PV array can be calculated as

$$E_{sol} = f \times Y \times \frac{I_T}{1000 \times I_S} \quad (13)$$

where
E_{sol} = The hourly electricity generated from a PV array (kW)
Y = The rated capacity of the PV array (kW), the amount of power it would produce under standard test conditions of a panel with 25°C and 1 kW/m^2 irradiance
I_S = The standard amount of radiation used to rate the capacity of the PV array (1 kW/m^2)
I_T = The global solar radiation incident on the surface of the PV array (W/m^2), which is detailed in (WHNCM 2022, Ren et al. 2019)
f = The PV derating factor, considering system losses, impacts of shading, etc.
1000 converts W to 1 kW.

The total system losses are detailed in (Ren et al. 2019).

2.7. Energy value and whole of home rating

Societal cost

The energy value of a home is calculated by multiplying the net hourly fuel consumption by the 'societal cost' of the relevant energy source, and adding them together over a period of one year. The societal cost of a fuel source is the sum of the energy tariff and the cost of the carbon emissions associated with the fuel. To calculate societal cost of electricity, different tariffs for peak, off-peak and shoulder are applied. The costs of electricity, natural gas LPG and wood can be obtained from market survey to identify the average tariff in each state and territory, which are detailed in (WHNCM 2022).

Energy value of the house being assessed

As described above, this tool has been designed to calculate hourly energy consumption of fixed appliances (including for space heating and cooling, water heating, lighting, pool and spa, cooking and other plug-in loads), and hourly electricity generated by the roof-top PV system. The hourly electricity imported from grid is the hourly electricity consumption of the fixed appliances offset by the PV system (limited by its availability at the time). The imported electricity is segmented into peak, shoulder, off-peak and controlled load. For other fuel sources (such as natural gas, LPG and wood) only annual totals are required. This data is then multiplied by the relevant societal costs to calculate the energy value.

Energy value of the benchmark house

The energy value of the benchmark building is based on a 7-star NatHERS rating, a 3-star (2019 GEMS) ducted reverse-cycle air conditioner for space heating and cooling, a 5-star gas instantaneous water heater, and a lighting power density of 4W/m^2. The plug and cooking loads of the assessed house are also applied to the benchmark house. For calculating loads of the benchmark house, the assessed dwelling model is applied, i.e., the same floorplan, climate zone, orientation, and so on.

Energy rating of the house being assessed

The energy rating of the assessed house is calculated using the energy value of the benchmark building as a reference (WHNCM 2022). The rating scale is defined between 0 and 150 in (WHNCM 2022) where:

- 0 represents the worst performance of existing houses
- 50 (Benchmark 1) represents the benchmark building
- 60 (Benchmark 2) represents 70% of the regulated loads for Benchmark 1 plus the plug and cooking loads
- 100 represents net zero societal cost
- 150 represents the maximum rating awarded under NatHERS.

3. CASE STUDY

To demonstrate the impact of jurisdictions on the energy consumption and rating of residential houses, a detached single-storey double cavity brick house built in 1990 was used for simulations for capital cities of Australia states and territories. The house has a gross floor area of 293 m^2 and a net air-conditioned floor area of 207 m^2. The house has four bedrooms, a kitchen/family area, a living/dining room, a rumpus, a kids TV room, a laundry, a separate bathroom and toilet, and a double garage. It faces north.

As shown Figure 1, with the TMY weather files the house achieves the highest rating (4.7 stars) in Perth and lowest in Darwin (2.7 stars). In Australia the first minimum energy efficiency requirements for dwellings were incorporated into the Building Code of Australia in 2003 (Ren et al. 2012). For residential buildings built in the 1990s or earlier, their energy performance varied among the states and territories.

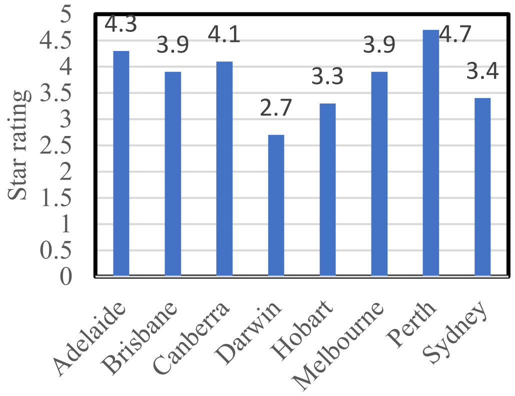

Figure 1. Star rating of the house in the eight cities

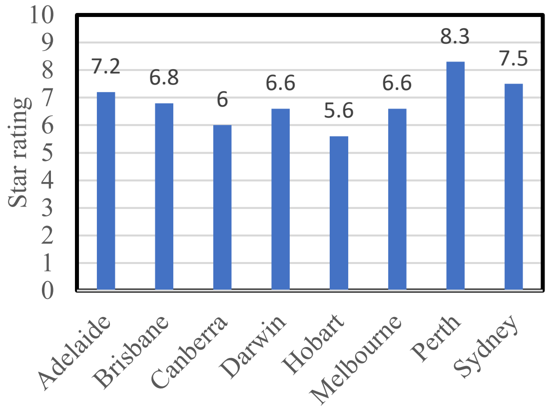

Figure 2. Star rating of the house after it was retrofitted in the eight cities

To analyse energy performance of the house, energy supply is considered to be electricity only. 1-star ducted single speed heat pump (more than 10 years old) is used for space heating and cooling, instant electric water heater is used for water heating, and electric cooktop and oven is used for cooking. There are 5 halogens installed in the family/kitchen room and LED lighting for others. There isn't swimming pool and solar PV installation. The annual energy consumptions of individual modules and whole house and energy value are summarized below.

There is no need for space heating in Darwin (tropical region) and little energy requirement for space cooling in Hobart. A large amount of energy is required for space heating in Hobart and Canberra. The ratio of electricity consumption for space heating and cooling (H/C) to the whole-of-home electricity consumption is 72.4% (highest) in Darwin and 25.5% (lowest) in Brisbane. In Sydney it is also less than 30% (29.4%). In Canberra and Hobart, they are over 60%. The electricity consumption is greater than 24000 kWh in Darwin, and over 9000 kWh in other cities. To operate the house, it is the cheapest in Brisbane and the most expensive in Darwin (near A$7000). Sydney, Melbourne and Perth are relatively cheaper. The energy rating scale is 0 in Canberra, Darwin, Hobart and Melbourne.

Considering the orientation of the house unable to change and expensive (or difficult) to insulate to external walls and floor, we improve the house thermal performance by insulating the roof with R5, sealing the exhaust fans and weather stripping the windows and doors, and replacing the windows with high performance windows of timber double glazed with Argon fill and their outdoor covered with 40% shade cloth. For lighting the 5 halogens were replaced with LED lighting. The hot water system was replaced with electric boosted solar hot water system. The space heating and cooling systems were updated with 5-star ducted heat pump system.

The star rating of the house retrofitted is shown in Figure 2. The retrofitted house achieves the highest star (8.3 stars) in Perth and the lowest star (5.6 stars) in Hobart. The star rating in three cities (Perth, Sydney and Adelaide) is greater than the NCC2022 energy efficiency provisions requirement of the equivalent of NatHERS 7 stars. The star rating in the other cities (except Hobart) is greater than the equivalent 6 stars of the NCC 2019 energy efficiency requirement.

Annual electricity consumption of the updated house in the eight cities is summarized: significant reductions in space H/C and more than 50% in total electricity in all the cities after the house was retrofitted. The greatest saving is 68.6% in Darwin and the smallest saving is 50.4% in Hobart.

This tool is used to investigate sizing roof-top PV system to achieve zero energy (carbon) housing, i.e., the electricity generated by solar PV is not less than the total electricity consumption. The results are summarized for the updated house in the eight cities: in Darwin and Hobart, the house needs be installed with 5 kW, and in Brisbane and Perth only 3 kW is required. 3.5 kW is required for Sydney and Adelaide, and 4 kW is required in Melbourne and Canberra. With the house updated and installation of the PV, it is free for whole year operation of the house (-A$181.2, i.e., will be paid $181.2 by the energy retail company) in Darwin and energy rating scale is 103 (greater than 100). For the other cities, several hundred Australian dollars is required and energy rating scale is greater than 85.

4. CONCLUSIONS

With some assumptions being adopted from Scorecard (Scorecard 2022), including insulation to roof space, external wall and floor, and water heating, and other assumptions being adopted from the NatHERS whole of home national calculations method (WHNCM 2022), a benchmark tool was developed for calculating whole-of-home energy calculation and energy value for existing housing in Australia. The tool includes modules of space heating and cooling, water heating, lighting, swimming pool, plug and cooking loads, solar PV, and energy value and rating. The modules were implemented into the AusZEH design tool. To make sure the modules implemented properly, the simulated hourly and annual data by the tool were tested against the data generated by the modules constructed with Excel files.

The tool was used to demonstrate the calculations of whole-of-home energy consumption, and energy value and rating for capital cities of Australia states and territories. For a detached house built in 1990 with a gross floor area of 293 m^2, as expected, a large amount of energy is required for space heating in Hobart and Canberra, and for space cooling in Darwin. To operate the house, when electricity supply is available only, Darwin is the most expensive city (near A$7000); Brisbane is the cheapest. With the scenario of electricity supply available only, the energy rating scale is 0 in Canberra, Darwin, Hobart and Melbourne. That means the energy performance of the house in these four cities is under the worst energy performance condition.

With the house being updated with high energy performance building envelope and high energy efficient equipment and appliances, more than half energy was saved in all the eight cities. To achieve zero energy (carbon) housing, installation of 5 kW solar PV is required in Darwin and Hobart, 4 kW in Melbourne and Canberra, 3.5 kW in Adelaide and Sydney, and 3 kW in Brisbane and Perth. As the difference in tariffs for electricity imported and exported, except in Darwin, it needs several hundred Australia dollars to operate the retrofitted house even it was achieved zero energy (or exported energy is greater than imported).

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